EVALUATING STUDENTS’ PERFORMANCE IN ORGANIC CHEMISTRY AT ADVANCED LEVEL

Joseph Jude Bellizzi

A Dissertation Presented to the Faculty of Education in Part Fulfilment of the Requirements for the Degree of Master in Teaching and Learning (Science/Chemistry) at the University of Malta

June 2018

Abstract

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Evaluating students' performance in Organic Chemistry at Advanced Level

This study focused on students' performance in organic chemistry questions in the 2017 chemistry A-level examination. It aimed to highlight difficulties in organic chemistry answers. For the purpose of this study, three paper I organic chemistry questions were analysed. All the A-level scripts were sorted, ranked from highest to lowest obtained mark and allotted a code, where the first 150 scripts from the top band and the last 150 scripts from the bottom band were analysed. The study of the 300 scripts involved a deep analysis of the students' responses by using error and item analysis for which facility index, item difficulty and item discriminating power were calculated. In this research, errors in organic chemistry were found to be numerous, in agreement with the literature. The most common difficulties were those related to nomenclature, application of inorganic, analytical and physical chemistry principles to organic chemistry questions and application of organic chemistry principles. The least common mistakes were made for questions at the lowest level of Bloom's taxonomy, recall, however there were still numerous errors related to recall and understanding.

Supervisor MTL in Science

Dr J. Farrugia June 2018

Organic chemistry Advanced level Difficulties

Item analysis Error analysis

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Acknowledgements

With immense gratitude, I'd like to start off by thanking my supervisor Dr J. Farrugia, B.Ed (Hons.), PhD (York) with whom I have worked for the past two years. This was a new challenge to us both given that I'm the first MTL (science) student, and with tremendous work and rigour from both parties, this dissertation was a success story. The morale boost from the science lecturers within the department throughout these two years was constant, namely by: Dr C. Bonello, Prof D. Chetcuti, Dr M. Musumeci and Prof P. Pace.

Secondly I'd like to thank the MATSEC board for accepting my proposal to carry out a research study on A-level chemistry. My appreciation also extends to Mr G. Zahra with whom I was in contact and who guided me throughout the collection of the scripts.

I'd like to also show my gratitude to the people who mean a lot to me. In spite of my peculiar character throughout the studies, I always found a helping hand from my family, namely my mother Nathalie, my father Pierre, my grandmother Doris, my brother Colin, my step-father Paul and other close relatives. Considering my closest friends as family, I thank them too.

I grew a passion for chemistry since a young age, and this was possible thanks to some of my past lecturers, namely: Mrs J. Mifsud and Mrs P. Jones. Nevertheless, I owe the accomplishment of this thesis to one of the greatest chemists I ever met, Dr. Robert Atkins. When I started my journey at Junior College, I recall how fascinated I was by the way he taught organic chemistry, which mirrored his passion for it. I can still hear him say that students tend to encounter various difficulties in organic chemistry and the only way to overcome them is to employ time and understand underlying principles. I used to spend lots of time discussing organic chemistry with him, and I'll cherish those memories for a lifetime. Nine years down the line, as a chemist I was lucky to write a dissertation about what he had told us and prove his statement right. I owe all I know and all I've become to Dr. Robert Atkins, and whilst I eternally express my admiration, I dedicate this thesis to him.

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2 –D	2 – Dimensional
3 - D	3 – Dimensional
A-level	Advanced Level
MATSEC	The Matriculation and Secondary Certificate Examinations Board
PAO	Principle Area Officer
SEC	Secondary Education Certificate

1. Introduction

1. Introduction

1.1. Introduction

As it has been indicated by literature and examiners' reports, students at A-level far badly in organic chemistry. With hindsight, I can also recall how course-mates at A-level struggled with organic chemistry. Literature suggests that the field is studied very superficially, which shows an inability to relate the macroscopic, submicroscopic and symbolic levels (Johnstone 1991). Therefore learning does not take place, because the underlying chemistry principles are not comprehended and this leads to numerous difficulties when tackling organic chemistry questions. In part, this is also due to the abstract nature of organic chemistry, which further creates misconceptions at A-level. Present literature backs the fact that students perform badly in organic chemistry across the board, ranging from ordinary level to post-secondary and university levels. Nevertheless, not much literature is present to highlight the difficulties encountered by students in organic chemistry.

1.2. Aim of study and research questions

The aim of this study was to highlight and deal with difficulties, misunderstandings and errors made by students in organic chemistry questions in the chemistry A-level 2017, and thus evaluate their overall performance in organic chemistry. Given that the difficulties are highlighted, the main areas of concern were established. Therefore, due to this aim, the research questions guiding this study were the following:

1. To which extent do the organic chemistry questions at A-level discriminate between high and low achievers?

2. Following the consistent poor performance in organic chemistry questions at A-level, what are the main areas of concern?

3. What are the most common difficulties encountered by students, and how does the abstract nature of organic chemistry relate to all this?

1.3. Motivation behind this study

This study about students' difficulties in organic chemistry at advanced level is significant for a number of reasons. First off, not all A-level lecturers and teachers might be aware of the grave performance of students in organic chemistry. Hence, highlighting these misconceptions will help educators identify areas where students need further help and support. Secondly, the study will highlight ways of how organic chemistry is related to physical and inorganic chemistry and how the principles of all areas are meant to intertwine, presenting a collective understanding of the subject. In spite of the fact that organic chemistry is taught separately from inorganic, physical and analytical chemistry, it is still one subject and principles from one area to another need to be applied in another area.

Moreover, local and foreign literature related to students' difficulties in organic chemistry at A-level is limited. Not dealing with one branch of chemistry, namely organic chemistry, would signify a serious deficiency especially since, A-level chemistry is an entry requirement for various university courses. Linking organic chemistry and other branches of chemistry A-level, ensure a better understanding of underlying principles.

On a personal note, I can recall the frustration of my fellow A-level course mates due to the inability of understanding organic chemistry, leading to poor grades in tests and consequently even in the actual exam. This failure to understand had made learning chemistry a challenge. I strongly believe that the importance of not learning superficially but learning by understanding underlying concepts, is of utmost importance. Not only will this lead to getting a good grade, thus extrinsic motivation, but also an intrinsic one which is gained from the appreciation of how chemistry principles are connected. This would be beneficial for all students especially those intending to study chemistry at undergraduate level.

1.4. Conclusion

In this first chapter, an introduction about the study has been highlighted by giving the aims of the study and the motivation behind the study. The second chapter is the 'Literature review' which gives a theoretical background based on literature which highlights the fact that chemistry is deemed as difficult by students, especially organic chemistry, and how local examiners' reports had reported that students fared badly in organic chemistry questions at A-level in previous years. The third chapter deals with the methodology and the way the study was conducted, namely the collection of the scripts, the way they were sorted and the data retrieved and analysed from the organic chemistry questions of paper I. The fourth chapter is the 'Results and discussion' which presents the data of the study and the findings, which include a detailed analysis of the students' answers, the facility index, item difficulty and item discriminating power. These have led to answering of the research questions stated in Section 1.2. In the last chapter, a conclusion is drawn from the study which highlights the main findings of this study followed by the study's implications, limitations and recommendations for further research.

2. Literature review

2. Literature review

2.1. Introduction

As stated by scientists and chemistry teachers in the study conducted by Shwartz et al. (2006), chemical literacy is important to students as this imposes a direct shift from the chemical content per se to a framework which is more comprehensive. According to the OECD PISA framework (2015), the definition of scientific literacy is:

''the ability to engage with science-related issues, and with the ideas of science, as a relative citizen. A scientifically literate person, therefore, is willing to engage in reasoned discourse about science and technology which requires competencies to: 1. Explain phenomena scientifically; 2. Evaluate and design scientific enquiry; 3. Interpret data and evidence scientifically.'' (p.7)

In their paper, Sadler and Zeidler (2009) described how this phrase represents what students are expected to know following their science learning experiences. There are two visions of scientific literacy; Vision I and Vision II. The former promotes the scientific concepts and helps the development of students' understanding of scientific phenomena with the intention of producing scientists (Millar, 2008). To the contrary Vision II does not prioritise decontextualized science concepts, rather, it focuses on the applicability of the scientific concepts in real-life situations. This broader scope involves development of various skills such as critical thinking and decision-making. Thus, the articulations pertaining to Vision I science literacy go about the discipline of science per se, and what people who have a knowledge of science are expected to know. To the contrary, Vision II science literacy looks more into the contexts that give individuals a knowledge of science and the opportunity to use the scientific knowledge and reason solutions out.

Several curricular programmes are designed to promote Vision I science literacy (Millar, 2008) such as the Chemistry A-level syllabus (2017) for Malta. The Advanced Matriculation Syllabus (2017 – 2018, p.1) states that: "The course is intended to build both a theoretical knowledge base in chemistry that prepares students for further higher studies in the subject as well as to develop basic practical skills.” Thus the main aim of the Chemistry A-level syllabus, is to produce chemists (scientists) who would pursue with their studies in the subject at higher levels, promoting Vision I.

As Celik (2014) argues, teaching any science subject, including chemistry, will train scientifically literate people. Teaching chemistry contributes to chemical literacy and with special reference to the A-level, chemistry students have to be trained as scientists in order to read for chemistry degrees (Millar, 2008). This scenario is observed in the study of Garner-O’Neale et al. (2013) where the majority of undergraduate students reading for a chemistry degree at the University of the West Indies were at a good level of scientific literacy, following the A-level. This aspect of chemical literacy is important especially for organic chemistry as the latter requires a high degree of reasoning, piecing all of the knowledge together in order to obtain concrete answers when answering exam questions or desirable outcomes following organic lab sessions. The lack of chemical literacy will lead to what Nakhleh (1992) describes as an inappropriate construction of understandings of fundamental chemical concepts from the onset which will therefore impede students from fully understanding advanced concepts that build on the fundamentals. Sendur (2012) argues how students who have scientific conceptions from prior knowledge, which are different to those accepted by the scientific community, are labelled as misconceptions.

Chemistry is a subject which branches into several areas and being a requirement for many university courses, the chemistry A-level (advanced level) is an important milestone to all those who wish to pursue further their studies. Nevertheless the misunderstandings and misconceptions, being purely part of the learning and teaching experience, tend to be high in chemistry students resulting in an insecurity described by Karatjas (2013), where students who are sitting for a chemistry exam, particularly organic chemistry, have a feeling of apprehension before the exam itself. This may lead to unsatisfactory grades and having the subject labelled negatively, as being difficult. Zoller (1990) describes how these misunderstandings and misconceptions are constituting a problem to science educators, scientist-researchers and students, where chemistry now has a ‘particular status’ (p.1054) and this has stemmed from the difficulties students have faced throughout the years. Thus as far as learning difficulties and misunderstandings are concerned, chemistry majors and nonmajors agree that probably freshman chemistry (general and organic) is the most challenging and problematic science discipline. Zoller (1990) believes that the difficulties stem from the abstract, non-intuitive and not-directly-interrelated concepts and subconcepts. Sirhan (2007) took the concept of chemistry being difficult to another level, stating how the area proves to be difficult as the topics are mainly based or related to the structure of matter, where the curricula incorporate many abstract concepts, which nevertheless are essential.

The likelihood of choosing chemistry at higher levels, following an unpleasant past experience, is not promising. As Nakhleh (1992) describes in her paper, students struggle to create a cognitive structure of a complex body of knowledge in chemistry, thus it is small wonder that chemistry students across the board are more likely to be, what she calls, unsuccessful. It is true that a considerable number of students fail to apply concepts which are essential in chemistry, especially organic chemistry. As Ayas & Demirbaş (1997) state in their paper, the vast majority of students found it difficult to apply concepts and understandings in chemistry to new situations. In organic chemistry, unlike perhaps other areas, one has to apply the knowledge acquired and reproduce it several times into new forms, for example in designing synthetic pathways. The abstract nature of chemistry as a source of difficulty is highlighted in the study of Johnstone (1974) where he described how misconceptions about the mole had diminished over time but those relating to organic chemistry were more persistent and were exacerbated upon the introduction of spatial concepts surrounding the orbital theory.

2.2. Conceptual difficulties in chemistry

Students tend to perform badly in the organic chemistry questions set in the A-level examinations as often reported in the examiners' reports (2016, 2015). Several reasons have been suggested, as Tsaparlis (1997) argues, students would commence their university undergraduate courses with an incomplete body of knowledge and many conceptual difficulties. In his paper, Sirhan (2007) describes how there is an essential and constant interplay between the macroscopic and microscopic levels of thought, which aspect is posing a challenge to novice chemistry students. There are various reports tackling some of the most challenging areas in chemistry including organic chemistry, and these areas have been subject to scrutinous studies with the aim of finding a common factor between them. It resulted, as Chittleborough & Treagust (2007) argue, that the interplay between the macroscopic and microscopic facets of chemistry is one source contributing to the complex nature of chemistry. Conceptual difficulties further arise because, as Gkitzia et al. (2011) argue, chemistry is an area of study which deals with phenomena that are not available to direct experience, giving a sense to what is unseen and untouched by creating mental images for the corresponding phenomena.

2.2.1. The three different levels of chemical understanding

Chemical knowledge and understanding, the way it is perceived and communicated, can be categorised into three main levels according to Johnstone (1991), namely: macroscopic, submicroscopic and symbolic levels. These three levels compose a triangle of the multilevel thought and segregates ways of how students learn, and convey points of why students might find chemistry difficult. Talanquer (2011) described this triplet relationship and states how macrochemistry (i.e. macro level) relates to the entities and phenomena that are visible and tangible; the submicrochemistry relates to the particulate models of matter whilst the symbolic level encompasses the chemical and mathematical symbols/signs and their relationships, for instance in equations. The symbolic level incorporates a variety of algebraic and computational forms of the submicroscopic representations, which eventually leads to people being able to observe the macroscopic and use models to represent the submicroscopic levels. In his paper, Johnstone (1991) argues how certain educators believe that chemistry can be learnt and understood by switching from one level to another, yet the author goes on to say how even though this concept holds true, there are topics which may be learnt using two levels only, without the need of introducing the third one. This triangle of levels of thought shows how certain concepts fall under particular categories (levels).

Chittleborough & Treagust (2007) showed in their study how students with a sound knowledge of chemistry are at an advantage when understanding submicrochemistry. This does not necessarily mean that the skills have to be innate, rather these skills can be mastered over a period of time, but as the skills become more ingrained, the understanding of submicrochemistry is eased. Because chemistry is, what Gkitzia et al. (2011, p.5) describe as: "a representative, symbolic and visual science" it may be hard for students to understand and interpret the three chemical levels: macro, submicro and symbolic, and would experience difficulties in making translations between them and constructing them. There is also a special difficulty in the submicrochemistry where students encounter a greater amount of challenges as described by Sunyono et al. (2015); this stands to reason as it deals with aspects in chemistry that are not tangible.

2.2.2. Chemical topology

So far, the abstract nature of chemistry has been presented as one of the salient reasons why the subject is considered to be one of the most challenging, if not the most. Another reason which goes in tandem with the abstractness of chemistry is chemical topology. Babaev (1999) argues how the relation of chemical applications to topology and related fields of mathematics are rapidly growing and flourishing in an interdisciplinary field of mathematical chemistry, that is, chemical topology. Mathematics has now become singularly vital, as Coulson (1974, p. 17) has stated: "Mathematics is now so central, so much inside, that without it we cannot hope to understand our chemistry". Bucknum & Castro (2009) describe a systematic classification and mapping of polyhedra structures, having 2-dimensional tessellations and 3-dimensional networks in a self-consistent topological space, these being mathematical. This is an essential tool in order to fully understand 3-D structures which will aid in all aspects of chemistry; be it crystalline structures or some well-known organic structures. Some students' minimal understanding of chemical topology further bars any form of understanding at higher levels leading to a difficulty in fulfilling the Vision I of the Chemistry A-level. Frisch & Wasserman (1961) highlight how topology is important to understand features related to molecular structures, including: spatial arrangements consistent with the order in which given numbers of specific atoms are joined (stoichiometry), the type of bonds which connect them and the spatial arrangements around rigid centres (molecules with double bonds or asymmetric structures). Thus, chemical topology is an essential reason why students find chemistry difficult, where according to Francl (2009) the term chemical topology has been stretched by chemists to encompass many areas in chemistry, making it more essential to the understanding of the subject. Spatial arrangements are a way of depicting molecules and mechanisms especially in organic chemistry, thus the use of chemical topology, which aids the formation and development of such skills, is a requisite for A-level chemistry students who are required to visualise and manipulate organic molecules. Babaev (1999) describes how topology is important to organic chemistry as sets of related atoms or structures are grouped together into similar classes in accordance to important numerical variants such as saturation degree. Moreover, the ability of converting visual 3-D mental images into 2-D ones is of utmost importance to organic chemistry as 2-D models can be drawn but the 3-D mental images cannot.

2.3. Challenges encountered in organic chemistry

Concrete examples of organic chemistry difficulties show how its abstract nature leads to minimal understanding of the submicrochemistry and symbolic chemistry involved in this topic. Organic chemistry is very abstract and because little to none is tangible, especially when it comes to synthetic pathways and conversions, students find it challenging.

2.3.1. Students' perspective of organic chemistry

As already discussed, chemistry is one of the most challenging fields. Moreover, due to its abstract nature together with chemical topology, students tend to find organic chemistry daunting. In the study of Grove et al. (2008) the attrition rate for a year-long chemistry course intended for pre-medical majors ranges from 30 – 50%, where organic chemistry was regarded as a course with a difficult reputation and not being the vibrant discipline described by the National Research Council (NRC). The students reading for the course will observe their peers struggle their way through, and the myth that organic chemistry is tough is being passed on to the next generation of organic chemistry students. Grove et al. (2008) go on saying that first year organic chemistry students had heard 'horror stories' (p.159) from their relatives and friends about the level of difficulty of organic chemistry thus it comes as no surprise how students sitting for organic chemistry exams are apprehensive (Karatjas, 2013). Also, according to Pungente and Badger (2003), students start off their journey in organic chemistry with a feeling of apprehension. This emerges from declarations of organic chemistry students, where unfortunately some students view organic chemistry as a “rite of passage” (p. 779) or “the academic equivalent of hazing” (p. 779). Furthermore, mastery of organic chemistry cannot take place using the same study skills applied for other courses. Katz (1996) as cited in O’Dwyer and Childs (2011, p.2) described how students had a really bad perception of organic chemistry: “Among students, the organic chemistry course has a bad reputation of mythic proportions. From their viewpoint organic chemistry is a dreaded ‘wash-out’ course”.

2.3.2. Examples of misconceptions in organic chemistry

Organic chemistry is a field which gradually builds up and cannot have its sub-topics covered with no reference to previous ones. As Sendur (2012) argues, if students do not get the gist of initially taught topics in organic chemistry, such as alkenes, they will be barred from further understanding of organic chemistry, easily developing misconceptions. The study goes on highlighting various difficulties surfacing after the tests were conducted, including but not limited to nomenclature and isomerism of organic molecules. Sirhan (2007) discussed how difficulties in chemistry arise in topics relating to structure of matter. The representations of models of molecular structures are a requisite for chemists, chemistry teachers and students as this is a medium of communication in chemistry, as Head et al. (2005) describe in their paper. Head et al. (2005) carried out a study on the understanding and use of several styles in representing single organic molecules. The participants involved first-year undergraduate chemistry students, thus those who had just sat for their A-level and were asked to discuss whether a pair of molecular structures were enantiomers. Thus, students not only had to be able to retrieve information from past experiences about enantiomers, but clearly understand the submicrochemistry underlying it, showing how important submicrochemistry is to understanding chemical topology in organic chemistry.

As Luisi, & Thomas (1990) argue, modelling in chemistry, that is the pictorial images transcribed into models, has become the dominant way of thinking in organic chemistry and these models denote the phenomena observed (for chemists) and phenomena learnt (for chemistry students) at a macroscopic level. For example, chemists and chemistry teachers are aware that a pair of enantiomers will rotate plane-polarized light in opposite directions. In order to rationalize this concept, a model of molecular structures should be drawn in 2-D, where chemical topology is a requisite for the full understanding of the molecules' chirality and 3-D shape, making the argument of Bucknum & Castro (2009) regarding chemical topology, very applicable. It is to note how these molecular shapes are represented symbolically, thus the three levels of chemistry thinking might at times intertwine to give the desired outcome. Just like Luisi, & Thomas (1990) had argued about the importance of depicting models, in their paper, Strickland et al. (2010) also argue how representations in organic chemistry are a cornerstone to scientific practice, and scientists along with other people in the field use it as a primary means to communicate and solve problems. The external representations, that is the knowledge and structure within one's mind made public for example on paper, may be divided into sentential and diagrammatic categories. The former are expressed as propositional statements in linguistic or mathematical form, whilst the latter are graphical displays containing spatial relationships between symbols. Strickland et al. (2010) go on discussing how organic chemistry is full of diagrammatic representational systems, thus the students with an inadequate or inaccurate level of understanding of diagrams will be unable to solve problems in organic chemistry and this may impede subsequent development of them becoming scientists. In fact, students interviewed in the study had a tough time expressing mental models of terminology used frequently in organic chemistry to describe organic reactions and diagrams used to represent the organic reactions and pertaining mechanisms. Moreover, the conceptualisation of the participants had little mechanistic and process-oriented attributes, such as in the case where students could not distinguish properly between nucleophilicity and basicity. The study also shows how none of the participants had noted that nucleophilic and electrophilic species refer to kinetic behaviour. The students who then had process-oriented definitions of some terms had a difficult time applying the definitions to their diagrammatic descriptions. Lack of understanding of terms related to nucleophiles and electrophiles would intertwine with other misconceptions presented by Zoller (1990) who in his study asked students why species with double bonds (alkenes) are more prone to attack by electrophiles than single bond species (alkanes).

Another keystone of organic chemistry are mechanisms, used to indicate how changes in the reaction schemes take place. Bhattacharyya & Bodner (2005) describe how in sum, students interviewed in their study did not value the importance of the curved-arrow or electron-pushing formalism. Because to the students these curved-arrows had no physical meaning, it became more apparent how the study conducted by Schwartz (1995) on diagrammatic reasoning holds true. The ground for people to reason on the real object is based on realistic images referring to the object. However, when the images progressively become more abstract (going from a simple molecule to its retrosynthetic pathway for instance) the persons' reasoning tends to rely on the representation itself and does not go beyond, impeding further reasoning and chances of problem-solving solutions.

It is more important to possess an understanding of concepts of chemistry in order to make informed decisions, rather than mastering a mass of knowledge. This could have been the case why students could not differentiate between a spectrum of a primary halogenoalkane to that of a secondary one as highlighted in the examiners' report 2015. The study of Celik (2014) goes on saying how in its findings, students were not able to explain the mechanism of the oxidation of hydrocarbons, where only 23% of the students attempted the question in the study and only 34% of that percentage got the answer correct. According to Celik (2014) the students' reading and studying habits do not seem to contribute to the required chemical literacy resulting from the passive learning environment students have become accustomed to.

2.3.3. Trends in local students' misunderstandings and misconceptions

The aim of this dissertation is to highlight general difficulties students face in the organic component of their chemistry A-level, thus a detailed summary of the past ten years has been prepared. The information has been gathered from examiners' reports published over the past ten years. In this summary, a general overview of areas in organic chemistry in which students had performed badly was gathered in the form of a table. Table 2.1 illustrates how similar difficulties were also present in scientific literature.

Table 2.1 – List of most common difficulties encountered in organic chemistry questions for chemistry A-level 2006 – 2016

Year	Identification of organic compound	Naming/drawing/ interpreting organic structures	Synthetic routes	Mechanistic principles	Conditions and reactants for chemical reactions	Interpretation of mass spectra /spectroscopy
2006	✓	✓	✓	✓	✓	
2007	✓	✓	✓	✓	✓	✓
2008	✓	✓	✓			✓
2009	✓	✓	✓	✓	✓	
2010	✓	✓	✓	✓	✓	
2011	✓	✓	✓	✓	✓	
2012		✓	✓	✓		✓
2013			✓	✓	✓	
2014		✓			✓	✓
2015	✓	✓	✓	✓	✓	✓
2016	✓	✓	✓	✓	✓	

It is to note how the most common difficulties listed in Table 2.1 were ticked, accordingly representing the majority of students who struggled to arrive at the right answer, as highlighted by the examiners' reports (2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009, 2008, 2007, 2006).

2.3.4. General comments for Chemistry A-level 2015

Organic chemistry is by far that component in chemistry which students tend to struggle most to study and deal with in exams. According to several examiners' reports, including the most recent ones for the examination sessions of 2015 and 2016, the questions pertaining to organic chemistry were the ones where students lost the bulk of their marks. The 2015 A-level is being chosen as a means to illustrate some of the most common difficulties students encounter in organic chemistry, given that the paper is one of the most recent and encompasses most of the difficulties mentioned in Table 2.1.

In the general comments of the 2015 examiners' report, the first lines describe how question 7 in paper 1 regarding the interpretation of the mass spectrum of an organic compound, resulted to be one of the most challenging, whilst question 4 which regarded the ideal gas law resulted to be less challenging. In question 7, students failed to distinguish between a primary and a secondary halogenoalkane and were not able to give reasons why the mass spectrum of 2-chloropropane would be different from that of 1-chloropropane. Furthermore, question 8 needed a knowledge of synthesis, where students were expected to convert an unknown substance into a primary alcohol through a synthetic process using the Grignard's reagent, however most of them failed to state the reagents and reaction conditions. The facility index is given in each report, and this represents the difficulty of the question and gives an indication of how difficult a question was for a particular cohort of students; the smaller the facility index the more difficult the questions resulted based on the answers and performance of the students. In question 7 the facility index was 0.27 (where 1.0 is the maximum). The report goes on saying, that in paper 2, the most challenging and least attempted question was question number 7 regarding the interpretation of an IR spectrum, where the facility index was 0.30 and the percentage of candidates who attempted the question was 26%. This question regarding carboxylic acids and IR spectra was attempted by few candidates and some of those who tried it, gave incorrect synthetic pathways for the conversion of ethyne to butenedioic acid. On the other hand the least challenging and most attempted was question 5 tackling ionic equilibria with a facility index of 0.47 and a percentage attempt of 89%.

2.4. Conclusion

Whilst the results depicted over the past ten years may be restricted to the respective particular cohort of students, they are consistent with research carried out with chemistry students in other countries (Celik, 2014; Head et al., 2005; Strickland et al., 2010; Zoller, 1990). According to Sendur (2012) further studies, highlighting misconceptions in organic chemistry, should be conducted in order to investigate and understand learners' misconceptions and misunderstandings. Unfortunately, as Akkuzu & Uyulgan (2015) state in their paper, few research studies have been carried out in terms of international research addressing students' misconceptions in organic chemistry. Considering the findings of the study by Akkuzu & Uyulgan (2015) more fully, it is evident that there is an even more limited number of papers relating to students' level of understanding of functional groups, which are considered to be of paramount importance given that they play a critical role in the classification of organic compounds according to their reactivities, as well as in the type of chemical reactions and synthetic pathways the molecules undergo. A detailed study highlighting the difficulties and misconceptions in organic chemistry will aid teachers in supporting future chemistry students in dealing with organic chemistry. Thus the aim of this study is to highlight common difficulties in organic chemistry, bringing common misconceptions and misunderstandings to light with the intent of helping future chemistry educators and students.

3. Methodology

3. Methodology

3.1. Introduction

When it comes to methodology, there can be several approaches to one's study in education (Cohen et al., 2000). Depending on the nature of the study, one has to adopt a particular type of research method in way of analysing and presenting the data and interpreting it meticulously. In this chapter a detailed procedure of how the data were gathered and analysed will follow, along with a discussion of validity issues.

3.2. Aims and objectives

The main aim of this study was to identify errors and misconceptions shown by A-level students in organic chemistry and in order to do so, an analysis of 300 A-level scripts was carried out. The analysis focused on Paper 1 organic chemistry questions, namely questions 7, 8 and 9. As Yuan et al. (2012) argue, it is important to carry out statistical analysis and evaluation of examination results in order to provide good management of examinations as this would lead to theoretical basis for teaching evaluation, research and reform. The authors go on saying how such analysis may identify problems in the teaching process, consequently leading to analysis of whether learning is taking place or not. Hence, such analysis would help lecturers and students understand better whether learning of organic principles has taken place and how this can be improved. In their paper, Kumar & Patel (2014) argue about the importance of conducting analysis and evaluation on question papers as this would lead to improvement in the teaching-learning process and to improve future level of learning.

3.3. Research design

The approach adopted for this study followed a mixed methods approach. In his paper, Gelling (2015) states how a quantitative approach is somewhat different from qualitative, thus prior to deciding which method to opt for, the research question has to be well formulated, as the study conducted will be part of the equation which will be finding knowledge and contributing to the truth. In this study, a qualitative approach would not suffice given that the analysis of several scripts took place. The quantitative approach involves a research question which is less personalised and involves directly or indirectly the input of many people, thus it encompasses the use of statistical and numerical data assuming that the phenomenon under study is measurable. One of the main aims is that through the data collected, trends, links and relationships emerge which will substantiate the measurements made in relation to the research question. As explained by Watson (2015) the measurable traits are called variables of which there are two main types: independent and dependent, where the latter may be influenced by the former. In the case of this study, the quantitative approach would not suffice as deep analysis of each question will take place. As Halcomb & Hickman (2015) argue in their paper, some studies require the use of the hybrid produced between qualitative and quantitative methods, as in order to fully answer the research question one method will not suffice, rather both methods in tandem will give optimal results. The use of the mixed methods included item and error analysis as highlighted in Section 3.3.1.

3.3.1. Error analysis leading to facility index and item discriminating power

In his paper, Sreekanth (2007) argues how evaluation is a broad term as it includes both quantitative and qualitative description of the performance and value judgement. Another type of method used in order to carry out description of performance and value judgement is item and error analysis following the scrutiny of the responses to organic chemistry questions in the A-level examination for the 2017 cohort. The exam may be regarded as being composed of several items, and the effectiveness and performance in each item can be determined through analysis of student responses, where item analysis is associated with the norm-referenced perspective, that is, a comparison of the test takers in relation to one another. The results and response of items will show whether an item is able to discriminate between high and low achieving students. This may also highlight faulty questions which might have mislead students (if at all), exposing technical defects in items and tasks, revealing any possible ineffective distracters which might have led to students getting low marks. The analysis included calculation of the item difficulty, facility index and item discriminating power. An error analysis was carried out on each organic chemistry question and their respective sub-questions of paper 1 for 300 A-level scripts from the 2017 cohort.

3.3.2. Population and sampling

For the analysis of responses to organic chemistry questions, a targeted population and sample were required. Sreekanth (2007) argues about the importance of the way research is conducted by means of a sample drawn from a targeted population on the basis of which generalizations are drawn and made applicable. Hence in this study, the 2017 cohort was analysed as it happened to be the latest cohort sitting for the chemistry A-level exam.

In this study, 300 scripts out of 454 were analysed. The scripts were marked with an office number assigned by the examination board and the pertaining global mark, thus the office number was used as a means of identifying particular scripts. In order to segregate the scripts, all the marks were noted and ranked from highest to lowest marks, taking 150 scripts from the high achievers group and 150 scripts from the low achievers group. The middle band consisting of 154 students, have attained a mark which was assumed to reflect a performance in-between that of high and low achievers. Eventually a new number was given to each script, substituting the office number. The script with the highest mark was given number 1 and that with the lowest mark was given 300. In this way, further discretion was assured.

3.3.3. Data collection

The chemistry A-level students sit for their exam in May, the scripts are collected and graded. Graded scripts are stored for any research required. The scripts were available in November. An email was sent in June 2017 to the PAO (principle area officer) within the Assessment Research and Development unit at MATSEC. The email comprised a formal request to carry out a study using examination scripts and a meeting was arranged. During the meeting we discussed how the scripts would have been used, that is how organic chemistry questions would be tackled and analysed in order to identify any misconceptions related to organic chemistry. A formal agreement signed by all parties was made and the board accepted my request and in November I collected the scripts. The scripts were to be kept in a safe place as such documents contain sensitive data. Moreover, no information was to be divulged if not for the purpose of the research project and once this was completed, all the scripts were to be returned to the MATSEC unit. Study focused on paper I, as it contained a considerable amount of organic chemistry questions from which several misconceptions and errors were highlighted, generating a considerable amount of data.

3.4. Data analysis

Data analysis took place as outlined hereunder and involved the following questions:

7. a, b, c (I & II), d.
8. a, b, c, d (I & II), e.
9. a, b, c, d.

The above include all the sub-questions for the organic chemistry questions analysed.

3.4.1. Coding system

Coding was a way of dealing with data, hence a coding system was developed for each and every question and sub-question of the organic chemistry questions in the 2017 chemistry A-level paper.

"Any researcher who wishes to become proficient at doing qualitative analysis must learn to code well and easily. The excellence of the research rests in large part on the excellence of the coding" (Strauss, 1987, p. 27).

Marks for each answer of these questions and sub-questions were inputted in an excel sheet, making sure that the order of the marks was from the highest mark to the lowest mark. Following the inputting of the marks, every answer was analysed for errors and misconceptions and a code was given. Each code was made up of two digits for every answer, apart from question 8.a which required three digits. The codes given may be found in Appendix 1. During the coding it was noted how at a certain point a saturation level was reached, and how on the other hand certain responses were too unique in nature to create a code for. In the study a two-digit code of 10 was given to a correct answer with no mistakes, signifying that the response was 100% correct. Answers which scored between 1 – 99% where considered as partly correct and answers were coded accordingly. On the other hand, responses which scored 0% were considered as incorrect, and those with no response were marked as unattempted.

For the purpose of the calculation of the facility index, item difficulty and item discriminating power, the responses which were deemed 'correct' for the calculations were identified; the correct responses with no mistakes (100%) and a section of the partly correct answers which scored between 75 – 99%, as outlined in Section 3.4.3.

3.4.2. Calculation of percentage students' responses.

The study sought to group similar responses together and calculate a percentage frequency. The calculation was carried out over 300 responses following the grouping, and tabulated in the Results and Discussion chapter. The percentages obtained were rounded up to 1.d.p. and this lead to a limitation as not all the percentages in the tables lead to a 100%.

3.4.3. Calculating the 'Facility index', 'Item difficulty' and 'Item discriminating power'

In their book *Research Methods in Education*, Cohen et al. (2000) give a detailed account of how the three parameters could be calculated. The scripts were ranked from high percentage scores to low percentage scores and the organic chemistry questions were analysed, determining whether the answers are correct or incorrect. Main points in marks lost stood out and described in the study. Once this was done, the difficulty of each item was then computed, that is the percentage of students who got the answer right, through the following equation:

$$P = \frac{R}{T}\ x\ 100\%$$

Where;

P = Facility index

R = the number of students who got the question right

T = the number of students who tried the question

The lower the P value, the more challenging the question was and as indicated by Yuan (2012), if P is higher than 0.75, then the question was relatively easy, whilst if P is lower than 0.45, then the question is challenging. Taking question 7.d. as an example where 300 responses were analysed. The question carried 2 marks, therefore the passing mark is 1.5 mark or higher (i.e. minimum of 75%). The 75% criterion did not apply for questions carrying 1 mark, as in this case it would be all or none. From 290 students who attempted the question the percentage of students who got 75% or above was:

$$P = \frac{R}{T}\ x\ 100\%$$

$$P = \frac{71}{290}\ x\ 100\%$$

$$P = \ 24.5\%$$

Assuming that the middle groups essentially follow the same pattern, the facility index from the 24.5 % indicating that the question was challenging. In order to calculate the item difficulty, the following equation is employed:

$$Item\ difficulty = 100\% - facility\ index$$

$$Item\ difficulty = 100\% - 24.5\ \%$$

$$Item\ difficulty = 75.5\ \%$$

The lower the facility index, the higher the item difficulty and the more challenging the question is. Following the 'Item Difficulty', the 'Item Discriminating Power' of each item was calculated. This will give an indication of the discrimination in the achievement between the number of students who got the question right in the upper and lower bands. An item will discriminate positively if a greater number of students in the upper group got the question right and therefore the item is discriminating in the same direction as the test score. It would be ideal that all the test items show positive discrimination. In order to mathematically compute this, the following equation is used:

$$D = \frac{(RU - RL)}{0.5\ (T)}$$

Where:

D = Item Discriminating Power

RU = Number of students in the upper band who got the item right

RL = Number of students in the lower band who got the item right

T = Total number of students included in the item analysis

Thus, D is determined by subtracting the total number of students in the lower band who got the item right from the total number of students in the upper band who got the item right, and dividing this by the half the number of students included in the item analysis. Calculating this for question 7.d.

$$D = \frac{(RU - RL)}{0.5\ (T)}$$

RU = 64

RL = 7

T = 300

$$D = \frac{(64 - 7)}{0.5\ (300)}$$

$$D = 0.38$$

This would follow a considerable discriminating power. For maximum discriminating power, where the only students who get the question right are those in the upper band and those in the lower band get it wrong, then the equation would give a discriminating power of 1. On the other hand, if the item question presented no discriminating power, then there is no discrimination between the students in the upper and lower groups and the index is zero. The item discriminating power might also have a negative value which shows the poor performance of students in the upper band and a good part in the low band.

The calculations for all the facility index and the item discriminating power for all the questions and sub-questions may be found in Appendix 2 and Appendix 3 respectively.

3.4.4. Ethical considerations

"Honesty is perhaps another way to describe this, but I deliberately choose the phrase because it implies that you will always be: rigorously ethical with your participants and treat them with respect; rigorously ethical with your data and not ignore or delete those seemingly problematic passages of text and rigorously ethical with your analysis by maintaining a sense of scholarly integrity and working hard toward the final outcomes" (Saldana, 2009, p.29).

All the data contained in the scripts was respected in this study and included attention to reporting, anonymity and confidentiality.

3.5. Conclusion

A detailed description of the methodology employed in this study was described in this chapter, showing how the data were retrieved, assimilated and analysed, leading to a description of errors and misconceptions in organic chemistry at A-level.

4. Results and discussion

4. Results and discussion

4.1. Introduction

Responses given by students in the chemistry A-level 2017 paper were categorised, in order to highlight common errors, such as but not limited to those of nomenclature, recall and application. Each category will be analysed through questions present in the 2017 A-level chemistry paper I, comprising error analysis, item difficulty, facility index and item discriminating power. The coding was allotted accordingly, grouping errors together and tabulated. The main difficulties were then expanded, tackled one by one and presenting results pertaining to difficulties.

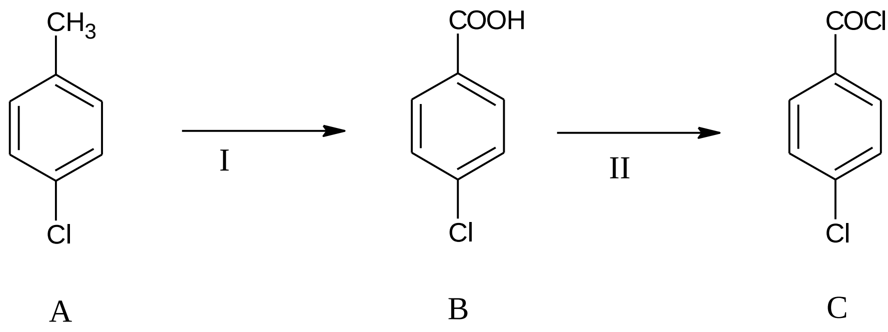
4.2. Nomenclature

Nomenclature is an inherent part of organic chemistry, which rules must be well-understood and interpreted in order to get the name of a desired compound. It was noted how in the 2017 A-level chemistry paper, molecules with a number of substituents were given for nomenclature. Students made several mistakes, where errors about nomenclature came to light in this study. Such errors were dealt with according to the question asked in the exam. In each question, the facility index, item difficulty and item discriminating power were determined. Each mistake was given a code, which code represents a category. Due to the vast amount of mistakes and due to their unique nature, certain names given by students might fit into more than one code-category. The names given for the compounds were placed under the category which fits best. The aim is to bring out the difficulties and not allot a unique code to each and every unique mistake.

4.2.1. Naming 1-chloro-4-methylbenzene

The following question was given in paper 1:

7. This question concerns the following sequence of reactions:



(a). Give the systematic name of A. (2 marks)

Suggested answer: 1-chloro-4-methylbenzene.

The name derives from a set of rules set by IUPAC (International Union of Pure and Applied Chemistry). Numbering has to start from smallest to highest, whereas certain functional groups are given precedence. In fact, the halogen group is ranked higher than the alkyl group (which comes close to the lowest of priorities). Moreover benzene is the base molecule and not phenyl, as no substituent on the benzene ring has a second substituent or functionality. Hence the compound remains aromatic and does not become an aliphatic compound with a phenyl substituent. Given that the chloro- ranks before methyl- and that chloro- comes before methyl- alphabetically, the name is 1-chloro-4-methylbenzene. There is no use of commas in this name as there is only one number which pertains to a particular functional group. The use of hyphens is used to separate numbers from their substituents, but substituents are not to be separated from the base compound, in fact there is no hyphen or space between methylbenzene.

In this question, 300 students' responses were analysed. Two students from the lower band did not attempt the question. From the facility index it was shown how 49 students out of 298 who attempted the question, arrived at the actual name of the molecule. An answer was considered correct if a student scored 75%, or higher which in this case translates into a mark of 1.5 – 2. With such a low number of students who got the answer correct, the facility index was found to be 16.4%, thus the item difficulty being 83.6%. With such a high item difficulty, it is proved even alongside error analysis, how difficult the question was for the students.

There were various responses for the name given and several errors observed. Table 4.1 lists students' responses and their respective frequency.

Table 4.1 - Responses for molecule A, with pertaining description and percentage of students giving such an answer

Description	Frequency (%) to 1 d.p.
Correct with no mistakes	16.4
Partly correct. Wrong position of numbers and lack of numbering	58.0
Partly correct with wrong position of numbers	11.1
Partly correct. Wrong position of numbers and substituents	3.0
Incorrect. Wrong position of numbers and substituents, as well as lack of numbering	1.7
Incorrect. Wrong naming of substituents	1.2
Incorrect. Wrong numbers and wrong position of numbers	1.0
Partly correct with lack of numbering	0.7
Incorrect with wrong numbers	0.7
Incorrect with lack of numbering	0.6
Incorrect. Wrong naming of substituents, lack of numbering and hyphens/commas in wrong position	0.6
Partly correct. Wrong position of numbers, lack of numbering and hyphens/commas in wrong position	0.6
Incorrect. Wrong naming of substituents, wrong position of numbers, wrong position of substituents, lack of numbering and hyphens/commas in wrong position	3.0
Not attempted	0.7

There were 27 different types of answers given by students, only one of which was correct and acceptable by IUPAC. The percentages given in Table 4.1 do not add up to 100% because they were rounded up to the nearest decimal place. Thus, there were mistakes which were not the same (due to different nomenclature) but had similar characteristics. The item discriminating power was found to be -0.08 which does not mean that students in the lower band did not make mistakes. Rather, the students in the high band made more mistakes which were similar in nature (such as for the high-frequency mistakes), but the students in the lower band, who percentage-wise made less mistakes, had a large variety of diverse errors. Given that the item discriminating power is almost zero, it confirms how the overall performance was poor.

4.2.1.1. High-frequency mistakes (11.1% - 58.0%)

The most frequent error made by students was naming the compound 4-chloromethylbenzene, with a response of 58%. Such high-frequency mistakes were found mainly in the top band, given that the mistakes made in the lower band were very diverse in nature.

4.2.1.1.1. Prioritising functional groups

The molecule was identified as a haloaromatic compound by 58% of the students who could not distinguish between the priorities of functional groups. Here, the chloro- takes precedence over the methyl- and the former takes '1' whereas the latter takes '4'. The reasons for which students gave such an answer could be various and include:

1. Students recall this molecule as being 4-chloromethylbenzene. Methylbenzene (toluene) per se is a benzene ring with a methyl group attached, thus, if some students view the molecule as methylbenzene with a chloro substituent attached (i.e. the chloro was foreign and now part of the molecule), they then would have labelled the Cl- substituent as '4'.

2. Students fail to rank the functional groups accordingly, giving $-CH_3$ a higher priority than –Cl.

The second most common mistake in relation to numbering and prioritizing, ranged across the whole spectrum where the typical answer was '4-chloro-1-methylbenzene' and it showed that according to the students, methyl- ranks first. In this case, students clearly did not view the molecule as 'methylbenzene' but as benzene having two separate substituents to which they both gave numbers, but giving the wrong prioritisation. In relation to this error, students have to realise that a functional group gives the characteristics to a compound. Even though the -CH_3 does give properties, the functional group which makes this aromatic compound different is the -Cl; students failed to show this.

4.2.1.2. Low-frequency mistakes (0.3% - 3.0%)

Most of the low-frequency mistakes were found in the lower and were often unique.

4.2.1.2.1. Archaic nomenclature

From the analysis, it is evident that the archaic use of 4-chlorotoluene is still present. Despite the fact that the name was accepted in archaic chemical literature, nowadays such names are discarded (even though they are still widely used in chemical industry) so as to avoid confusion. Nevertheless students are expected to give the name according to IUPAC rules and such names are to be avoided as described by Vollhardt and Schore (2011).

4.2.1.2.2. Homologous series and functional groups

Analysis also showed that some students are still not familiar with what a functional group is, and how the functional group places a particular compound in a category, that is the homologous series. In the case of 1-chloro-4-methylbenzene, the categories are various. The compound is an aromatic compound, as opposed to aliphatic, but the molecule is also a haloaromatic compound due to the presence of the -Cl substituent. Some students also failed to identify the category of the compound and others giving the category as the name. Whilst the category is correct and identified by the students, the name was not correct, thus there are students who might not understand the difference between the homologous series under which the compound falls and the name, or students who are able to identify the category but not the name.

Apart from not being sure of what a functional group might represent, students also revealed that they are not able to distinguish between different functional groups, leading to confusion between the actual haloaromatic compound with phenols, aromatic aldehydes and salts. From the answers, some students thought that the compound might be ‘4-chlorophenol’ or ‘1-methyl 4-chlorophenol’, not being aware that phenols must contain a hydroxyl group directly bonded to the benzene ring.

4.2.1.2.3. Salts

The issue with nomenclature extends also to the fact that students included in the study mixed up the nomenclature of salts with those of this aromatic compound, giving answers such as ‘1-methyl,4-chloride Benzene’ and ‘Methyle benzene chloride’. The latter answer shows not only that students might not be able, and are not accustomed to writing the term ‘methyl-‘, but were also unable to identify that the –Cl substituent is not an ion, because there is a covalent bond between the –Cl and the benzene ring. The distinction between ionic and covalent bonding and its understanding is a must to tell apart ionic and covalent species, but giving ‘Methyle benzene chloride’ clearly shows that this may still problematic at A-level.

4.2.1.2.4. Commas, hyphens and numbering

Other errors related to nomenclature include those related to hyphenating and use of commas, where students gave answers such as ‘3-chloro, 6-methylbenzene’ and ‘1-methyl,4-chloride Benzene’, who clearly did not understand the connection related to the use of commas and hyphens in organic chemistry nomenclature.

Another error highlighted in this study was that of numbering, students could not number clockwise or anticlockwise appropriately, giving ‘1-chloro-3-methylbenzene’ as an answer.

The fact that the $-CH_3$ group was given number 3 shows, that when students started counting the position, they thought that even though -Cl is on the first carbon, the next carbon is not the second, but the first again, leading to position number 3 for the methyl group.

4.2.1.2.5. Alphabetical order

The final most common error is that of students who gave '1-methyl-4-chlorobenzene' as an answer. Here not only the students showed that they are not ranking the substituents accordingly, but they are also swapping their position. Given the chloro starts with a C and methyl starts with an M, their positions should be the other way round.

4.2.2. Naming 2,3-dihydroxybutanedioic acid

The following question was given in paper 1, question 8a:

8. Tartaric acid, (**D**), is a naturally occurring compound found in grapes. The molecule has two *chiral carbons*.

HOOC-CH(OH)-CH(OH)-COOH

(a) Give the systematic name of **D.**
Suggested answer: 2,3-dihydroxybutanedioic acid

The name once again derives from a set of rules set by IUPAC. In this case, the carboxyl (-COOH) moiety takes precedence over the hydroxyl group (-OH), the reason being that 2,3-dihydroxybutanedioic acid is in fact an acid and has acidic properties due to the presence of the carboxyl groups. The base molecule is butane, including two carboxyl groups bonded at the ends, and two hydroxyl groups on carbons 2 and 3. Thus the full name would be 2,3-dihydroxybutanedioic acid, with a comma between the numbers to distinguish the respective hydroxyl groups and a hyphen to separate numbers from name. There were various responses for the name given and mistakes made.

In this question, 300 students' responses were analysed. Eleven students from the lower band did not attempt the question. From the item difficulty it was shown how 149 responses out of 289 analysed were correct. An answer was considered correct if the student got 75% or higher, which in this case translates into a mark of 1.5 – 2. The facility index was in fact, 51.6%, which although being low, it is significantly higher than the 16.4% for question 7a, showing that it was less challenging. The item difficulty was thus 48.4%. Nevertheless such a molecule might have appeared in examples in books throughout the course, because the tartaric acid molecule is often used as an example for chirality, isomerism and effect on plane polarised light. Thus there might have been a degree of recall by students, rather than comprehension and application, hence the higher facility index and lower item difficulty. Each mistake was given a code and Table 4.2 lists the description and the percentage of students' answers.

Table 4.2 – Responses for molecule D, with description and percentage of students giving such an answer

Description	Frequency (%) to 1 d.p.
Correct with no mistakes	48.7
Incorrect. Wrong naming and numbers	15.3
Partly correct with excess numbering	11.3
Partly correct with wrong naming	6.0
Incorrect. Wrong naming, wrong position of substituents and lack of numbering	4.7
Incorrect with wrong naming	4.3
Incorrect. Wrong naming, wrong numbers and excess numbering	4.3
Incorrect. Wrong naming, excess numbering and hyphens/commas not used appropriately	1.3
Incorrect. Wrong naming, wrong position of numbers and excess numbering	0.3
Incorrect. Wrong naming, wrong position of numbers and wrong position of substituents	0.3
Not attempted	3.7

The item discriminating power was 0.53, showing how the question slightly discriminating between students in the high band and those in the low. From analysis, it was shown once again that students in the high band are more likely to attempt the question, giving mistakes which are subtle, such as excess numbering. However, the students in the low band tend to come up with names which do not make sense, in fact some of the names given as answers by students in the low band included functional groups which are not part of the tartaric acid molecule.

4.2.2.1. High-frequency mistakes (11.3% - 15.0%)

High-frequency mistakes were mainly made by students across the spectrum, giving rise to mistakes which could have been easily avoided, such as numbering. Students gave '2,3-dihydroxybutane-1,4-dioic acid' as their answer where respondents failed to realise that excess numbers, just as those mentioned later on in this section, are not to be part of the name, and despite the fact that the 1,4 is not deemed as 'incorrect', excess number might lead to confusion.

The most common mistake was however that of incorrect numbers. Anything which violates the reason for which numbers are given, was considered as wrong numbering in this study. The responses which fell under this category, had both the numbers per se and the numbers allotted to the pertaining substituents wrong, making the whole name incorrect. Students gave answers such as '2,2-dihydroxybutanediol' and 'butan-2,3-ol-dioic acid'. In 2,3-dihydroxybutandioic acid, the 2,3 refer to the hydroxyl groups on carbons 2 and 3. If the digits are wrong and/or the reference of the digits is not to the hydroxyl groups, then numbering is incorrect; hence the vast array of mistakes of this type.

4.2.2.2. Low-frequency mistakes (0.3% - 6.0%)

The lower percentage marks in this case gave a lower number of mistakes percentage-wise but not in terms of variety. Nevertheless a number of errors were brought to light.

4.2.2.2.1. Incorrect naming of functional groups

The main reason for which molecules' names were wrong is due to the wrong naming of the functional groups. The two main functional groups were the hydroxyl (or hydroxy) and the carboxyl group, with the latter being prioritised as indicated by Skonieczny (2006). The hydroxyl group was meant to be identified twice, placing di- in front, which becomes dihydroxy (where the l of hydroxyl drops). From analysis it can be concluded that the vast majority of the students identified this functional group but failed to give the proper name. The names identified in this study were numerous, giving names such as '2,3-dihydroxobutane dioic acid'.

Other students in the study were unable to distinguish between a 'diol' and a compound with two hydroxyl groups. In diols, the main functional groups are two hydroxyl groups, where other functional groups are ranked lower, such as alkyl groups. In this case, the main functional groups were the carboxyl groups, thus the compound is not a diol but a dioic acid. Names such as 'butan-2,3-dioldioic' acid and '2,2-dihydroxybutanediol' prove how students are puzzled by the naming of the correct functional groups, their priorities and ranking. Moreover, some students could not distinguish between the carboxyl group and the carbonyl group, where the latter has no –OH group. This was evident in answers such as '2,3-dihydroxobutandial' and '2,3-hydroxobutan-1,4-al'. Students in this case made a striking mistake in the end, believing the –COOH group is –CHO and giving dial instead of dioic acid. In this same category 'But-2,3-diol-1,4-dianoate' was given, showing that some students are still not capable of distinguishing the salt from the parent molecule.

4.2.2.2.2. Incorrect naming of base compound

Another common error was the incorrect naming of the base molecule. The base molecule in this case was 'butandioic acid' as the parent molecule is butane. However, as could be observed in various categories, this was not identified by some students. Names such as '2,3,4-trihydroxopenten-dioic acid' and '2,3-hydroxypropanoic acid' where students believed that the base molecule is a pentane and propane respectively as illustrated by Figure 1 and Figure 2 respectively. The ability to identify the longest chain and the chain which makes up the molecule is of utmost importance, because failing to identify the longest chain will lead to incorrect nomenclature.

Figure 1 – The answer of a student for question 8a from the low band who believed that the parent molecule is pentane

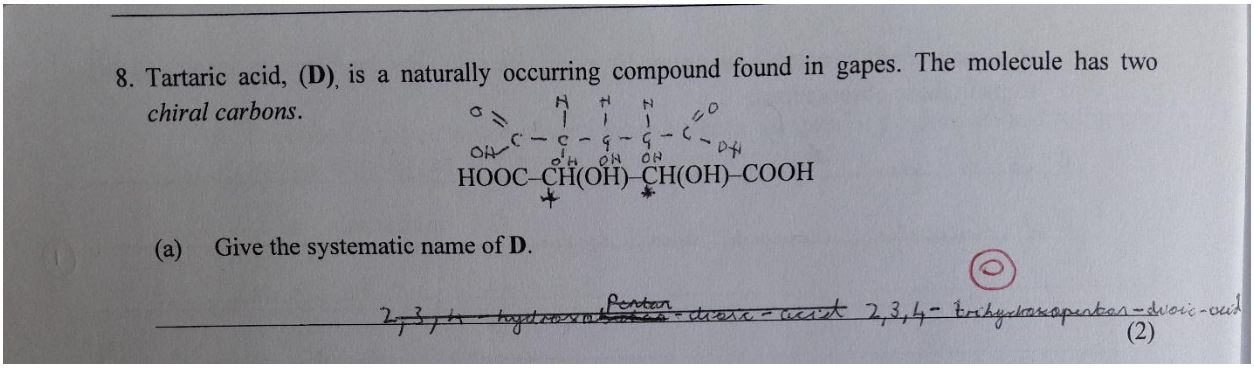
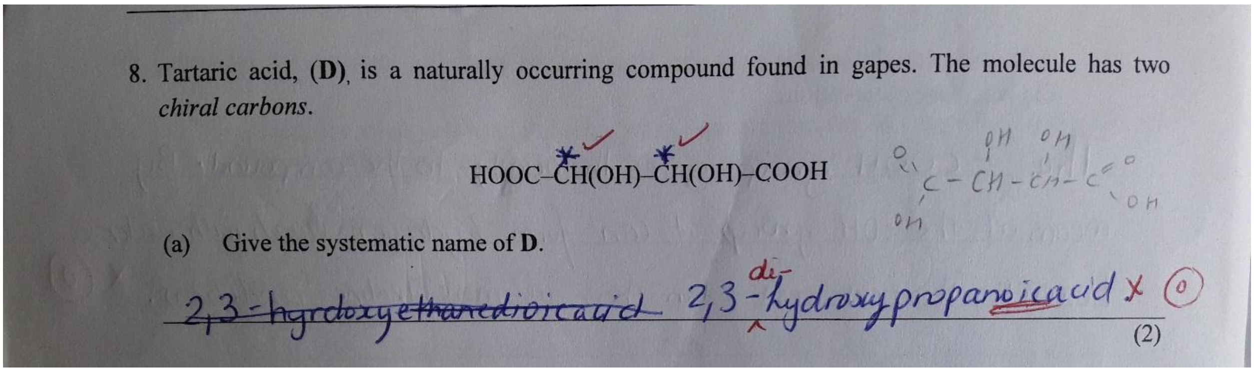


Figure 2 – The answer of a student for question 8a from the low band who believed that the parent molecule is propane



4.2.2.2.3. Excess numbers

The usage of excess numbers was again observed. Taking '2,3-dihydroxobutan-1,4-diacid', the students clearly thought of the 1,4 as being the carbon numbers of the carboxyl groups. Putting the other mistakes at a side for the sake of this explanation, here the students identified the position of the carboxyl groups, but did not realise that the carboxyl groups are in fact carbon number 1 and 4 themselves. Without them, there would be no dioic acid and here is where chemical topology comes into play. Students have to picture the molecule before answering such questions. Numbering might perhaps not be as easy as educators depict it, because the 3-D structure and numbering are essential tools which students have to master before giving the name of a compound, especially one which contains more than one number.

4.2.2.2.4. Lack of numbering

Lack of numbering was also an evident error. As stated by IUPAC, numbering is essential in order to identify the position of substituents and functional groups, where students gave names such as 'Dihydroxybutanoic acid' and 'Butandioic acid' which clearly show a lack of understanding. With such lack of numbers, one would not be able to understand where the hydroxyl and/or the carboxyl groups are.

4.2.3. Concluding nomenclature

From this analysis it was concluded how students found it more difficult to name an aromatic compound rather than an aliphatic one. The reason could be that aromatic chemistry is taught towards the end of the A-level course and students might get confused. This is because there are rules in aromatic chemistry (such as numbering 1,2 – 1,3 and 1,4 systematically) which are not present in aliphatic organic chemistry. Nevertheless it was shown how students are still making many mistakes when it comes to nomenclature and that there are rules they are still not sure about. In this section of organic chemistry, recall rarely works out to be a good method of answering such questions, as understanding and application are required.

4.3. Application of inorganic, analytical and physical chemistry principles to organic chemistry questions

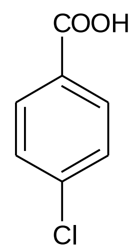
Chemistry is a subject that is often organised in four main areas, namely: organic, inorganic, physical and analytical. These areas are highly intertwined, thus students are expected to apply principles from one area to another very easily in order to answer questions. In addition, as indicated by Johnstone (1991), people dealing with chemistry (be it scientists, educators and learners) have to easily move from the macroscopic to the submicroscopic and symbolic levels.

When responses of students were analysed, it was evident how challenging it is for the students to apply inorganic, analytical and physical chemistry principles to organic ones, in order to arrive at a conclusion. There was a high similarity between the mistakes related to this point. Along the same lines of previous analysis, facility index and item discriminating power were calculated so that a more complete picture is sought.

4.3.1. Acidic nature of 4-chlorobenzoic acid

The following question was given in paper 1:

B is only slightly soluble in water. However its solubility increases on increasing pH. Explain these observations. (3 marks)



B

Despite the complexity of this answer, and the great detail of chemistry knowledge required. Students had to summarise all this mainly in three points:

1. There are weak intermolecular bonds forming between 4-chlorobenzoic acid and water.

2. At higher pH the H of –COOH dissociates to form the more stable, strong conjugate base/or show equilibrium between the weak acid and the strong conjugate base resulting in equilibrium lying highly to the right and therefore solubility increases.

3. The strong conjugate base forms strong electrostatic interactions with water.

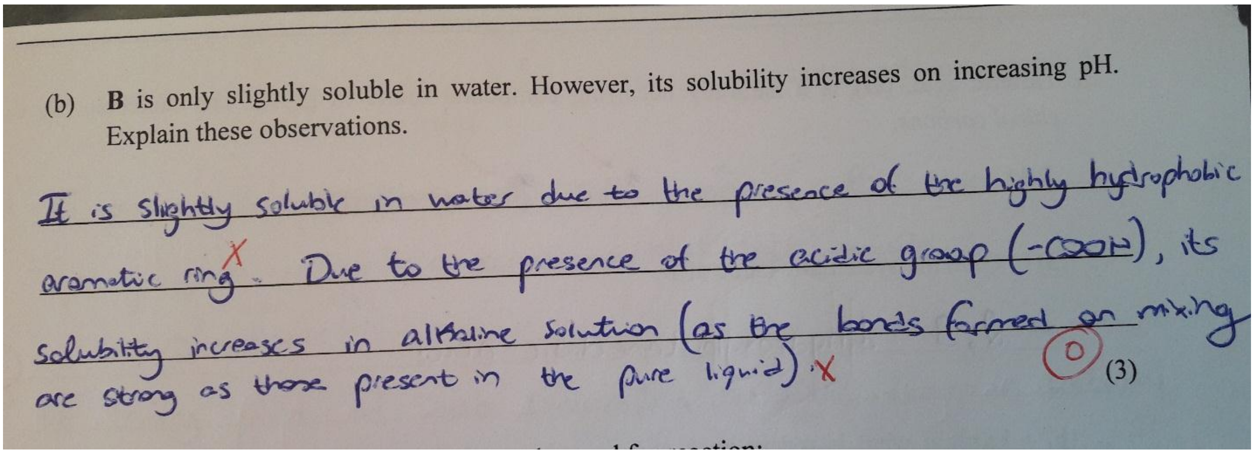
In this question, 300 students' responses were analysed. Ten students from the lower band did not attempt the question. The analysis showed that 43 students out of 290 who attempted the question, arrived at the actual full answer. An answer was considered correct if a student gets 75%, or higher which in this case translates into a mark of 2.25 - 3. With such a low number of students who got the answer correct, the facility index was found to be 14.8%, thus the item difficulty was 85.2%. With such a high item difficulty, it is evident that the question was difficult. The categories of responses are shown in Table 4.3 alongside their frequency. Unlike nomenclature, here mistakes could be grouped in larger clusters as they are more similar in nature.

Table 4.3 – Responses for application of inorganic and physical chemistry principles to organic questions with pertaining description and percentage of students

Description	Frequency (%) to 1 d.p.
Correct with no mistakes	11.0
Incorrect due to no mentioning of points 1, 2 and 3	22.3
Partly correct due to no mentioning of points 1 and 2	22.3
Partly correct due to no mentioning of point 2	17.0
Partly correct due to no mentioning of point 1	11.7
Partly correct due to no mentioning of points 1 and 3	8.7
Partly correct due to no mentioning of points 2 and 3	3.7
Not attempted	3.3

The item discriminating power for this section of results was found to be 0.23, which indicates that even though there is a low discrimination between students in the high band and those in the low band, there is still a degree of discrimination and those in the upper band performed better than those in the lower band. Moreover there was a 3.3% of the students, all from the lower band, who did not attempt the question. Figures 3 and 4 depict answers by students who went totally out of point and did not understand the chemistry behind the process going on.

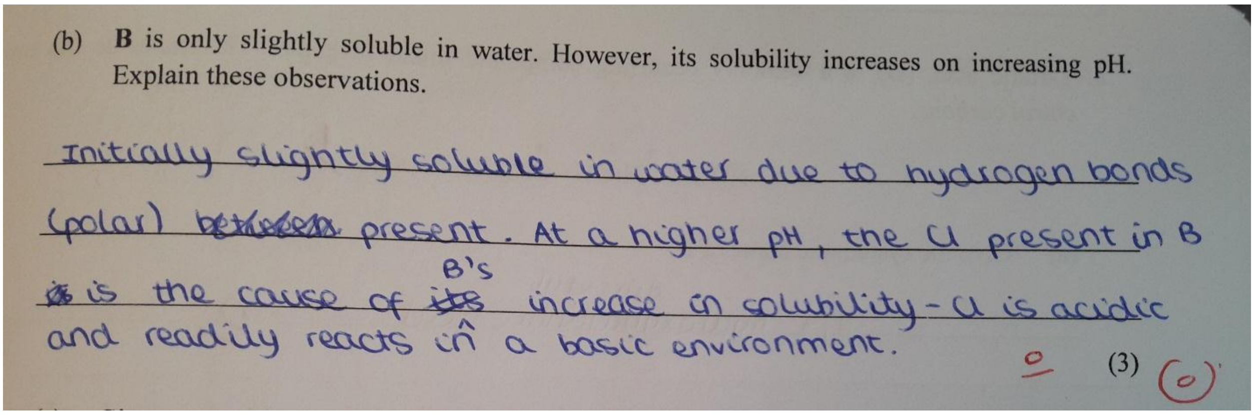
Figure 3 – The answer of a student for question 7b from the high band who failed to answer the question correctly and make links between physical and organic chemistry


(b) **B** is only slightly soluble in water. However, its solubility increases on increasing pH. Explain these observations.

It is slightly soluble in water due to the presence of the highly hydrophobic aromatic ring ✗. Due to the presence of the acidic group (-COOH), its solubility increases in alkaline solution (as the bonds formed on mixing are strong as those present in the pure liquid) ✗

0 (3)

Figure 4 – The answer of a student for question 7b from the low band who failed to answer the question correctly and make links between physical and organic chemistry


(b) **B** is only slightly soluble in water. However, its solubility increases on increasing pH. Explain these observations.

Initially slightly soluble in water due to hydrogen bonds (polar) ~~between~~ present. At a higher pH, the Cl present in B ~~is~~ is the cause of ~~its~~ B's increase in solubility – Cl is acidic and readily reacts in a basic environment.

0 (3) (0)

4.3.1.1. High frequency mistakes (17.0 – 22.3%)

Students who failed to mention all three points above gave the totally incorrect answers and most often this was accompanied by responses which were totally irrelevant and out of point. In fact, these answers were mainly found in the lower band, where answers included reference to the electronegativity of Cl and the neutralisation properties, for instance. Not only are these points irrelevant, but it shows that either the students did not know the answer, or else the students failed to understand what was expected from them. It is more plausible that students might have failed to apply the inorganic principles of acid/conjugate base and/or the physical principles of equilibrium to those in organic chemistry. This is point 2 and it is where the majority of the students lost their marks. In fact, in the high percentages section, this point was always missed by students. The reasons for this could be various.

Some students might not realise that aliphatic carboxylic acids and aromatic carboxylic acids have certain properties which are similar, and fail to realise that the way most aliphatic carboxylic acids dissociate is also similar to the way most aromatic carboxylic acids dissociate, i.e. they are generally weak acids and both tend to form an equilibrium in solution. This might lead to another possible error: do students really know why there are weak and strong acids? Perhaps such essential topics and principles have to be revisited before proceeding the more complex ones. It is important to realise that strong acids fully dissociate in water because they form a weak conjugate base which is not potent enough to attract protons and form the acid back, hence the equilibrium lies forward. This is the reverse concept for 4-chlorobenzoic acid, and students who failed to mention this might not be fully aware of this association. Linking this to the other most frequent mistake found also in the low frequency mistakes is the reason why the solubility of 4-chlorobenzoic acid is low. Despite the fact of having the highly polar carboxyl and chloro groups, benzene partially hinders full solubility of the molecule as the attractions of the groups with water are not strong enough to make it fully soluble, hence why its solubility increases on increasing pH. Students had the opportunity to explain this via the equilibrium too, but those who failed to do so either gave a more descriptive answer or else failed to do so completely.

4.3.1.2. Low frequency mistakes (3.7 – 11.7 %)

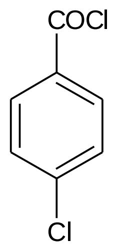
Certain mistakes were possibly made because students did not fully understand what was expected and not because they did not understand the question or failed to apply the principles. In fact, this is the area where students did explain why solubility takes place at higher pH but failed to mention some points which were essential in this answer, such as failing to give reasons why solubility is low for 4-chlorobenzoic acid but then give a full explanation for the equilibrium. Another common mistake is that of failing to give a reason why the acid becomes more soluble at higher pH. Students tended to give a full explanation of what is going on but then failed to state that the solubility gets higher due to the formation of the strong electrostatic forces between the conjugate base and water.

Students who took a different approach towards the explanation of all this included reasons such as heating. It is to note that while heating might aid solubility, this is not the chemical explanation required.

4.3.2. The strong covalent bond between Cl and the benzene ring

The following question was given in paper 1 (7d):

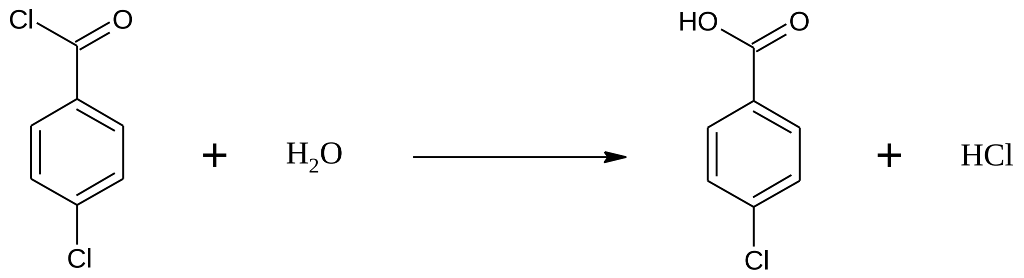
Reaction of 1 mole of **C** with excess aqueous silver nitrate (V) produces 1 mole of silver chloride. Explain this observation. (2 marks)



C

In this answer, students had to use both their knowledge of organic, inorganic, analytical and physical chemistry.

1. In an aqueous environment, 4-chlorobenzoyl chloride (C) converts to 4-chlorobenzoic acid and HCl:



C

2. The HCl formed in the reaction would then react with the silver nitrate (V) to give 1 mole of silver chloride, which is a white precipitate, in the following reaction:

$$AgNO_{3\,(aq)} + HCl_{(aq)} \rightarrow AgCl_{(s)} + HNO_{3\,(aq)}$$

3. The bond between the Cl and the benzene ring is a partial double bond due to the delocalisation of the electrons, and thus it is energetically not favourable to break that bond. Hence only the covalently bonded Cl of the benzoyl chloride is substituted.

This reaction may be viewed as a substitution reaction as a hydroxyl moiety displaces the chloride moiety. Due to their electron-withdrawing properties, the oxygen atom of the carbonyl group and the chlorine atom, shift the electron cloud away from the carbon to which they are attached, rendering the sp^2 carbon atom δ+ and thus prone to attack by nucleophiles. The hydroxyl moiety from the water molecule acts as a nucleophile, attacks the sp^2 carbon atom of the acyl chloride. This could not be done with the chloride directly bonded to the benzene ring as this bears a partial double bond which is stronger than the single bond found between the sp^2 carbon atom and the chloride, on the acyl chloride group.

In this question, 300 students' responses were analysed. Ten students from the lower band did not attempt the question. The analysis showed that 71 students out of 290 who attempted the question, arrived at the actual full answer. An answer was considered correct if a student gets 75%, or higher which in this case translates into a mark of 1.5 -2. With such a low number of students who got the answer correct, the facility index was found to be 24.5 %, thus the item difficulty being 75.5 %. With such a high item difficulty, it is clear how difficult the question was for the students. However, students seemed to have struggled less compared to question 7b. The responses are shown in Table 4.4 alongside the respective percentages.

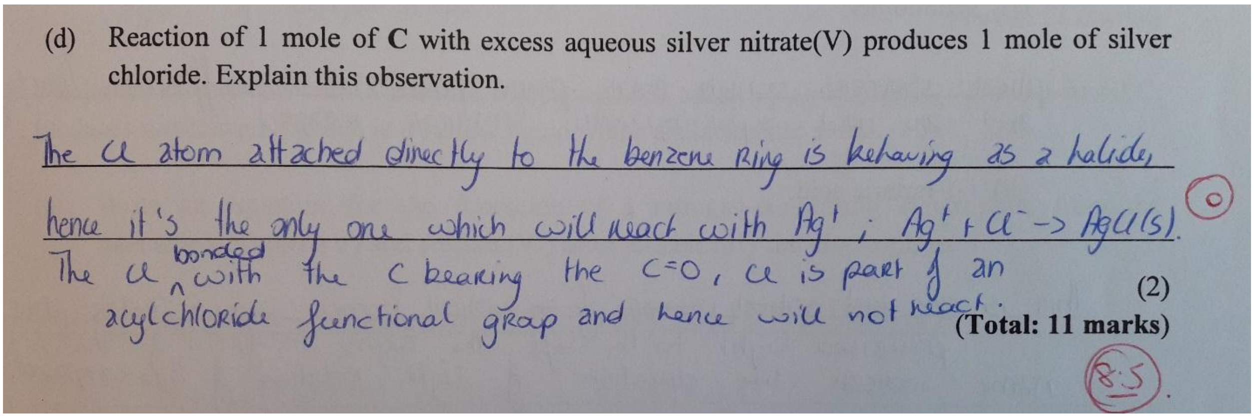
Table 4.4 – Responses for application of inorganic and physical chemistry principles to organic chemistry questions with pertaining description and percentage of students

Description	Frequency (%) to 1 d.p.
Correct with no mistakes	8.3
Incorrect due to no mentioning of points 1, 2 and 3	32.3
Partly correct due to no mentioning of points 1 and 3	19.7
Partly correct due to no mentioning of points 1 and 2	17.7
Partly correct due to no mentioning of point 1	14.0
Partly correct due to no mentioning of points 2 and 3	2.3
Partly correct due to no mentioning of point 3	1.7
Not attempted	3.3

The item discriminating power for this sub question was found to be 0.38, which indicates that even though there is discrimination between students in the high band and those in the low band. Once again, this question requires the use of several principles pooled together.

It was noted how the students in the low band gave answers which only dealt with the formation of the precipitate and failed to point out the fact that the chlorine bonded to the phenyl ring has a stronger bond. Whilst this mistake was seen throughout the scripts, it was particularly evident in the lower band. In the following illustrations, Figures 5 and 6, show some typical answers given by students who did not come close to the answer, showed a high level of misconceptions and also proved that certain basic concepts ought to be revised.

Figure 5 – The answer of a student for question 7d from the high band who failed to answer the question correctly and make links between physical and organic chemistry

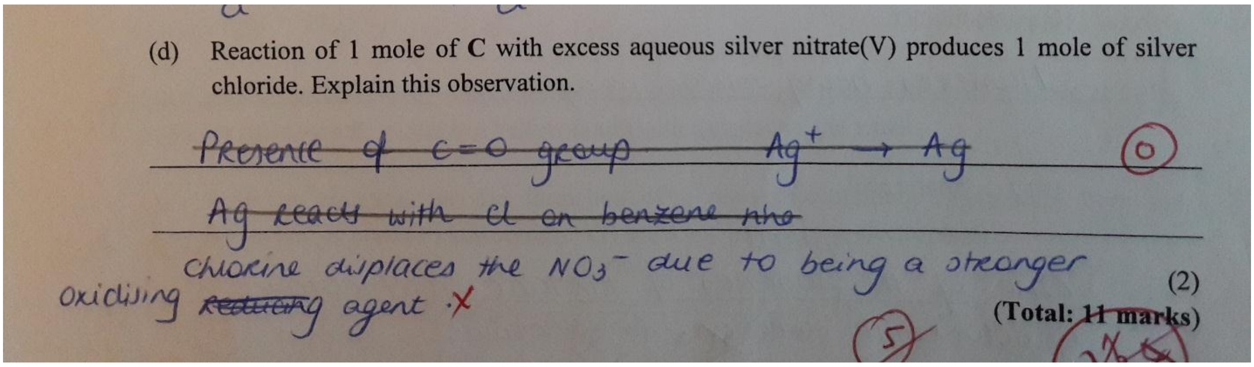

(d) Reaction of 1 mole of **C** with excess aqueous silver nitrate(V) produces 1 mole of silver chloride. Explain this observation.

The Cl atom attached directly to the benzene ring is behaving as a halide, hence it's the only one which will react with Ag+; Ag+ + Cl- -> AgCl(s). The Cl bonded with the C bearing the C=O, Cl is part of an acylchloride functional group and hence will not react.

(2)

(Total: 11 marks)

Figure 6 – The answer of a student for question 7d from the low band who failed to answer the question correctly and make links between physical and organic chemistry


(d) Reaction of 1 mole of **C** with excess aqueous silver nitrate(V) produces 1 mole of silver chloride. Explain this observation.

~~Presence of C=O group Ag+ → Ag~~

~~Ag reacts with Cl on benzene ring~~

Chlorine displaces the NO3- due to being a stronger oxidising ~~reducing~~ agent ✗

(2)

(Total: 11 marks)

4.3.2.1. High frequency mistakes (14.0 – 32.3%)

In this section, a number of mistakes and difficulties will be dealt with as well as the way the students answered or failed to answer the question. The most common misconception was that of believing that the silver chloride forms as the silver nitrate would directly attack the 4-chlorobenzoyl chloride, draw away the chlorine and precipitate silver chloride. From this study it was observed how the majority of the students failed to mention/realise that water is an inherent part in this reaction as it hydrolyses 4-chlorobenzoyl chloride to 4-chlorobenzoic acid. This is in fact the main feature of the reaction and the part where students had to apply the organic concepts they know.

Another common mistake falling within the category of the high-frequency mistakes was that of failing to point out that the chlorine atom directly bonded to the benzene ring is not going to react via S_N2 mechanism because the bond between the chlorine atom and the sp^2 carbon atom of the phenyl group is a partial double bond and too strong to break. Some students pointed out that in fact that chlorine atom will be displaced to precipitate silver chloride, and thus prove that students are not aware of the fact that the benzene ring possesses delocalised electrons and that the delocalised electrons are constantly moving and extending to the Cl. This makes the bond between the phenyl carbon atom and the chlorine a partial double bond, which is stronger than a single bond, but weaker than a double bond.

4.3.2.2. Low frequency mistakes (1.7 – 2.3 %)

Some students failed to make the connection between the formation of silver chloride as a white precipitate and HCl. As pointed out in Section 4.3.2.1., some students failed to conclude that the partial double bond of the chlorine with the phenyl ring would not break to precipitate the silver chloride. Had this been the case, the answer would still be wrong because once again, students would be believing that the chlorine precipitating the silver chloride is coming directly from the 4-chlorobenzoyl chloride and fail to conclude that the HCl precipitates the silver chloride.

4.3.3. Conclusion.

Whilst the most common answers and mistakes were similar in nature, that is failing to mention one or more of the three points, some students took a different approach and mentioned irrelevant points. It seems that some students fail to link chemistry areas together; in this case the application of physical, analytical and inorganic chemistry principles to explain the properties of organic molecules and their respective reactions.

4.4. Recall and understanding in organic chemistry

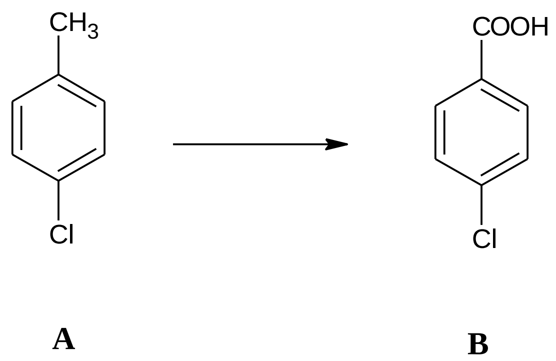
Organic chemistry is not based only on application and calculations, just to mention a few, but also on recall and understanding. As Pungente & Badger (2003) argue in their paper, Bloom's taxonomy defines how the cognitive level conjoins with the skills demonstrated by the student. Recall is an important aspect in organic chemistry as in order to arrive at certain conclusions, the basic knowledge is required, upon which one then builds the applications. Understanding is also an important aspect in organic chemistry, as it requires thought in order to arrive at an answer, encompassing recall within it.

Some of the questions analysed in this study required the use of both recall and understanding in order to arrive at the final answer.

4.4.1. Recall and understanding of reagents and reaction conditions for reaction I

The following question was given in paper 1:

7.c.i. Give reagents and conditions that can be used for reaction:
(I)



In this reaction an oxidation reaction is taking place, where the methyl group on 1-chloro-4-methylbenzene is converted into a carboxylic acid group to give 4-chlorobenzoic acid. In order to carry out this reaction, $KMnO_4$ in alkaline conditions is added under gentle heat (not refluxing as this would be too strong for the reaction) to form the 4-chlorobenzoate salt. Then the reaction is followed by acidification to form the 4-chlorobenzoic acid.

Thus students had to specify that:

1. $KMnO_4$ has to be under alkaline conditions.
2. the reaction has to be carried out under gentle heating (not refluxing) following the addition of MnO_4^-/OH^-.
3. after adding $KMnO_4/OH^-$ and forming the salt, the reaction mixture has to be acidified/ followed by H^+ and not refluxed.

Alternatively, students could have opted to give the reaction conditions and reagents instead of describing each step.

In this question, 300 students' responses were analysed. Ten students from the lower band did not attempt the question. A total of 114 students out of 290 who attempted the question, arrived at the actual full answer. An answer was considered correct if a student gets 75%, or higher which in this case translates into a mark of 1.5 -2. With a relatively low number of students who got the answer correct, the facility index was found to be 39.3 %, thus the item difficulty being 60.7 %. Even though the item difficulty is less than for that of questions mentioned in earlier sections, it is still relatively high and it is showing how even for recall and understanding, certain students struggle to obtain 75% of the answer correct. The students' responses are shown in Table 4.5 alongside their frequency.

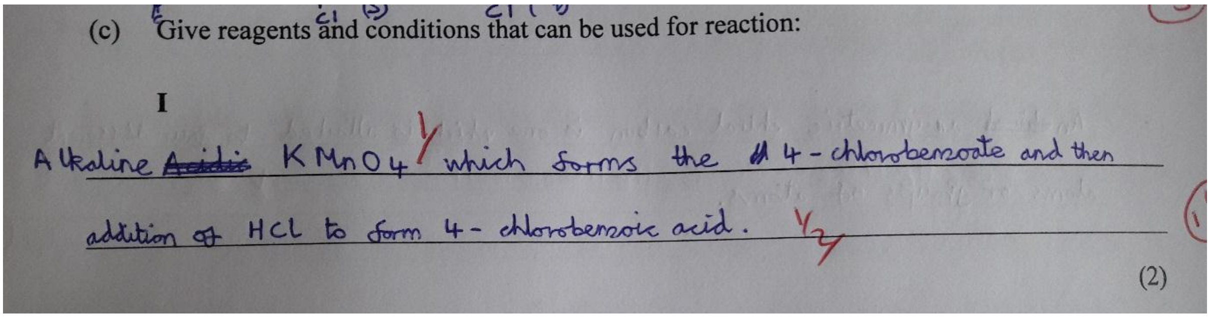
The item discriminating power for this question was found to be 0.57, which indicates that there is a considerable degree of discrimination between students in the high band and those in the low band. Moreover, 3.3% of the students, all from the lower band, did not attempt the question.

Table 4.5 - Responses for recall of reagents and reaction conditions for the conversion of 1-chloro-4-methylbenzene to 4-chlorobenzoic acid with pertaining description and percentage of students

Description	Frequency (%) to 1 d.p.
Correct with no mistakes	19.0
Incorrect due to no mentioning of points 1, 2 and 3, and use of totally incorrect reagents	20.3
Partly correct due to no mentioning of point 1	14.3
Partly correct due to no mentioning of points 1 and 2	13.7
Incorrect due to no mentioning of points 1, 2 and 3	9.0
Partly correct due to no mentioning of point 2	6.3
Partly correct due to no mentioning of point 3	5.7
Partly correct due to no mentioning of points 1 and 3	5.0
Partly correct due no mentioning of points 2 and 3	3.3
Not attempted	3.3

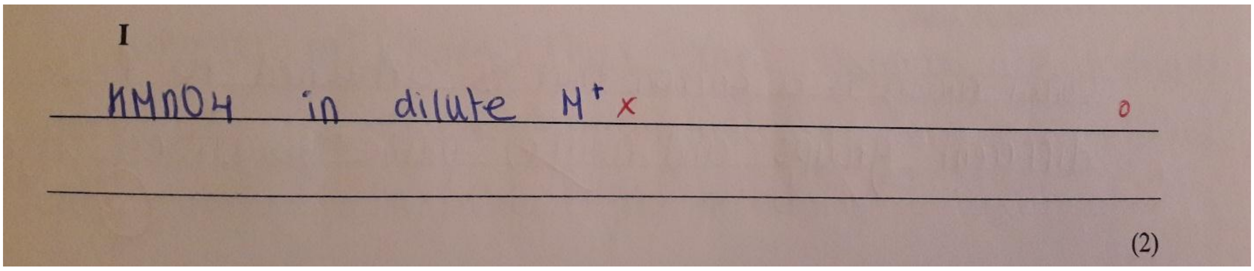
This question requires both recall and understanding, given that students are required to understand the conversion of 1-chloro-4-methylbenzene to 4-chlorobenzoic acid and then recall the reagents and conditions for the conversion to take place. Whilst the majority of the students simply gave the reaction conditions, others opted to give a full explanation as illustrated in Figure 7, even though the number of students who gave a full explanation was limited (and it is not the aim of this study to analyse who gave full answers and who did not).

Figure 7 – Illustration of an answer by a student in the high band who gave the answer in descriptive steps



On the other hand those students who either did not understand the change from methyl to salt to carboxylic acid and/or failed to recall the right reaction conditions and reagents, gave incorrect answers such as the one in Figure 8.

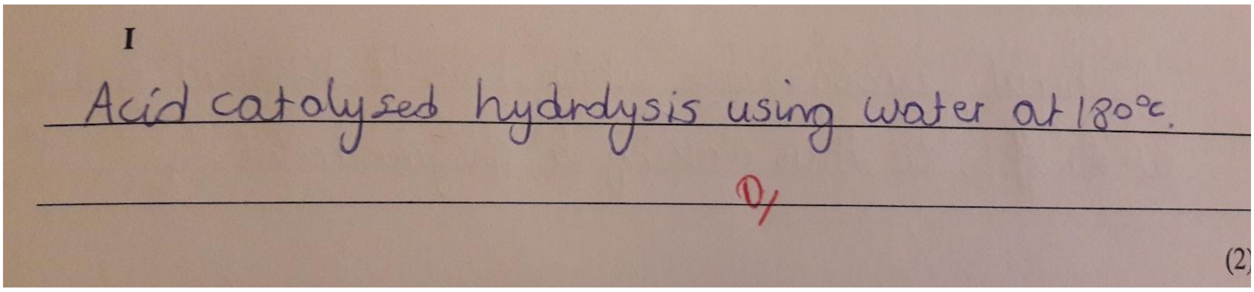
Figure 8 – Illustration of an answer by a student in the low band who gave an answer which is not made up of steps



4.4.1.1. High frequency mistakes (9.0 – 20.3%)

Responses showed that recall and understanding may in fact be challenging in organic chemistry. In this section, most of the students gave totally incorrect answers which were not relevant to the question. The reagents and reaction conditions given by some students were related to other reactions, such as the dehydration of alcohols to form alkenes for instance, as shown in Figure 9.

Figure 9 – Incorrect reagents and reaction conditions the conversion of 1-choro-4-methylbenzene to 4-chlorobenzoic acid



In such instances, the mistake about the reaction taking place was evident. On the other hand, there were numerous students who mistook the medium in which the $KMnO_4$ should be in.

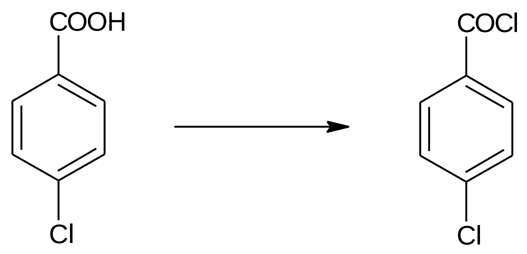
4.4.1.2. Low frequency mistakes (3.3 – 6.3 %)

Some of the students made multiple mistakes and showed that not only were they not sure which reagents to choose, but neither of the reaction taking place proving that they neither comprehended the type of reaction taking place, nor recalled the appropriate reagents and reaction conditions.

4.4.2. Recall and understanding of reagents and reaction conditions for reaction II

The following question was given in paper 1:

7.c.ii. Give reagents and conditions that can be used for reaction:
(II)



B **C**

In this reaction the chlorine is displacing the hydroxyl moiety and converting 4-chlorobenzoic acid to 4-chlorobenozyl chloride. The mechanism of the reaction is too complex for A-level and students are not expected to know it or picture it to arrive at the final molecule, however there are two methods by which this reaction can take place:

1. Addition of PCl_5 at room temperature and pressure.
2. Addition of $SOCl_2$ in dry ether at room temperature and pressure.

It is ideal that either reaction is carried out at room temperature and pressure however gentle heating would be accepted too as an answer. Both answers would have been accepted as long as it is clear what the students are referring to when it comes to recall of reagents and reaction conditions, and understanding what kind of reaction is taking place (i.e. from a carboxylic acid moiety to an acyl chloride moiety) and the ensuing steps.

In this question, 300 students' responses were analysed. Seven students from the lower band did not attempt the question. When attempting this question, 208 students out of 293 arrived at the actual full answer. An answer was considered correct if a student gets 75% of the marks, or higher which in this case translates into a mark of 1.5 -2. A high percentage of students gave the correct answer and the facility index was found to be 71.0 %, thus the item difficulty being 29.0 %. The students' responses are shown in Table 4.6 alongside their respective frequency.

Table 4.6 – Responses for recall of reagents and reaction conditions for the conversion of 4-chlorobenzoic acid to 4-chlorobenzoyl chloride with pertaining description and percentage of students

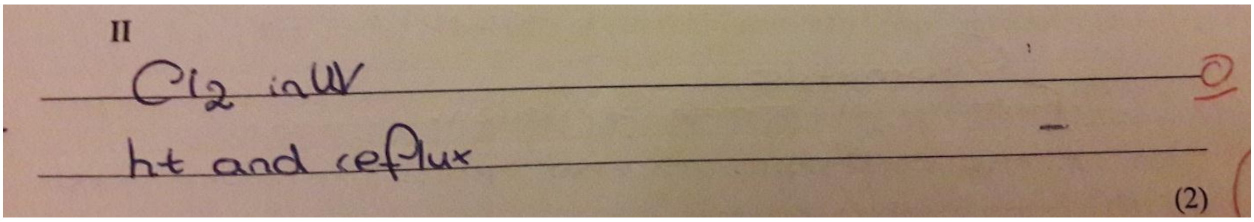
Description	Frequency (%) to 1 d.p.
Correct with no mistakes	69.0
Incorrect due to not specifying point 1 or 2, not specifying that reaction is carried out at r.t.p or gentle warming and not reflux, and use of wrong reagents	25.0
Partly correct due to: Not specifying that reaction is carried out at r.t.p or gentle warming and not reflux	3.7
Not attempted	2.3

The item discriminating power for this section of results was found to be 0.41, even though there is a considerable amount of discriminating power, it is less compared to the recall and understanding question analysed in Section 4.4.1. This is because some students from the lower band managed to answer this question. Moreover, 3.7% of the students, all from the lower band did not attempt the question.

4.4.2.1. High frequency mistakes (25%)

The drawback behind such a question is that students do not know the mechanism of this reaction. One of the most common mistakes was that to give Cl_2/UV as the reaction conditions, which is incorrect. Had the students knew the mechanism of how the chlorine atom displaces the hydroxyl, then they might have not opted for that answer. It is thus a misconception of how the chlorine atoms are furnished in a reaction. Figure 10 illustrates a typical answer giving Cl_2/UV as an answer.

Figure 10 – Typical mistake by students giving Cl_2/UV reaction conditions for the conversion of 4-chlorobenzoic acid to 4-chlorobenzoyl chloride



4.4.2.2. Low frequency mistakes (3.7 %)

In this section, most of the students failed to give the exact conditions of the reagents and thus had some marks deducted. These would include refluxing or boiling to the reaction.

4.4.3. Recall and understanding of the formation of electrophile for the nitration of benzene

The following question was given in paper 1:

9. Treatment of benzene with a mixture of concentrated nitric (V) and sulfuric (VI) acids at 60 °C, produces substance E, which is a yellow liquid with a characteristic smell.

a. Write an equation for the formation of a nitrogen-containing electrophile from the interaction of nitric (V) and sulfuric (VI) acids and identify the electrophile.

In this question, students were expected to:

1. Give the reaction between HNO_3 and H_2SO4 giving the following equation:

$$HNO_{3\,(aq)} + H_2SO_{4\,(aq)} \rightarrow HSO_4^-{}_{(aq)} + NO_2^+{}_{(aq)} + H_2O_{(l)}$$

2. Following this, students would highlight that NO_2^+ is the electrophile.

Alternatively to the above equation, the following equation was also accepted, where the complex would first form and then break down to give the nitronium ion and water:

$$HNO_{3\,(aq)} + H_2SO_{4\,(aq)} \rightarrow {}^-O\text{-}SO_3H_{(aq)} + H_2O^+\text{-}NO_{2\,(aq)}$$
$$H_2O^+\text{-}NO_{2\,(aq)} \rightarrow NO_2^+{}_{(aq)} + H_2O_{(l)}$$

Both answers would have been accepted as long as in the end the student shows that there are three products, namely: hydrogensulfate ion, nitronium ion and water. The nitronium ion is the electrophile.

In this question, 300 students' responses were analysed. Fifteen students from the low band and 1 student from the high band did not attempt the question. Out of 284 students who attempted the question, 134 arrived at the actual full answer. An answer was considered correct if a student gets 75% of the marks or higher which in this case translates into a mark of 1.5 -2. With a relatively low number of students who got the answer correct, the facility index was found to be 47.2 %, thus the item difficulty being 52.8 %. The students' responses are shown in Table 4.7 alongside the respective frequency.

Table 4.7 – Responses for recall of formation of electrophile for the nitration of benzene, with pertaining description and percentage of students

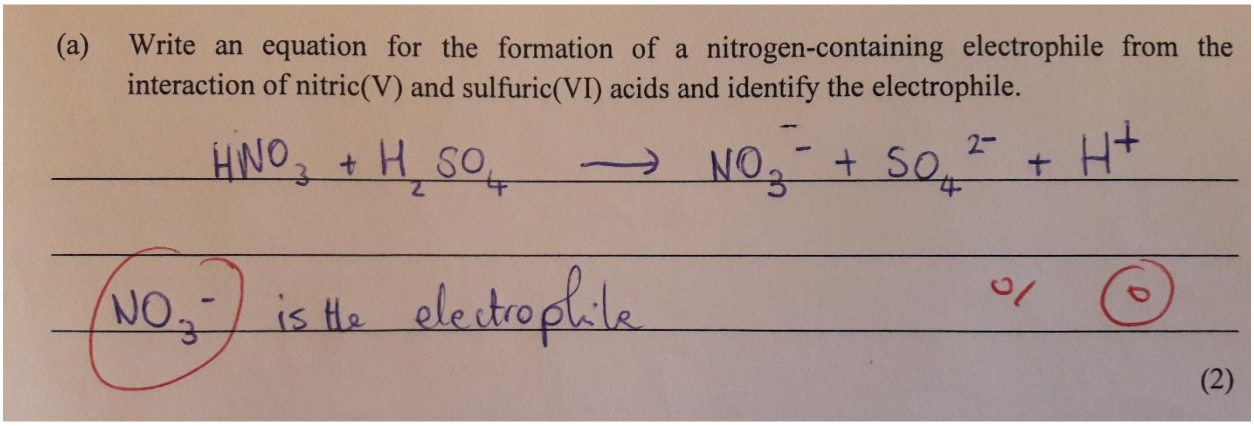
Description	Frequency (%) to 1 d.p.
Correct with no mistakes	42.0
Incorrect due to: Incorrect balancing of equation Incorrect reagents and products Wrong identification of the electrophile	31.7
Partly correct due to incorrect/unclear products	10.4
Partly correct due to wrong identification of the electrophile	4.3
Partly correct due to incorrect balancing of the equation	3.3
Partly correct due to incorrect reagents and products and wrong identification of the electrophile	3.0
Not attempted	5.3

The item discriminating power for this section of results was found to be 0.35, which indicates that there is a considerable degree of discrimination between students in the high band and those in the low band. There were 5.3% of the students who did not attempt the question presumably because this question consisted of two parts, namely the recall of the equation and the understanding that the electrophile is the nitronium ion, making it a challenging question.

4.4.3.1. High frequency mistakes (31.7%)

In the high-frequency mistakes section, students proved how even though this question was not complex to answer, given that at A-level both the equation and definition of electrophiles are learnt, a large number of students failed to obtain any marks in this question. Those who failed, did so, because they did not know how to formulate the correct chemical equation and did not know what an electrophile is. An electrophile is a positively charged species which is attracted to electron-rich species. Students gave incorrect answers by giving the nitronium ion as being negatively charged and thus it seems that there is a misconception amongst a particular percentage of students who believe that electrophiles are negatively charged species, as illustrated by Figure 11.

Figure 11 – Illustration of an answer by a student in the low band who gave an incorrect chemical equation for the reaction between HNO_3 and H_2SO_4 and thus giving an electrophile with a negative charge rather and a positive charge


(a) Write an equation for the formation of a nitrogen-containing electrophile from the interaction of nitric(V) and sulfuric(VI) acids and identify the electrophile.

$HNO_3 + H_2SO_4 \longrightarrow NO_3^- + SO_4^{2-} + H^+$

NO_3^- is the electrophile

0/ 0

(2)

There were also several mistakes made when it comes to writing the chemical equations. At A-level, students are expected to know how to formulate chemical equations between a base and an acid. Even though HNO_3 and H_2SO_4 are both acids, their reaction is an acid-base reaction since:

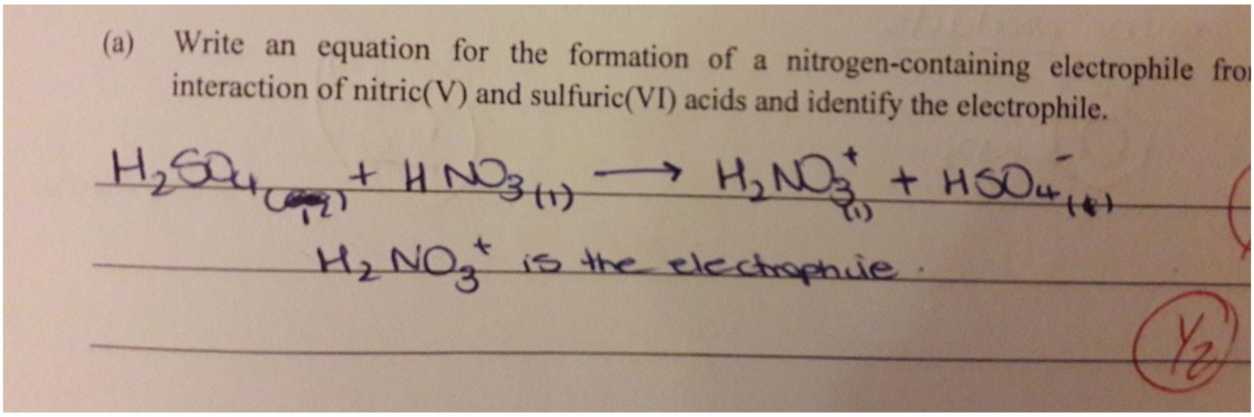
$$HNO_{3\,(aq)} + H_2SO_{4\,(aq)} \rightarrow {}^{-}O\text{-}SO_3H_{(aq)} + H_2O^{+}\text{-}NO_{2\,(aq)}$$

where hydrogensulfate ion is the conjugate base and the nitronium hydrate is the conjugate acid. Students should be able to understand and explain this from their knowledge of acids and bases. It seems that the students who gave an incorrect answer were not aware of this reaction taking place and thus could not give the right equation and right electrophile.

4.4.3.2. Low frequency mistakes (8.7 – 1.7 %)

In the low frequency mistakes section, most of the students left out some important parts of the answer. Students showed once again the misconception of electrophiles being negatively charged. Some students gave the correct chemical equation and then failed to point out the correct electrophile, by giving the nitronium hydrate ion, which instead was meant to dissociate, as illustrated by Figure 12.

Figure 12 – Illustration of an answer by a student in the high band who failed to show the right electrophile by not dissociating nitronium hydrate ion into nitronium ion and water molecule



4.4.4. Recall of definition for enantiomer

The following question was given in paper 1:

8.d. Explain the following (two) term(s):

i. enantiomer

In order to get full marks for this question, students had to mention that:
1. An enantiomer is an optical isomer.
2. This optical isomer is not superimposable on its mirror image.

In this question, 300 students' responses were analysed. Twenty-two students from the lower band did not attempt the question. Analysis showed that 85 students out of 278 who attempted the question, arrived at the actual full answer. Since the question carried one mark, it was all or none, and a response was considered correct if the student got 1 mark.

With a relatively low number of students who got the answer correct, the facility index was found to be 30.5 %, thus the item difficulty being 69.5 %. The students' responses are shown in Table 4.8 alongside the respective percentages.

Table 4.8 – Students' responses for recall of definition for enantiomer with pertaining description and percentage of students

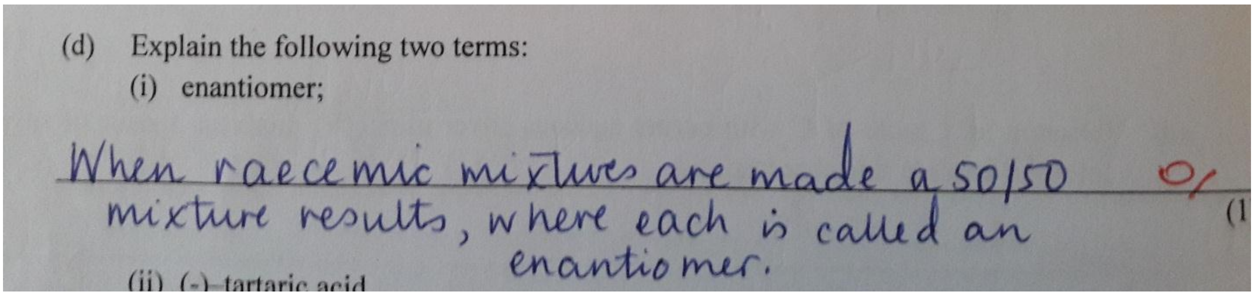
Description	Frequency (%) to 1 d.p.
Correct with no mistakes	28.3
Incorrect due to no mentioning of points 1 and 2	31.0
Incorrect due to not fully specifying point 2	13.7
Partly correct due to no mentioning of point 2	16.3
Partly correct due to no mentioning of point 1	3.7
Not attempted	7.0

The item discriminating power was found to be 0.31, which indicates that there is a considerable but not large degree of discrimination between students in the high band and those in the low band. Once again, the percentage of students who failed to attempt the question was higher, being 7.0%. The low percentage of students who got the item correct shows that even though recall is deemed as the most simple and concrete in Bloom's taxonomy, where Pungente & Badger (2003) argue that it is a lower cognitive level, its degree of challenge should not be underestimated.

4.4.4.1. High frequency mistakes (31.0%)

It has become apparent from this study that students were not aware that an enantiomer is an optical isomer because this was missing in many answers. Alongside this, students were not aware that an enantiomer is one of a pair which has a different spatial arrangement to that of its counterpart and therefore cannot be superimposed on its mirror image. Some students resorted to answer the questions with a series of related terms which still gave no proper definition of what an enantiomer is. As illustrated by Figure 13, a student failed to recall the proper definition and listed a series of points which are all related to enantiomer but not related in their sequence in the answer.

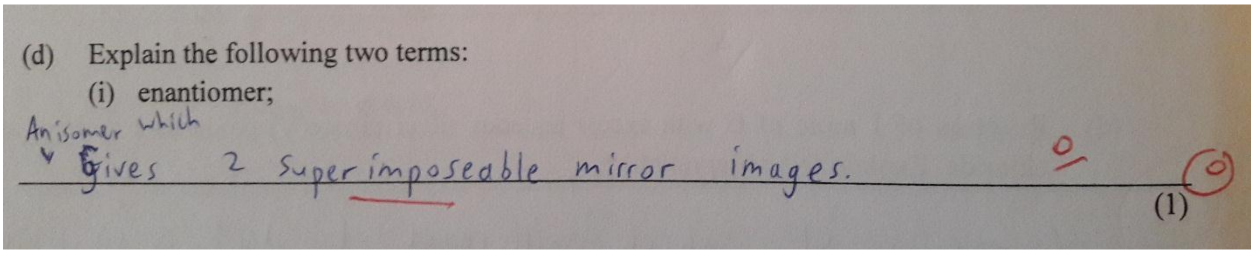
Figure 13 – Illustration of an answer by a student in the low band who failed to recall the proper definition for enantiomer.


(d) Explain the following two terms:
(i) enantiomer;
When raecemic mixtures are made a 50/50 mixture results, where each is called an enantiomer.
0/
(1
(ii) (-)-tartaric acid

4.4.4.2. Low frequency mistakes (7.0 – 16.3 %)

Among the low frequency mistakes, most students failed to mention one point from the definition that is, that an enantiomer is an optical isomer and that it is non-superimposable with its mirror image. Common mistakes in this section were that enantiomers are optical isomers and are superimposable with their mirror image. Had that been possible, there would be no difference in the 3-D spatial orientation of the molecules and therefore no optical isomerism. This misconception may arise from the fact that students are unable to visualise molecules, because as argued by Frisch & Wasserman (1961), chemical topology is also important to understand features related to molecular structures which include spatial arrangement. This is illustrated in Figure 14.

Figure 14 – Illustration of an answer by a student in the high band who failed to recall the proper definition in terms of their spatial arrangement of molecules

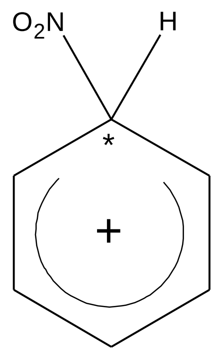

(d) Explain the following two terms:
(i) enantiomer;
An isomer which gives 2 superimposeable mirror images.
0/
(1)

4.4.5. Recall of aromatic chemistry to intermediate structures

The following question was given in paper 1:

9.b. The electrophile in part (a) reacts with benzene and forms an intermediate, F, which has a positive delocalised charge. Draw the structure of F and indicate with an (*) the carbon atom which is NOT involved in delocalisation.

In order to get full marks for this question, students had to draw the above intermediate with no missing or added components to it.



F

Namely:

1. Show the nitro group, consisting of $–NO_2$.
2. Show the carbon not involved in delocalisation marked with an asterisk.
3. Show the hydrogen atom bonded to the carbon with the asterisk since lack of it might indicate substitution, rather than addition for the formation of the intermediate.
4. Show the positive delocalised charge in the middle of the ring.

In this question, 300 students' answers were analysed. Twenty-five students from the low band did not attempt the question. On the other hand, 159 students out of 275 who attempted the question, arrived at the actual full answer. An answer was considered correct if a student gets 75%, or higher which in this case translates into a mark of 1.5 - 2. With a moderate number of students who got the answer correct, the facility index was found to be 57.8 %, thus the item difficulty being 42.2 %. Once again, this question showed that nearly four out of every ten students gave an incorrect answer and that recall of organic principles proves to be a challenging task. Students' responses are shown in Table 4.9 alongside the respective percentages.

Table 4.9 – Students' responses for recall of aromatic chemistry to intermediate structures with pertaining description and percentage of students

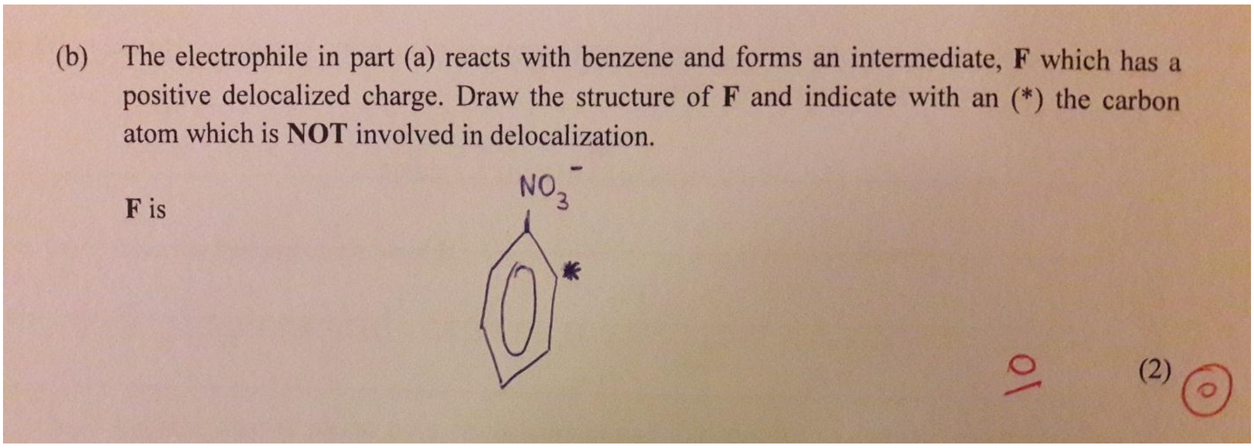
Description	Frequency (%) to 1 d.p.
Correct with no mistakes	50.3
Incorrect due to not illustrating point 1	17.3
Incorrect due to not illustrating point 4	3.7
Incorrect due to not illustrating point 2	2.0
Partly correct due to partly illustrating point 3	5.0
Partly correct due to not fully illustrating point 4	4.0
Partly correct due to not fully illustrating point 1	4.0
Partly correct due to not fully illustrating point 2	5.3
Not attempted	8.3

The item discriminating power for this section of results was found to be 0.67, which indicates that there is a considerable degree of discrimination between students in the high band and those in the low band.

4.4.5.1. High frequency mistakes (17.3 %)

Given that this question is a continuation of question 9.a., students who did not figure out the electrophile present, that is the nitronium ion, presumably failed to give the correct intermediate. Students gave an array of different possible electrophiles, some of which do not chemically make sense, such as the one depicted in Figure 15. In the latter illustration, the student believed that the intermediate would carry the charge precisely on the electrophile bonded to the benzene ring, and indicated that the NO_3-related compound is the electrophile. This is one of the many incorrect answers, and with such a variety of answers, not all could be grouped.

Figure 15 – Illustration of an answer by a student in the low band who believed that the electrophile is related to NO_3 and still carries the charge

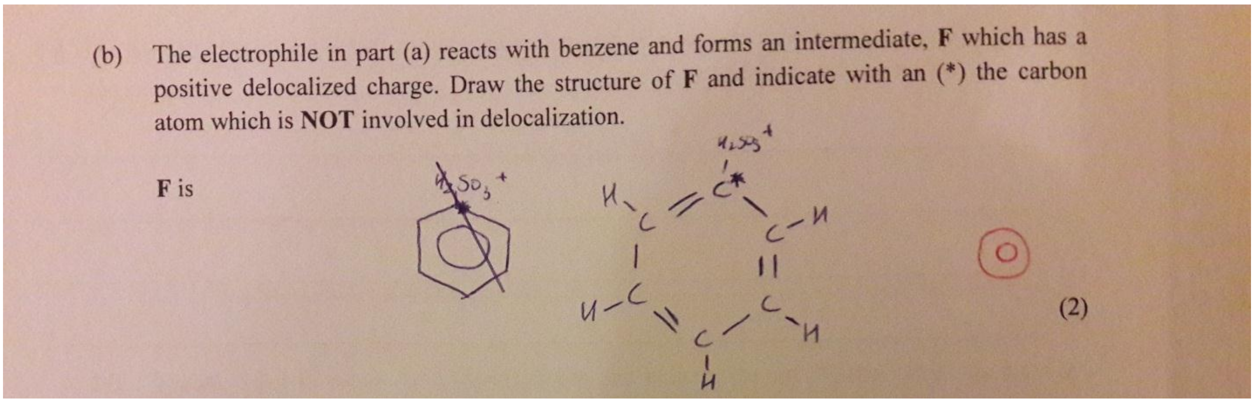

(b) The electrophile in part (a) reacts with benzene and forms an intermediate, **F** which has a positive delocalized charge. Draw the structure of **F** and indicate with an (*) the carbon atom which is **NOT** involved in delocalization.

F is

(2)

During this study it was also noted how students believed that the hydrogensulfate ion would act as the electrophile in this reaction. This brings several misconceptions with it. The first one is that some students are not aware of what an electrophile is and what a nucleophile is, and the difference between them. The second misconception is that the intermediate product following an electrophilic attack would involve the hydrogensulfate ion. Following these misconceptions, students indicated that the hydrogensulfate ion would in some way bond to the benzene ring, giving answers such as the one depicted in Figure 16. Moreover the student giving the answer in Figure 16, gave a group which may be thought of as 'charged sulfurous acid'. The students probably confused this reaction with sulfonation where the substituent is SO_3H. This seems to suggest that learning is superficial and at a recall level with little attempts to understand.

Figure 16 – Illustration of an answer by a student in the low band who believed that the electrophile is related to the HSO_4^- ion

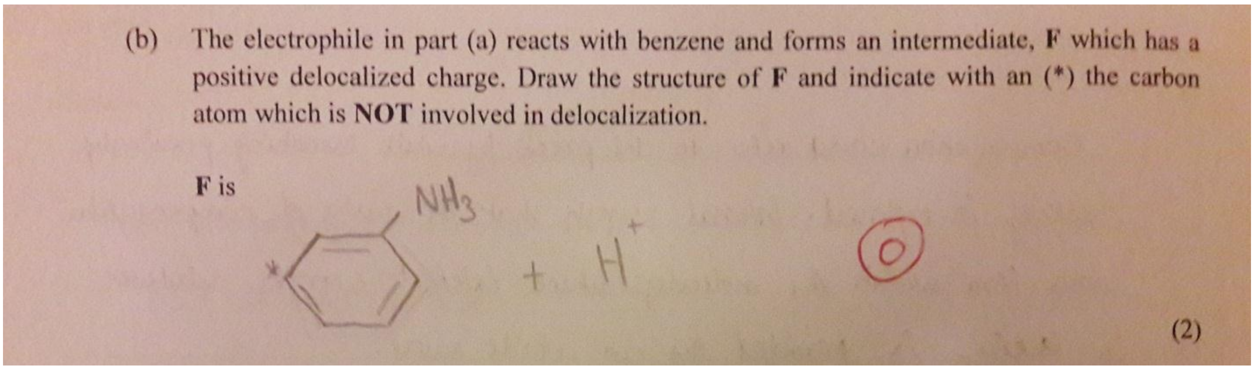

(b) The electrophile in part (a) reacts with benzene and forms an intermediate, **F** which has a positive delocalized charge. Draw the structure of **F** and indicate with an (*) the carbon atom which is **NOT** involved in delocalization.

F is

(2)

Other groups were also mentioned in this answer, which were not merely related to HNO_3, H_2SO_4 or the respective NO_2^+ and HSO_4^- formed, such as NH_3. These answers were classified as incorrect answers due to the wrong group. Figure 17 illustrates a typical example.

Figure 17 – Illustration of an answer by a student in the low band who gave the wrong group bonded to the benzene ring



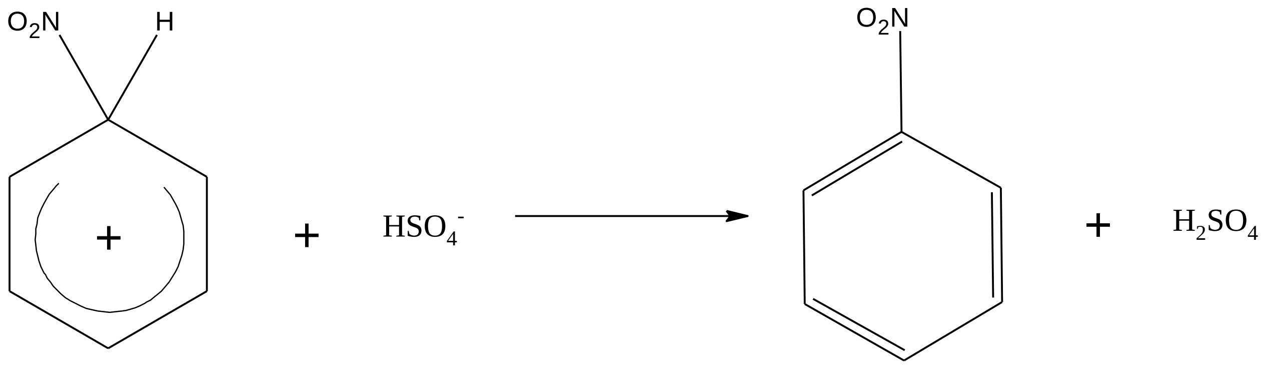
4.4.5.2. Low frequency mistakes (1.3 - 5 %)

Among the low frequency mistakes we find: not marking the asterisk, not showing that H atom is still bonded to the C not involved in positive delocalisation and failing to show the positive charge in the ring. Such mistakes show that students did not understand precisely what the intermediate molecule is and therefore failed to point vital parts of it. One of the most common misconceptions arises as to which carbon atom is not involved in the positive delocalisation, where once again students gave an array of possible carbons to which this might happen. Following the electrophilic attack, C number 1 is taken as that which does not participate in the delocalisation, but students listed several other carbons, with students pointing out even more than one single C atom. Once again, due to the variety of answers, these could not be grouped into a single category.

4.4.6. Recall and understanding of aromatic chemistry related to the formation of nitrobenzene and regeneration of sulfuric acid catalyst

The following question was given in paper 1:

9.c. F reacts to form E. Write an equation for this reaction.



F E

In order to get full marks for this question, students had to draw the above equation with no missing or added components to it. Namely show:

1. The correct structure for intermediate F as intermediate ("reactant").
2. The hydrogensulfate ion to be shown as intermediate ("reactant").
3. The final product nitrobenzene (E).
4. The sulfuric acid which is the regenerated catalyst.

In this question, 300 students' answers were analysed. One student from the high band and 46 students from the low band did not attempt the question. On the other hand, 79 students out of 253 who attempted the question, arrived at the actual full answer. An answer was considered correct if a student gets 75% of the marks, or higher which in this case translates into a mark of 1.5 - 2. With a relatively low number of students who got the answer correct, the facility index was found to be 31.2 %, thus the item difficulty being 68.8 %. Once again, this question proved how nearly 7 out of every 10 students found recall and understanding of organic principles to be a challenging task. Students' responses are shown in Table 4.10 alongside the respective percentages.

Table 4.10 – Responses for recall of aromatic chemistry related to the formation of nitrobenzene and regeneration of sulfuric acid catalyst with pertaining description and percentage of students

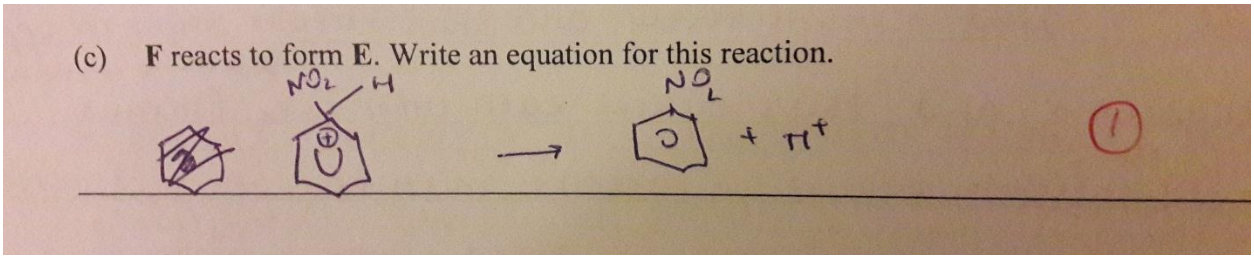
Description	Frequency (%) to 1 d.p.
Correct with no mistakes	19.0
Incorrect due to not highlighting points 1, 2 and 4	17.7
Incorrect due to not highlighting points 1, 2, 3 and 4, and drawing an incorrect product	15.7
Incorrect due to not highlighting points 1, 2, 3 and 4	12.3
Partly correct due to not highlighting points 2 and 4	19.7
Not attempted	15.7

The item discriminating power for this item was found to be 0.43, which indicates that there is a considerable but not large degree of discrimination between students in the high band and those in the low band. The percentage of students who failed to attempt the question was 15.7 % making it the second least attempted question. One common feature in the many answers given was that students gave the correct formation of the product nitrobenzene but failed to show how it is formed. Relating this section to Section 4.4.5., students showed that they are not able to break up a reaction into components and give the chemistry involved for each part.

4.4.6.1. Errors made (12.3 – 19.7%)

The errors made by students in this section were based upon misconceptions or errors throughout the whole question. Whereas the majority of the students gave nitrobenzene as the correct final product, there were others who gave molecules which were not related. The most common misconception was that of H_2SO_4. The majority of the students gave H^+ as the regenerated catalyst along with the final product, which is not correct because had the proton been the only regenerated part of sulfuric acid, then where would have the HSO_4^- ended? This proves that some students were not aware that the sulfuric acid is a catalyst. Furthermore, the majority of the students failed to point out that HSO_4^- ought to be on the "reactants" side as this will re-form the original H_2SO_4. Failure to include the HSO_4^- as part of the reaction was viewed across the whole spectrum of respondents as illustrated by Figure 18.

Figure 18 – Illustration of a student from the high band who failed to show the regeneration of H_2SO_4 catalyst and listed H^+ as being regenerated



Along such a mistake was the drawing of the incorrect structure of the intermediate. Those students who failed to give the correct structure in question 9.b. also failed to give the right equation for the formation of nitrobenzene and the regeneration of the catalyst. Once again it was shown how the majority of the students studied this recall reaction very superficially and thus lacked the understanding part, where the H_2SO_4 is regenerated.

4.4.7. Understanding of the term (-)tartaric acid

In question 8.d., students were also expected to explain the following term:

ii. (-)-tartaric acid.

In order to get full marks for this question, students had to mention that:

1. The enantiomer is an optical isomer.
2. The (-) notion denotes that the enantiomer is laevorotatory/ rotates plane polarised light to the left/ rotates plane polarised light anticlockwise.

In this question, 300 students' responses were analysed. Twenty-four students from the lower band did not attempt the question. Following the analysis, 173 students out of 276 who attempted the question, arrived at the actual full answer. Since the question carried one mark, it was all or none, and a response was considered correct if the student got 1 mark. With a considerable number of students who got the answer correct, the facility index was found to be 62.7 %, thus the item difficulty being 37.3 %. The students' responses are shown in Table 4.11 alongside their respective frequency.

Table 4.11 – Responses for comprehension of (-) enantiomer with pertaining description and percentage of students

Description	Frequency (%) to 1 d.p.
Correct with no mistakes	57.0
Incorrect due to not specifying points 1 and 2.	28.3
Incorrect due to no mentioning of point 2.	4.3
Partly correct due to no mentioning of point 1.	2.3
Not attempted	8.0

The item discriminating power for this section of results was found to be 0.51, which indicates that there is a considerable degree of discrimination between students in the high band and those in the low band. Once again, the percentage of students who failed to attempt the question was slightly higher compared to the recall questions, being 8.0%, whereas the number of students who failed the question was lower compared to question 8.d.i

4.4.7.1. High frequency mistakes (28.3%)

The mistakes in this section are very much related to those mentioned in Section 4.4.4.1. since students failed to mention that (-)-tartaric acid is an optical isomer and that it rotates plane polarised light to the left. Such a property is denoted by the symbol given to the enantiomer before its name and such symbols are used to tell apart enantiomers. Many of those who failed to mention these two points included answers which were totally unrelated to the topic.

4.4.7.2. Low frequency mistakes (2.3 – 4.3 %)

The low frequency mistakes are also very related to those in Section 4.4.4.2. as students failed to mention at least one of the two points required to get full marks.

4.4.8. Conclusion

It may be concluded that compared to other questions, students perform relatively better in recall questions, and poorly in recall/understanding and understanding questions which present a challenge to numerous students, who generally, do not make an association with the chemistry involved. As Stowe & Cooper (2017) argue in their paper, students who have an ability to recall content knowledge do not necessarily mirror a deep and meaningful understanding of the chemistry principles.

4.5. Application of organic chemistry principles

In this paper, there were a number of organic chemistry questions which required the application of organic principles, other than nomenclature which was tackled separately in Section 4.2. Once again, it was challenging for the students to apply principles of organic chemistry. Nevertheless is was observed how organic principles covered at the start of the chemistry A-level course were less challenging than those covered at a later stage, such as aromaticity.

4.5.1. Application of chirality to tartaric acid

The following question was given in paper 1:

8.b. Explain what is meant by a *chiral carbon* and indicate, by an (*) the *chiral carbons* in tartaric acid.

In order to be awarded full marks for this question, students had to:

1. State that the chiral carbon is an asymmetric centre.
2. State the chiral carbon is bonded to four different groups.
3. Indicate on the molecule the two chiral carbons.

$$HOOC\text{-}\overset{*}{C}H(OH)\text{-}\overset{*}{C}H(OH)\text{-}COOH$$

In this question, 300 students' responses were analysed out of which three from the lower band did not attempt the question. Analysis has shown that 242 students out of 297 who attempted the question, arrived at the actual full answer. An answer was considered correct if a student scored 75%, or higher which in this case translates into a mark of 1.5 – 2. With a relatively high number of students who got the answer correct, the facility index was found to be 81.5 %, thus the item difficulty was 18.5 %. In this question the number of misconceptions was relatively low, even though it may be appreciated how nearly 1 out of 5 students still made mistakes resulting from misconceptions. The students' responses are shown in Table 4.12 alongside the respective percentages.

Table 4.12 – Responses for application of chirality to tartaric acid with pertaining description and percentage of students

Description	Frequency (%) to 1 d.p.
Correct with no mistakes (2/2)	77.3
Incorrect due to no mentioning of points 1, 2 and 3, and indicating other carbon atoms as chiral centres	7.0
Partly correct due to no mentioning of point 2.	9.0
Partly correct due to not highlighting point 3.	3.0
Partly correct due to indicating other carbon atoms as chiral centres	2.7
Not attempted	1.0

The item discriminating power for this section of results was found to be 0.35, which indicates that there is a considerable but not large degree of discrimination between students in the high band and those in the low band. The percentage of students who failed to attempt the question was only 1.0% which is the lowest in all of the organic chemistry questions analysed in this study. The few mistakes made will be discussed in Section 4.5.1.1.

4.5.1.1. Mistakes made by students (2.7 – 9.0 %)

The mistakes made in the application of chirality to tartaric acid were relatively low where the highest percentage of students failed to mention that the carbon atom is bonded to four different groups. The percentage included students who state that carbon is bonded to different atoms, two different atoms/groups or to functional groups. Other students who failed to achieve a correct answer were not aware of which carbon atoms are chiral, and including students who labelled all four carbon atoms on tartaric acid, and those who labelled the carboxylic carbon atoms.

4.5.2. Application of isomerism to tartaric acid

The following question was given in paper 1:

8.c. Name the type of isomerism which may be exhibited by tartaric acid.

In order to be awarded full marks for this question, students had to mention that optical isomerism is the type of isomerism exhibited by tartaric acid.

In this question, 300 students' responses were analysed. Four students from the lower band did not attempt the question. Analysis has shown that 239 students out of 296 who attempted the question, arrived at the actual full answer. Since the question carried one mark, it was all or none, and a response was considered correct if the student got 1 mark. With a relatively low number of students who got the answer incorrect, the facility index was found to be 80.7 %, thus the item difficulty being 19.3 %. In this question the number of misconceptions was relatively low, even though it may be appreciated how nearly one out of five students still made mistakes or had misconceptions. Students' responses are shown in Table 4.13 alongside the respective percentages.

Table 4.13 – Students' responses for application of chirality to tartaric acid with pertaining description and percentage of students

Description	Frequency (%) to 1 d.p.
Correct with no mistakes	79.7
Incorrect due to: Not specifying/being clear that the type of isomerism is optical isomerism	8.0
Incorrect due to: Giving stereoisomerism as the type of isomerism	5.0
Incorrect due to: Giving geometric isomerism as the type of isomerism	3.3
Incorrect due to: Giving enantiomers as being the type of isomerism	1.7
Partly correct due to: Not specifying/being clear that the type of isomerism is optical isomerism	1.0
Not attempted	1.3

The item discriminating power for this section of results was found to be 0.27, which indicates that there is a considerable but not large degree of discrimination between students in the high band and those in the low band. The percentage of students who failed to attempt the question was only 1.3% which is the slightly higher than that for application of chirality in tartaric acid. The few mistakes made will be discussed under one heading in Section 4.5.2.1.

4.5.2.1. Mistakes made by students (1.0 – 10.0 %)

The mistakes made were relatively low in the application of isomerism to tartaric acid. Nevertheless there were a number of misconceptions where students included in the percentages of mistakes, confused optical isomerism with stereoisomerism and geometrical isomerism. Even though the latter two and optical isomerism are related, they are not the same. Stereoisomerism is a category of isomerism which deals with the 3-D and spatial arrangement of atoms in a molecule, whereas geometrical isomerism and optical isomerism are sub-categories of stereoisomerism. Geometrical isomerism may occur in a molecule which does not allow free rotation of the substituents, such as alkenes which contain a double bond. Hence it seems that there is a percentage of students who are still unaware of the difference between geometrical and optical isomerism.

4.5.3. Application of internal and external compensation to tartaric acid

The following question was given in paper 1:

8.e. Distinguish between internal and external compensation, using tartaric acid to exemplify the differences between the two terms.

A mixture containing two enantiomers, (+) and (-), in equal proportions is called a racemic mixture and is optically inactive due to external compensation, that is, the optical activity of one enantiomer is cancelled by the other enantiomer. Thus a mixture of (+)-tartaric acid and (-)-tartaric acid in equal amounts will have zero optical rotation. Nevertheless, there are chiral molecules which contain more than one chiral carbon, as in the case of tartaric acid. Such molecules may still be optically inactive because half of the molecule is a mirror image of the other. In tartaric acid, half the molecule is the mirror image of the other and is superimposable i.e. the molecule has a plane of symmetry. Hence optical inactivity is due to internal compensation where the optical activity contributed by half of the molecule is cancelled by the other half of the molecule.

In order to get full marks for this question, students had to mention that:

1. A mixture containing equal amounts of the (+) and (-) enantiomers is a racemic mixture.
2. Equal amounts of (+) and (-) tartaric acid enantiomers will not rotate plane polarised light (making the link to tartaric acid) as they will cancel each other’s optical activity.

3. External compensation is due to enantiomers of different optical activity, whereas internal compensation is due to the same molecule which is symmetrical due to the presence of an internal mirror plane.
4. Tartaric acid has more than one chiral centre that may occur as the meso-compound which leads to internal compensation.
5. Internal compensation results due to the optical inactivity of a molecule, which has more than one chiral centre and therefore half of the molecule cancels the optical activity of the other half, leading to no optical activity.

In this question, 300 students' responses were analysed. Five students from the high band and 60 students from the low band did not attempt the question. Analysis showed that 38 students out of 235 who attempted the question, arrived at the actual full answer. An answer was considered correct if a student gets 75% of the marks or higher which in this case translates into a mark of 3.75 - 5. With a considerably low number of students who got the answer correct, the facility index was found to be 16.2 %, thus the item difficulty being 83.8 %. Students' responses are shown in Table 4.14 alongside the respective percentages.

Table 4.14 - Students' responses for application of chirality to tartaric acid with pertaining description and percentage of students

Description	Frequency (%) to 1 d.p.
Correct with no mistakes	1.3
Incorrect due to not highlighting points 1, 2, 3, 4 and 5	20.3
Partly correct due to making associations between internal compensation with intramolecular bonding and external compensation with intermolecular bonding	14.3
Partly correct due to no mentioning of points 3, 4 and 5	23.7
Partly correct due to no mentioning of point 3	10.7
Partly correct due to no mentioning of points 1, 3 and 4	5.0
Partly correct due to no mentioning of point 4	1.7
Partly correct due to no mentioning of point 1	1.3
Not attempted	21.7

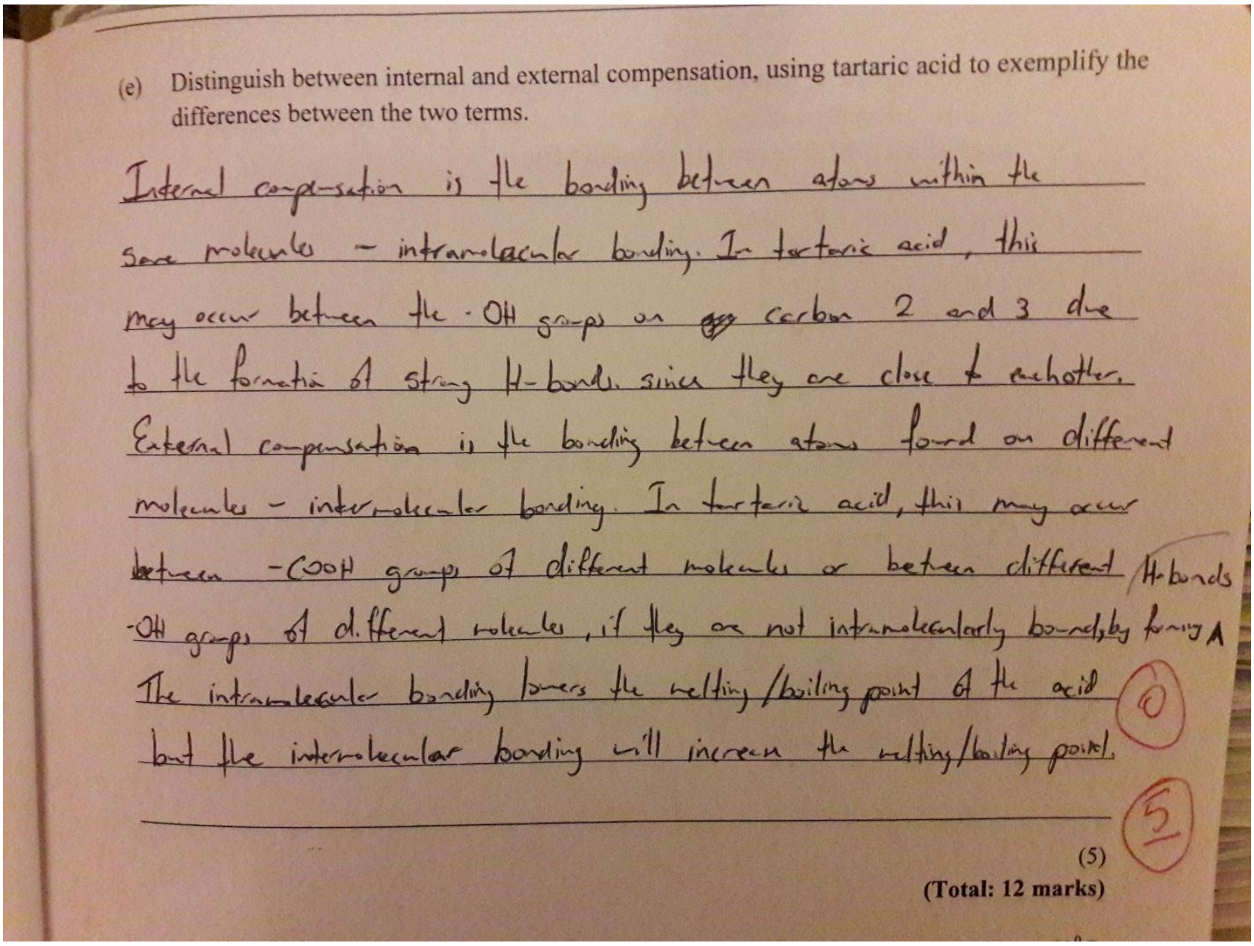
The item discriminating power for this section of results was found to be 0.24, which indicates that there is a considerable but not large degree of discrimination between students in the high band and those in the low band. The percentage of students who failed to attempt the question was 21.7% making it the organic chemistry question least attempted by students.

4.5.3.1. High frequency mistakes (14.3 – 23.7 %)

A large number of students failed to highlight vital points in relation to the answer, commencing from the most basic point to the most complex. It seems that many students were not able to make links between two different enantiomers which give a racemic mixture where the latter was not even mentioned in the answer. Having a vital reference such as racemic mixture is essential to show that one is referring to equal amounts of enantiomers which leads to optical inactivity. Eventually it was noticed how those students who failed to start off, or at least give this definition somewhere within the answer, failed throughout the whole answer as their argument would not be based on how optical activity might or might not take place, leading to errors in terms of internal compensation. Failing to do so led to other missing terms, including: symmetrical compound, meso-compound and the presence of an internal mirror plane. Students who did not answer correctly failed to make the association between these terms and consequently lost marks, leading to a very poor total mark. A number of students believed that the meso-compound tartaric acid contains two enantiomers rather than two stereocentres.

One major misconception which was evident in this study was that of students who linked internal compensation to intramolecular bonding and external compensation to intermolecular bonding. Students from both the high band and the low band proved to be unacquainted with internal and external compensations for optical activity, and were unable to relate this knowledge and apply it to tartaric acid. In Figure 19 an illustration of such an answer is shown.

Figure 19 –Answer by a student in the high band who believed that internal and external compensation are related to intra- and intermolecular H-bonding



(e) Distinguish between internal and external compensation, using tartaric acid to exemplify the differences between the two terms.

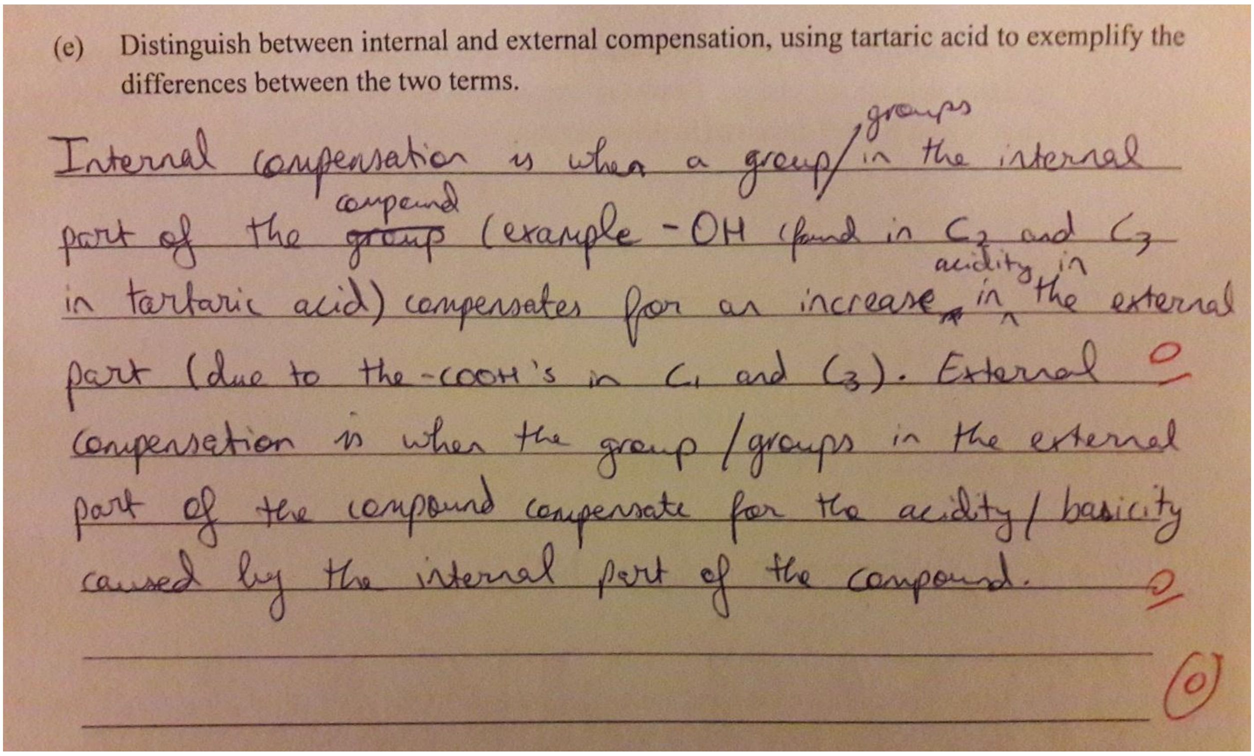
Internal compensation is the bonding between atoms within the same molecule – intramolecular bonding. In tartaric acid, this may occur between the -OH groups on carbon 2 and 3 due to the formation of strong H-bonds since they are close to eachother. External compensation is the bonding between atoms found on different molecules – intermolecular bonding. In tartaric acid, this may occur between -COOH groups of different molecules or between different -OH groups of different molecules, if they are not intramolecularly bonded, by forming H-bonds. The intramolecular bonding lowers the melting/boiling point of the acid but the intermolecular bonding will increase the melting/boiling point.

(5)

(Total: 12 marks)

In this study, it was noted how in this question, the students in the lower band not only made more mistakes but also came up with presumably guessed solutions. Most of the answers in the lower band where hence unique, giving rise to answers which were unrelated to internal and external compensation such as the one depicted in Figure 20.

Figure 20 – Illustration of an answer by a student in the low band who failed to mention vital points of internal and external compensation in relation to tartaric acid



(e) Distinguish between internal and external compensation, using tartaric acid to exemplify the differences between the two terms.

Internal compensation is when a group/groups in the internal part of the ~~group~~ compound (example -OH found in C_2 and C_3 in tartaric acid) compensates for an increase in acidity in the external part (due to the -COOH's in C_1 and C_3). External compensation is when the group/groups in the external part of the compound compensate for the acidity/basicity caused by the internal part of the compound.

0

0

(0)

4.5.3.2. Low frequency mistakes (1.3 – 10.7 %)

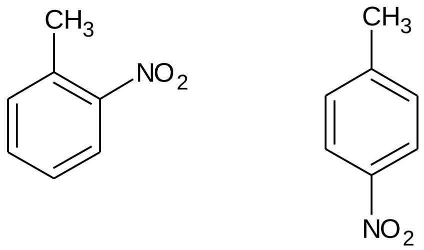
In the low frequency mistakes section most of the students understood well what internal and external compensation is, but failed to relate it to tartaric acid. Failing to relate with an example led to answers which were poorly structured and led to a certain degree of confusion. Moreover there were students who gave thorough answers but then left out particular details, such as those related to the internal mirror image within tartaric acid, or even failed to mention that tartaric acid has two chiral centres. Such details led to loss in marks which could have been avoided had students focused more on the question and related it to tartaric acid. Another group of students had difficulties with the term 'racemic mixture'. Students gave a detailed account of the fact that ratios of enantiomers are 1:1 but failed to state that such a mixture is called a 'racemic mixture'.

4.5.4. Application of aromatic chemistry to formation of major and minor products

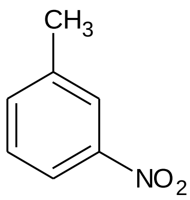
The following question was given in paper 1:

9.d. When methylbenzene is used instead of benzene in the reaction in part (a), two major products and one minor product are formed. Draw the structures of the two major products and the minor product.

In order to get full marks for this question, students had to draw the two major products and one minor product, namely:



2 major products



1 minor product

Methyl-2-nitrobenzene and methyl-4-nitrobenzene for the major products.
Methyl-3-nitrobenzene for the minor product.

When the nitration of methylbenzene takes place, two major products and one minor product form. The reason is that methyl group is electron-donating, where the activating methyl substituent is ortho and para directing, leaving the minor formation of the meta product.

In this question, 300 students' answers were analysed. Thirty students from the low band did not attempt the question. On the other hand, 135 students out of 270 who attempted the question, arrived at the actual full answer. An answer was considered correct if a student gets 75% or higher which in this case translates into a mark of 2.25 - 3. With a relatively low number of students who got the answer correct, the facility index was found to be 50.0 %, thus the item difficulty being 50.0 %. This question once again proved how application comes as a very challenging task for students with precisely half the students from those who attempted the question, failing this question. Students' responses are shown in Table 4.15 alongside the respective percentages.

Table 4.15 – Responses for application of aromatic chemistry to the formation of intermediate structures with pertaining description and percentage of students

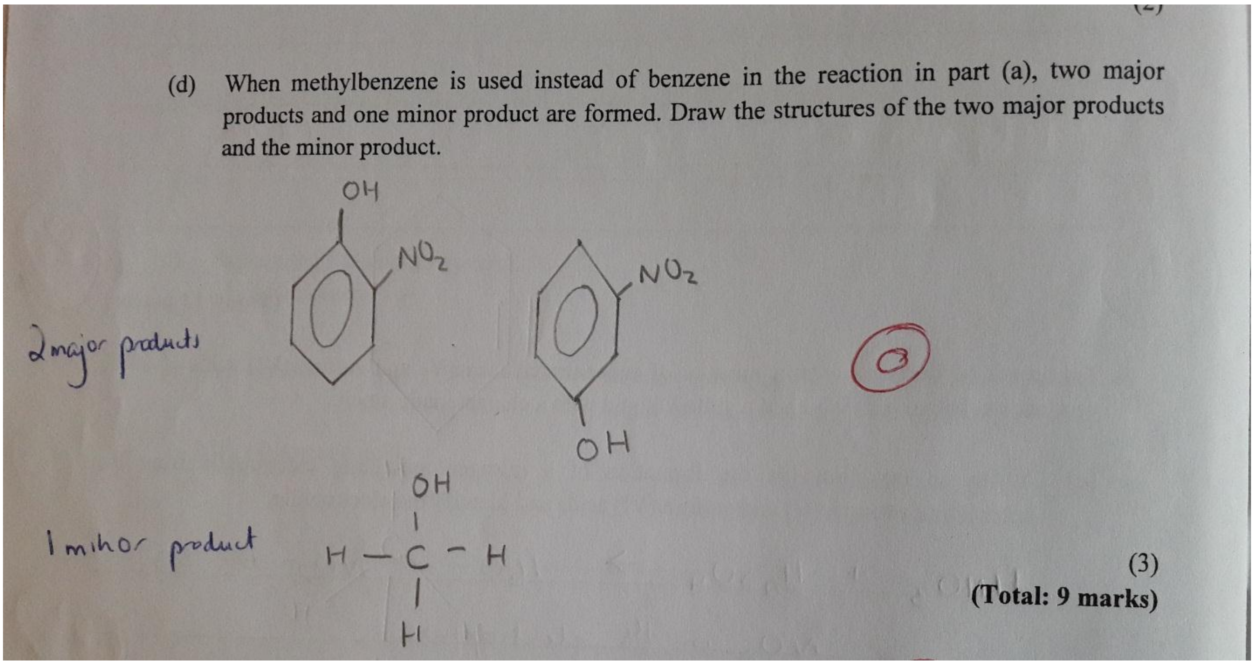
Description	Frequency (%) to 1 d.p.
Correct with no mistakes	45.0
Incorrect due to: Not giving all three nitro products in the correct major/minor formation and/or with additional groups which are not nitro groups	14.0
Partly correct due to: Giving 2,4-dinitromethylbenzene as minor product	9.3
Partly correct due to: Giving 2,4,6-trinitromethylbenzene as minor product	9.0
Partly correct due to: Not giving methyl-3-nitrobenzene as minor product	4.7
Partly correct due to: Not giving all three nitro products in the correct major/minor formation and/or with additional groups which are not nitro groups	4.0
Partly correct due to: Not giving methyl-4-nitrobenzene as major product	2.0
Partly correct due to: Giving 2,4,6-trinitromethylbenzene as minor product Giving multiple nitro substitutions for major products	2.0
Not attempted	10.0

The item discriminating power for this sub-question was found to be 0.54, which indicates that there is a considerable but not large degree of discrimination between students in the high band and those in the low band. The percentage of students who failed to attempt the question was 10 % making it one of the least attempted questions. The question required application of chemistry knowledge about synthesis and students found this question rather challenging, most of them giving answers which were not related to the question.

4.5.4.1. High frequency mistakes (9.0 – 14.0 %)

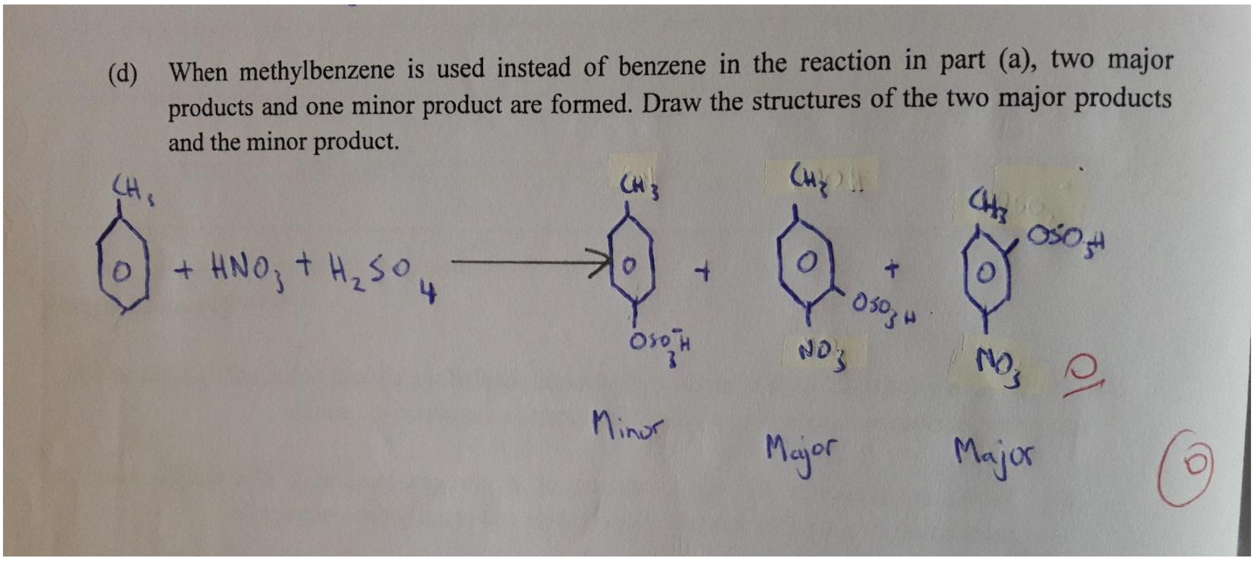
This question linked to question 9.a and students who gave responses which were not correct in 9.a, eventually fared badly in 9.b, 9.c. and also in this question. It was noted how some students in this study did not know the difference between a major and a minor product, where answers were evidently showing that the structures drawn, if at all, did not correspond to benzene, methylbenzene or even the products asked for, as illustrated by Figure 21.

Figure 21 – Illustration of an answer from a student in the low band who did not give the right major and minor products for the nitration of methylbenzene



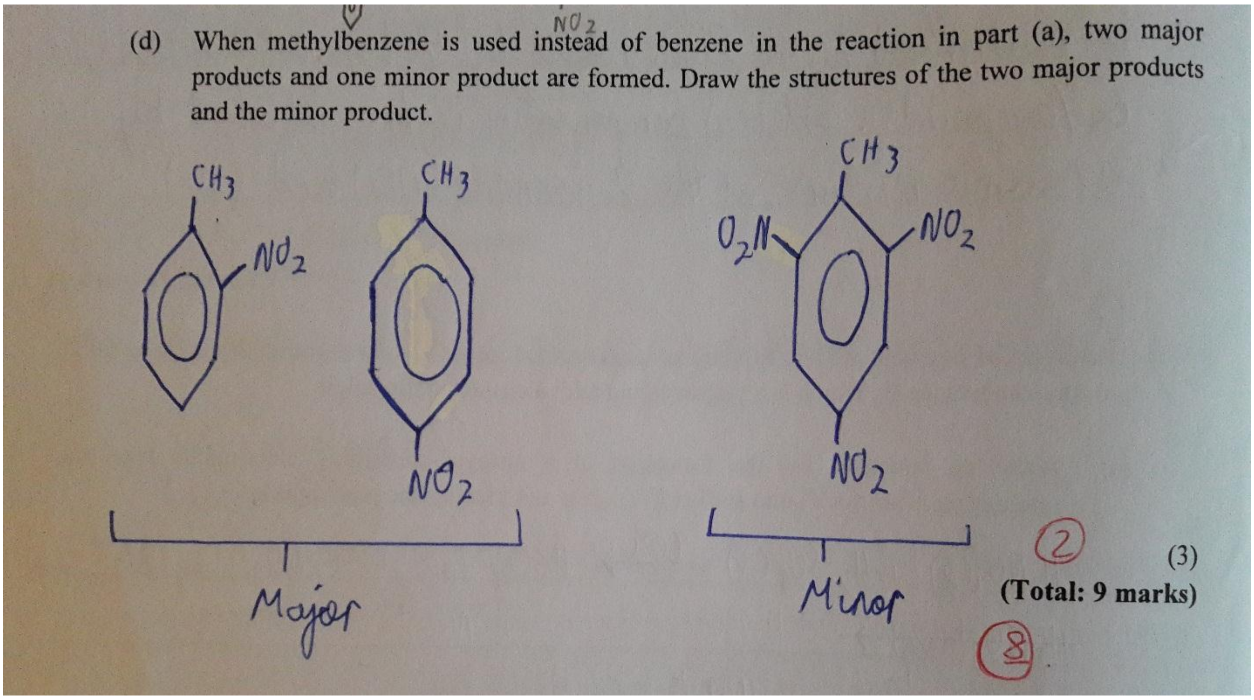
Such answers prove how students are not adequately acquainted with aromatic chemistry. Students often showed that they did not to know that sulfuric acid is used as a catalyst to activate the nitric acid which is a poor electrophile. In this scenario, students included hydrogensulfate groups bonded to the methylbenzene ring, giving answers which are not related to the actual products. Hence this error was carried over, and students assumed that sulfuric acid participates in the reaction and becomes part of the final product. Figure 22 depicts a typical example of this, whereby students included the hydrogensulfate group in all three products along with the nitro side group. It seems that students in this study were not aware that methyl is an electron-donating group, rendering the ring more nucleophilic and therefore leading to several products, including the minor one.

Figure 22 – Illustration of an answer by a student in the low band who believes that sulfuric acid acts as a reagent and not as a catalyst to activate the nitric acid



Not knowing the difference between a reagent and a catalyst and the role of the catalyst was linked to lack of knowledge of the mechanisms. The mechanism of electrophilic substitution would have led to the conclusion of how the electrophilic nitration of methylbenzene takes place. Not knowing how this reaction proceeds, a number of students stated that the minor product would be either '2,4,6-trinitromethylbenzene' or '2,4-dinitromethylbenzene' instead of methyl-3-nitrobenzene. This would have been the case only if the temperatures were high enough. However high temperatures were not indicated in any part of the question. This shows how some students assume that the nitration of methylbenzene would anyhow produce ‘2,4,6-trinitromethylbenzene’ or ‘2,4-dinitromethyl benzene’, which is not the case. This idea was very common and is illustrated by Figure 23.

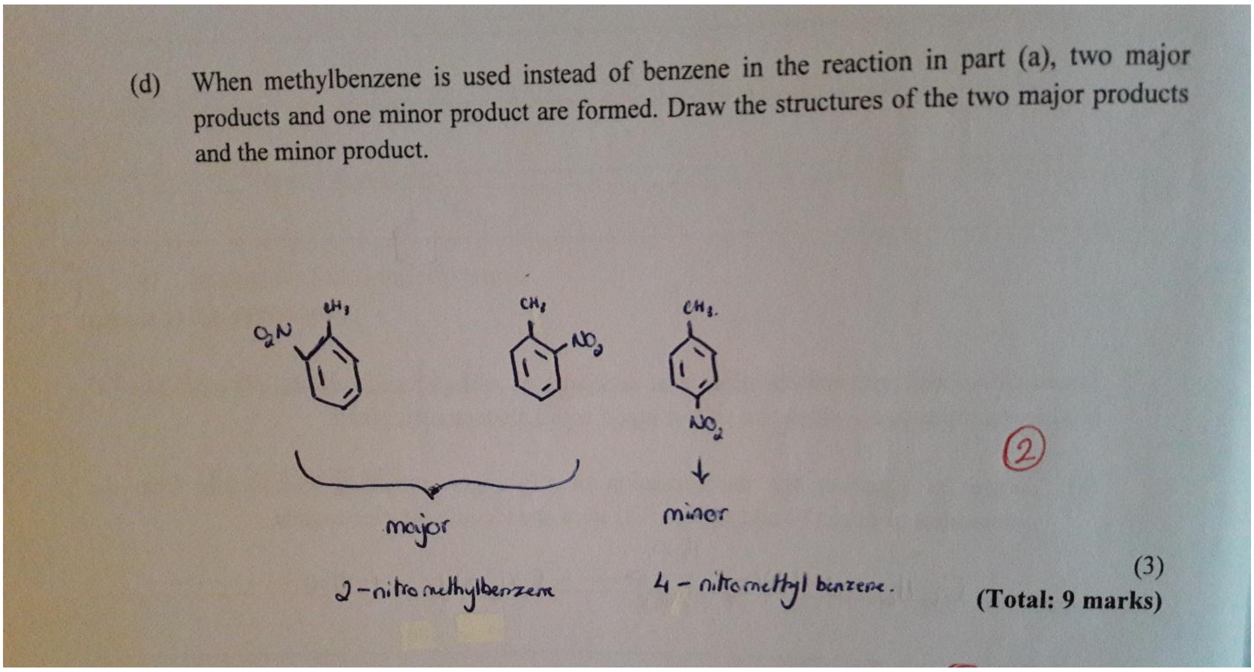
Figure 23 – Illustration of an answer by a student in the high band who gave 2,4,6-trinitromethylbenzene as the minor product instead of methyl-3-nitrobenzene



4.5.4.2. Low frequency mistakes (2.0 – 4.7 %)

Among the low frequency mistakes there is failure to give all three products, giving one missing major product or the minor product. The way in which they did not give all the three products varied, including answers who had only two products instead of three, and answers who had errors in the structures. One of the most common errors in the low frequency mistakes was that of assuming that one of the products is “methyl-6-nitrobenzene” as illustrated in Figure 24. Following their answer for methyl-2-nitrobenzene, students did not realise that the “mirror image” of the latter molecule is in fact the same, and doing so they believed that the position would be 6. This shows how some students are not aware of the fact that molecules may be rotated and how the numbering on the groups takes place according to which groups were placed first. In Figure 24, both major products are methyl-2-nitrobenzene.

Figure 24 – Illustration of an answer by a student in the low band who believed that the two major products were different by positioning them on the same C atom



4.5.5. Conclusion

The results have shown that the highest percentages of unattempted questions and errors in answers were given in the application of organic principles to organic questions. This shows that organic chemistry principles are some of the most challenging. Moreover, the highest percentage of errors was observed for principles in aromatic chemistry. This may be because these are dealt with towards the end of the chemistry A-level course. Aromatic chemistry also deals with an area which is not easy to visualise and understand.

5. Conclusions and recommendations

5. Conclusions and recommendations

5.1. Introduction

This study evaluated the students' performance in organic chemistry in the A-level examination of 2017. Following the analysis of the students' responses for the organic chemistry questions in paper 1, a number of errors and difficulties were outlined. The main difficulties were highlighted in the study.

In this chapter, a summary of the main findings of this study will be presented, along with the strengths and limitations of the research. The implications and future recommendations for further studies are also presented.

5.2. Summary of the main findings

The study started off by analysing responses related to nomenclature, where students had two organic molecules to name following IUPAC rules. It was found that students struggled and performed poorly in naming both compounds, with particular difficulty in naming the aromatic compound, in fact, the facility index for naming the aromatic compound was much lower compared to that of the aliphatic one. The study also found how challenging it is for students to apply inorganic, analytical and physical chemistry principles to organic chemistry questions, giving low facility index values.

The area which students seemed to have struggled less was where recall was required, where students had to recall definitions and reactions which were examined in the same way as learnt during the A-level course. Nevertheless, this does not imply that students did well, rather, the number of mistakes made was less. However, when recall and understanding questions were posed, once again students performed badly, showing how certain organic chemistry principles are learnt in a very superficial manner and that little understanding takes place. A poor performance was observed through analysis of recall and understanding of aromatic chemistry, once again, showing how aromatic organic chemistry presents a major challenge compared to aliphatic organic chemistry.

Finally, the study also outlined the difficulties present in application of organic chemistry principles. The study showed that students performed relatively well in identifying chiral carbon atoms and naming the type isomerism found in tartaric acid. However, when students had to apply organic chemistry principles of external and internal compensation in tartaric acid, their performance was very poor, giving the highest percentage of students who did not attempt the question and the lowest number of students who gave a correct answer with no mistakes. Furthermore, application of aromatic chemistry was proved to be also challenging, being again one of the least attempted questions. This shows how organic chemistry presents a challenge to students, who have a number of difficulties particularly in aromatic chemistry. Aromatic chemistry is covered towards the end of the chemistry A-level course which may imply limited time for assimilation and deep understanding. However, the nature of aromatic chemistry itself is complex. Apart from being difficult to visualise and understand, it presents a new set of rules which are different and more challenging to comprehend when compared to aliphatic chemistry. As the study found, this presents further difficulties to students.

5.3. Implications of the study

Organic chemistry is an important part of chemistry as it deals with the building blocks of life:

“Organic chemistry, which was believed to be presented in the structure of living organisms and was known as “carbon compounds” until the beginning of the 19th century, has always had an important place in our daily lives” (Akkuzu & Uyulgan, 2015, p.37).

As indicated by the A-level chemistry Examiners’ reports (2015, 2016), the performance of students in organic chemistry was consistently poor. Hence this study may serve lecturers and teachers of all branches of chemistry in their planning and teaching. The link between the main branches of chemistry, namely: organic, inorganic, physical and analytical has to be evident throughout the A-level and this study has shown how this has an impact when answering questions posed in exams due to students' difficulty with linking different areas. As stated by Ayas & Demirbaş (1997), most students find it difficult to apply chemistry principles to new situations, because the majority would study by heart. Akkuzu & Uyulgan (2015) argue how students deem organic chemistry as difficult because they believe that it is a memorization-oriented subject with many details to be learnt. However this is not the case, because as outlined in the study, there is a lot more than recall. If one learns and understands the principles of organic chemistry, then making links would become easier, and students need help in this respect, linking organic chemistry topics together and applying chemistry principles to organic chemistry.

Students might not be aware of the way organic chemistry should be studied and fail to visualise certain links and concepts. Students may need support so that they would be able to visualise the molecules in organic chemistry. In his paper, Zoller (1990) argues how difficulties stem from the abstract nature of organic chemistry, and how students need to work on chemical topology, to be able to visualise molecules in 3-D form, which helps them understand the underlying principles. This is the way forward for overcoming the difficulties.

As described by Zydney (2010) direct instruction methods still present in some schools use a linear presentation of material, such as textbooks, where memorisation rather than construction of knowledge takes place. This leads to little or no engagement and thus misconceptions which will rarely be dealt with in class, will eventually mould into difficult ideas which will be challenging to change with the same traditional instructional methods. In his paper, Lewis (2011) describes how general chemistry is functioning as a gatekeeper, preventing the progress of many students in science and science-related careers. Student retention and student performance are intertwined and reform in pedagogy would be needed in order for a better approach towards learning the subject.

5.4. Strengths of the study

One of the main strengths of this study was that a large number of scripts were analysed. In fact, 300 scripts were analysed and this presented a high number of errors made by students in organic chemistry which mirrors the high number of difficulties they have. Another main strength was that deep analysis was carried out for each question. Given that each question was analysed individually, a deeper understanding of the difficulties of students was established.

5.5. Limitations of the study

One of the main limitations of this study is that due to the nature of the study's duration and word limit, not all three papers could be analysed. In fact, only organic chemistry questions in paper I where analysed, whereas those of paper II where not. Paper III focuses on the practical side of the A-level chemistry. However, in paper II a considerable number of organic questions were not analysed, thus any other aspects of errors and misconceptions in organic chemistry might have not come to light.

5.6. Recommendations for future work

The following would be recommended suggestions to those who wish to pursue with further studies in this area, and possibly reduce any limitations such research studies might pose.

There were areas of organic chemistry which were not covered in this study. Such areas are deemed as very important to students' understanding and also very challenging, including but not limited to: mechanisms and reaction pathways. Both areas tend to be very challenging due to the fact that in mechanisms students have to visualise concepts which are very abstract, whilst in reaction pathways, students have to piece several areas of organic chemistry together. Thus the studies on these concepts would help educators and learners in their chemistry A-level course.

Further work can help understand how educators teach organic chemistry. Given the number of misconceptions and difficulties, studies may focus on ways of how teaching can be improved. Moreover, studies could also be carried out to determine the way students are learning and studying it. A study which helps outline ways of how students ought to approach organic chemistry would be of great help. There could also be a focus on students' difficulties and misconceptions in organic chemistry at SEC level. It is of great importance that difficulties start to be tackled at early stages, and further studies can help highlight this.

Lastly, the study has highlighted a number of areas which presented an array of errors and difficulties by students, however further work can be carried out in order to focus on aspects which were highlighted in this study. Focusing on particular areas would analyse the difficulties with more rigour can be of support to both educators and learners.

5.7. Conclusion

This study sought to focus on students' difficulties and misconceptions in organic chemistry in view of the limited number of studies available and the poor performance of students in organic chemistry. Following the numerous errors highlighted, this study recommends a more constructivist approach to teaching A-level organic chemistry, so that any misconceptions are tackled. The areas in which students' performance was of main concern were those of application and understanding. Both aliphatic and aromatic chemistry presented challenges to students, who fared badly in the majority of the questions. In aromatic chemistry it was observed how students held an even higher number of difficulties irrespective of whether the students were in the high or low band.

Studies related to student difficulties with organic chemistry are not very common. As Akkuzu & Uyulgan (2015) state in their paper "…in terms of national and international research, only a limited number of studies have been conducted regarding students' misconceptions in the field of organic chemistry" (p.38). The study may be of help to both educators and students as this would be a way of identifying students' difficulties and misconceptions.

References

References

Akkuzu, N., & Uyulgan, M.A. (2015). An epistemological inquiry into organic chemistry education: exploration of undergraduate students' conceptual understanding of functional groups. *Chem. Educ. Res. Pract.*, 17, pp. 36-57.

Ayas, A. & Demirbaş, A., (1997). Turkish Secondary Students' Conception of Introductory Chemistry Concepts. *J. Chem. Educ.*, 74 (5), pp 518–521.

Babaev, E.V. (1999). Intuitive Chemical Topology Concepts. *Chemical Topology: Introduction and Fundamentals*, 5, pp. 167 – 264.

Bhattacharyya G. & Bodner G. M., (2005), "It Gets Me to the Product": How Students Propose Organic Mechanisms. *J. Chem. Educ.,* 82, pp. 1402-1407

Bucknum, M.J. & Castro, E.A. (2009). Chemical topology of crystalline matter and the transcendental numbers ϕ, e and π. *J. Math. Chem.,* 46, pp. 117 – 138.

Celik, S. (2014). Chemical Literacy Levels of Science and Mathematics Teacher Candidates. *Australian Journal of Teacher Education.* 39 (1), pp. 1 -15.

Chittleborough, G.D. and Treagust D. F. (2007). The Modelling Ability of Non-Major Chemistry Students And Their Understanding Of The Sub-Microscopic Level. *Chem. Educ. Res. Pract*., 8, pp. 274-292.

Cohen, L., Manion, L. & Morrison, K. (2000). Research Methods in Education. New Fetter Lane, London: RoutledgeFalmer.

Coulson, C. A. (1974). Mathematics in modem chemistry. *Chemistry in Britain*, 10, pp. 16-18

Francl, M. (2009). Stretching topology. *Nature Chemistry*, 1, pp. 1- 2.

Frisch, H.L. & Wasserman, E. (1961). Chemical Topology. *J. Am. Chem. Soc.*, 1961, 83 (18), pp. 3789–3795

Garner-O'Neale, L. et al. (2013). Scientific literacy of undergraduate chemistry students in the University of the West Indies, Barbados: individual and joint contributions of age, sex and level of study. *International Letters of Social and Humanistic Sciences,* 13, pp. 41 – 55.

Gelling, L. (2015). Qualitative Research. *Nursing Standard,* 29:30, pp. 43 – 47.

Gkitzia, V., et al. (2011). Development and Application of Suitable Criteria for the Evaluation of Chemical Representations in School Textbooks. *Chem. Educ. Res. Pract.,* 12, pp. 5–14.

Gronlund, E.N. & Linn, R.L. (2000). Measurement and Assessment in Teaching. Upper Saddle River, New Jersey: Pearson Education.

Grove N. P., et al. (2008). Impact of a spiral organic curriculum on student attrition and learning. *Chem. Educ. Res. Pract.*, 9, pp. 157–162.

Halcomb, E., & Hickman, L. (2015). Mixed methods research. *Nursing Standard,* 29:32, pp. 41 – 47.

Head, J. et al. (2005). Exploring students' abilities to use two different styles of structural representation in organic chemistry. *Canadian Journal of Science, Mathematics and Technology Education*, 5(1), pp. 133–152

Johnstone, A.H., (1974). Evaluation of Chemistry Syllabuses in Scotland. *Studies in Science Education*, 1, pp. 20-49.

Johnstone, A.H., (1991). Why Science is Difficult to Learn? Things are Seldom What they Seem". *Journal of Computer Assisted Learning*, 7, pp. 75-83.

Karatjas, A.G. (2013). Comparing College Students' Self-Assessment of Knowledge in Organic Chemistry to Their Actual Performance. *J. Chem. Educ.,* 90, pp. 1096 – 1099.

Kumar, A. & Patel, S. (2014). An Analytic Study of Mathematics Question Papers of Madhya Pradesh Board With Respect to Its Patters/Design, Content Coverage, Difficulty Level, Objectivity in Marking and Its Impact on Achievement of Students. *International Journal of Advancement in Education and Social Sciences*, 2 (2), pp. 16 -23.

Lewis, S.E. (2011). Retention and Reform: An Evaluation of Peer-Led Team Learning. *J. Chem. Educ.,* 88, pp. 703 – 707.

Luisi, P.L., & Thomas, R.M. (1990). The pictographic molecular paradigm: Pictorial communication in the chemical and biological sciences. *Naturwissenschaften*, 77, pp. 67-74

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2016). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2015). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2014). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2013). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2012). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2011). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2010). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2009). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2008). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2007). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Matriculation and Secondary Education Certificate Examinations' Board (MATSEC) (2006). AM chemistry May 2016 session examiners' report. Msida: Malta University Press.

Millar, R. (2008). Taking scientific literacy seriously as a curriculum aim. *Asia-Pacific Forum on Science Learning and Teaching*, 9 (2), pp. 1 – 18.

Ministry of Education, Advanced Matriculation Syllabus (2017 – 2018): Chemistry: Malta Ministry of Education.

Nakhleh, M., (1992). Why Some Students Don't Learn Chemistry: Chemical Misconceptions. *J. Chem. Educ.,* 69 (3), pp. 191-196.

O'Dwyer A. and Childs P. E., (2011). Second-level Irish pupils' and teachers' view of difficulties in organic chemistry http://ioste-nwe.wikispaces.com/file/view/Second+Level+Irish+Pupils+and+Teachers+view+of+difficulties+in+Organic+Chemistry.doc, accessed on 21 August 2017.

OECD. (2015) PISA 2013: Draft Science Framework. Paris: OECD.

Pungente M. D. & Badger R. A., (2003). Teaching introductory organic chemistry: 'Blooming' beyond a simple taxonomy. *J. Chem. Educ.*, 80 (7), pp. 779–784.

Sadler, T.D. and Zeidler, D.L. (2009). Scientific Literacy, PISA, and Socioscientific Discourse: Assessment for Progressive Aims of Science Education. *Journal of Research in Scientific Teaching*, 46 (8), pp. 909 – 921.

Saldana, J. (2009). The Coding Manual for Qualitative Researchers. Los Angeles: SAGE Publications.

Schwartz, D. L. (1995). Reasoning about the referent of a picture versus reasoning about the picture as the referent: an effect of visual realism*, Mem. Cog.*, 23, pp. 709-722.

Sendur, G. (2012). Prospective Science Teachers' Misconceptions in Organic Chemistry: The Case of Alkenes. *Journal of Turkish Science Education,* 9 (3), pp. 186 – 190.

Shwartz, Y. et al. (2006). Chemical Literacy: What Does This Mean to Scientists and School Teachers? *Chemical Education Research,* 83 (10), pp. 1557 – 1561.

Sirhan, G. (2007). Learning Difficulties in Chemistry: An Overview. *Journal of TURKISH SCIENCE EDUCATION,* 4 (2), pp. 1 – 19.

Skonieczny, S. (2006). The IUPAC Rules for Naming Organic Molecules. *J. Chem. Edu*, 83 (11), pp. 1633 – 1637.

Sreekanth, Y. (2007). An Analysis of Question Papers of Different Boards of Examinations in Social Sciences. *Indian Educational Review*, 43 (2), pp. 18 -35.

Strauss. A,L. (1987) Qualitative Analysis for Social Scientists. United Kingdom: Cambridge University Press.

Strickland, A.M., et al. (2010). What happens when representations fail to represent? Graduate students' mental modes of organic chemistry diagrams. *Chem. Educ. Res. Pract*., 11, pp. 293 – 301.

Stowe, R.L. & Cooper, M.M. (2017). Practicing What We Preach: Assessing "Critical Thinking" in Organic Chemistry. *J. Chem. Edu*, 94, pp. 1852 – 1859.

Sunyono, L. et al. (2015). Supporting Students in Learning with Multiple Representation to Improve Student Mental Models on Atomic Structure Concepts. *Science Education International,* 26 (2), pp. 104 – 125.

Talanquer, V. (2011) Macro, Submicro, and Symbolic: The many faces of the chemistry "triplet". *International Journal of Science Education*, 33 (2), pp. 179-195

Tsaparlis, G. (1997). Atomic Orbitals, Molecular Orbitals, and Related Concepts: Conceptual Difficulties Among Chemistry Students. *Research in Science Education,* 27 (2), pp. 271 – 287.

Vollhardt, P. & Schore, N. (2011). *Organic Chemistry Structure and Function*. New York, NY: W.H. Freeman and Company.

Watson, R. (2015). Quantitative Research. *Nursing Standard,* 29:31, pp. 44 – 48.

Yuan, W. et al. (2012). The Statistical Analysis, and Evaluation of Examination Results of Materials Research Methods Course. *Scientific Research*, 3, pp. 162 – 164.

Zoller, U., (1990). Students' Misunderstandings and Alternative Conceptions in College Freshman Chemistry (General and Organic). *Journal of Research in Science Teaching*, 27(10), pp. 1053–1065.

Zydney, J. M. (2010). The effect of multiple scaffolding tools on students' understanding, consideration of different perspectives, and misconceptions of a complex problem. *Computers and Education*, 54, pp. 360 – 370.

Appendices

Appendices

Appendix 1: Coding

Coding question 7 a

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Wrong naming of substituents
2	Wrong numbers
3	Wrong position of numbers
4	Wrong position of substituents
5	Lack of numbering
6	Hyphens/commas in wrong position

Coding question 7 b

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	No mentioning of the weak bonds 4-chlorobenzoic acid forms with water.
2	No mentioning of the conjugate base formed and/or did not show the 4-chlorobenzoic acid in equilibrium with the strong conjugate base.
3	No mentioning of the strong electrostatic bonds the conjugate base forms with water.

Coding question 7 C(i)

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not specifying that $KMnO_4$ has to be under alkaline conditions.
2	Not specifying that reaction has to be carried out under gentle heating (not refluxing) following the addition of MnO_4^-/OH^-
3	Not specifying that after adding $KMnO_4/OH^-$ and forming the salt, the reaction mixture has to be acidified/ followed by H^+ and not refluxed
4	Use of wrong reagents which are not merely related to the reaction taking place

Coding question 7 C(ii)

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not specifying that PCl_5 in CCl_4 is added OR not specifying that $SOCl_2$ in dry ether is added.
2	Not specifying that reaction is carried out at r.t.p or gentle warming and not reflux.
3	Use of wrong reagents

Coding question 7 d

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	No mentioning of hydrolysis of 4-chlorobenzoyl chloride to form 4-cholorbenzoic acid and HCl
2	No mentioning of reaction of HCl with $AgNO_3$ to form white precipitate $AgCl_{(s)}$
3	No mentioning of the strong covalent bond (partial double bond) between Cl directly bonded to the benzene ring which does not react with $AgNO_3$, thus giving one mole of $AgCl_{(s)}$.

Coding question 8 a

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Wrong naming
2	Wrong numbers
3	Wrong position of numbers
4	Wrong position of substituents
5	Lack of numbering
6	Excess numbering
7	Hyphens/commas not used appropriately

3rd digit

1	Wrong naming of substituents
2	Wrong naming of base molecule

Coding question 8 b

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not specifying/not clearly stating that a chiral carbon has also/is also an asymmetric/optical centre
2	Not specifying that the chiral carbon is bonded to four different groups
3	Not indicating both chiral centres on tartaric acid
4	Indicating other carbon atoms as chiral centres

Coding question 8 c

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not specifying/being clear that the type of isomerism is optical isomerism.
2	Giving enantiomers as being the type of isomerism
3	Giving stereoisomerism as being the type of isomerism
4	Giving geometric isomerism as the type of isomerism

Coding question 8 d(i)

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not specifying that an enantiomer is an optical isomer
2	Not specifying that an enantiomer is non-superimposable on its mirror image

Coding question 8 d(ii)

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not specifying that (-)-tartaric acid is an optical isomer.
2	Not specifying that the optical isomer is laevorotatory/rotates plane polarized light to the left/anticlockwise

Coding question 8 e

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not specifying that a mixture containing equal amounts of the (+) and (-) enantiomers is a racemic mixture.
2	Not specifying that equal amounts of (+) and (-) tartaric acid enantiomers will not rotate plane polarised light (making the link to tartaric acid) as they will cancel each other's optical activity.
3	Not specifying that external compensation is due to enantiomers of with different optical activity, whereas internal compensation is due to the same molecule which is symmetrical due to the presence of an internal mirror plane.
4	Not specifying that tartaric acid has more than one chiral centre which leads to internal compensation and is called a meso-compound.
5	Not specifying that internal compensation results due to the optical inactivity of a molecule, which has more than one chiral centre and therefore half of the molecule cancels the optical activity of the other half, leading to no optical activity.
6	Made wrong associations: internal compensation with intramolecular bonding and external compensation with intermolecular bonding.

Coding question 9 a

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Wrong equation for the formation of nitrogen-containing electrophile from the interaction of nitric (V) and sulfuric (VI) acids due to incorrect balancing
2	Wrong equation for the formation of nitrogen-containing electrophile from the interaction of nitric (V) and sulfuric (VI) acids due missing/incorrect state symbols
3	Wrong equation for the formation of nitrogen-containing electrophile from the interaction of nitric (V) and sulfuric (VI) acids due incorrect reagents and products
4	Wrong identification of the electrophile

Coding question 9 b

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not showing the positive charge gained by the ring as the delocalisation is partly broken.
2	Not showing the correct nitro group on the intermediate and therefore wrong intermediate
3	Not indicating the carbon atom on the ring which is not involved in delocalisation.
4	Not showing the H atom still on the intermediate bonded to the same carbon as the nitro group.
5	Indicating the wrong carbon atom on the ring which is not involved in delocalisation.

Coding question 9 c

1st digit

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit

0	/
1	Not representing the hydrogensulfate ion (HSO_4^-) in the reaction.
2	Drawing the incorrect intermediate of benzene-nitronium ion.
3	Drawing the incorrect nitrobenzene.
4	Not showing the presence of H_2SO_4 when nitrobenzene forms
5	Showing only the presence of H^+/or the lack of it, and not the whole catalyst.

Coding question 9 d

1st digit.

1	Correct
2	Partly correct
3	Incorrect
4	Not attempted

2nd digit.

0	/
1	Not giving methyl-2-nitrobenzene as major product.
2	Not giving methyl-4-nitrobenzene as major product
3	Not giving methyl-3-nitrobenzene as minor product
4	Giving 2,4,6-trinitromethylbenzene as minor product
5	Giving 2,4-dinitromethylbenzene as minor product
6	Giving multiple nitro substitutions for major products
7	Not giving all three nitro products in the correct major/minor formation and/or with additional groups which are not nitro groups.

Appendix 2: Calculations – Facility index and item difficulty

Question 7

(a) Question had 2 marks, therefore the passing mark is 1.5 or higher (i.e. minimum of 75%). There was no one student who got 1.5 marks, in fact the passing mark had to be the highest, that is 2. From 298 students who attempted the question 49 students got a percentage of 75% or above, where the item difficulty was:

P = R/T x 100%

P = 49/298 x 100%

P = 16.4%

Item difficulty = 100% - 16.4% = 83.6%

(b). Question had 3 marks, therefore the passing mark is 2.25 or higher. There was no student who got 2.25, but a lower or higher score as quarter-marks are not given. From 290 students who attempted the question,

P = R/T x 100%

P = 43/290 x 100%

P = 14.8%

Item difficulty = 100% - 14.8% = 85.2%

(ci). Question had 2 marks, therefore the passing mark was 1.5 or higher. Some students managed to get 1.5 or even higher. From 300 students who attempted the question:

P = R/T x 100%

P = 115/290 x 100%

P = 39.3%

Item difficulty = 100% - 39.3% = 60.7%

(cii) Question had 2 marks, therefore the passing mark was 1.5 or higher. Some students managed to get 1.5 or higher. From 300 students who attempted the question:

P = R/T x 100%

P = 208/300 x 100%

P = 69.3%

Item difficulty = 100% - 69.3% = 30.7%

(d) Question had 2 marks, therefore the passing mark was 1.5 or higher. Some students managed to get 1.5 or higher. From 300 students who attempted the question:

P = R/T x 100%

P = 71/290 x 100%

P = 24.5%

Item difficulty = 100% - 24.5% = 75.5%

Question 8

(a) Question had 2 marks, therefore the passing mark is 1.5 or higher (i.e. minimum of 75%). From 289 students who attempted the question 1n mi49 students got a percentage of 75% or above, where the item difficulty was:

P = R/T x 100%

P = 149/289 x 100%

P = 51.6%

Item difficulty = 100% - 51.6% = 48.4%

(b) Question had 2 marks, therefore the passing mark is 1.5 marks or higher (i.e. minimum of 75%). From 298 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 242/297 x 100%

P = 81.5%

Item difficulty = 100% - 81.5% = 18.5%

(c) Question had 1 marks, therefore the passing mark is 0.75 marks or higher (i.e. minimum of 75%). From 296 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 239/296 x 100%

P = 80.7%

Item difficulty = 100% - 80.7% = 19.3%

(di) Question had 1 mark, therefore the passing mark is 0.75 or higher (i.e. minimum of 75%). From 279 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 85/279 x 100%

P = 30.5%

Item difficulty = 100% - 30.5% = 69.5%

(dii) Question had 1 mark, therefore the passing mark is 0.75 or higher (i.e. minimum of 75%). From 276 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 173/276 x 100%

P = 62.7%

Item difficulty = 100% - 62.7% = 37.3%

(e) Question had 5 marks, therefore the passing mark is 3.75 marks or higher (i.e. minimum of 75%). From 235 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 38/235 x 100%

P = 16.2%

Item difficulty = 100% - 16.2% = 83.8%

Question 9

(a) Question had 2 marks, therefore the passing mark is 1.5 marks or higher (i.e. minimum of 75%). From 284 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 134/284 x 100%

P = 47.2%

Item difficulty = 100% - 47.2% = 52.8%

(b) Question had 2 marks, therefore the passing mark is 1.5 marks or higher (i.e. minimum of 75%). From 275 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 159/275 x 100%

P = 57.8%

Item difficulty = 100% - 57.8% = 42.2%

(c) Question had 2 marks, therefore the passing mark is 1.5 marks or higher (i.e. minimum of 75%). From 253 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 79/253 x 100%

P = 31.2%

Item difficulty = 100% - 31.2% = 68.8%

(d) Question had 3 marks, therefore the passing mark is 2.25 marks or higher (i.e. minimum of 75%). From 270 students who attempted the question the percentage of students who got 75% or above was:

P = R/T x 100%

P = 135/270 x 100%

P = 50.0%

Item difficulty = 100% - 50.0% = 50.0%

Appendix 3: Calculations – Item discriminating power

Question 7

(a)

$$D = \frac{(RU - RL)}{0.5\ (T)}$$

RU = 18

RL = 31

T = 300

$$D = \frac{(18 - 30)}{0.5\ (300)}$$

$$D = -0.08$$

(b)

RU = 39

RL = 4

T = 300

$$D = \frac{(39 - 4)}{0.5\ (300)}$$

$$D = 0.23$$

(ci)

RU = 100

RL = 14

T = 300

$$D = \frac{(100 - 14)}{0.5\ (300)}$$

$$D = 0.57$$

(cii)

RU = 135

RL = 73

T = 300

$$D = \frac{(135 - 73)}{0.5\ (300)}$$

$$D = 0.41$$

(d)

RU = 64

RL = 7

T = 300

$$D = \frac{(64 - 7)}{0.5\ (300)}$$

$$D = 0.38$$

Question 8

(a)

RU = 113

RL = 36

T = 300

$$D = \frac{(113 - 36)}{0.5\ (289)}$$

$$D = 0.53$$

(b)

RU = 147

RL = 95

T = 300

$$D = \frac{(147 - 95)}{0.5\ (300)}$$

$$D = 0.35$$

(c)

RU = 140

RL = 99

T = 300

$$D = \frac{(140 - 99)}{0.5\ (300)}$$

$$D = 0.27$$

(di)

RU = 66

RL = 19

T = 300

$$D = \frac{(66 - 19)}{0.5\ (300)}$$

$$D = 0.31$$

(dii)

RU = 125

RL = 48

T = 300

$$D = \frac{(125 - 48)}{0.5\ (300)}$$

$$D = 0.51$$

(e)

RU = 37

RL = 1

T = 300

$$D = \frac{(37 - 1)}{0.5\ (300)}$$

$$D = 0.24$$

Question 9

(a)

RU = 119

RL = 15

T = 300

$$D = \frac{(119 - 15)}{0.5\ (300)}$$

$$D = 0.35$$

(b)

RU = 130

RL = 29

T = 300

$$D = \frac{(130 - 29)}{0.5\ (300)}$$

$$D = 0.67$$

(c)

RU = 72

RL = 7

T = 300

$$D = \frac{(72 - 7)}{0.5\ (300)}$$

$$D = 0.43$$

(d)

RU = 108

RL = 27

T = 300

$$D = \frac{(108 - 27)}{0.5\ (300)}$$

$$D = 0.54$$