Organic Chemistry through Visualisation

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Declaration

I hereby certify that this material which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, that I have exercised reasonable care to ensure the work is original and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

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OCV Manuals included on CD-ROM:

OCV Teacher Manual

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List of Abbreviations

Abbreviation	Meaning
2D	2-dimensional
3D	3-dimensional
ACS	American Chemical Society
ChiK	Chemie im Kontext
CMM	Computerised Molecules Modelling
CVT	Chemical Visualisations Test
DES	Department of Education and Science
FG	Focus Group
HL	Higher Level
IMFs	Inter-Molecular Forces
IUPAC	International Union of Pure and Applied Chemistry
IV	Interview
LC	Leaving Certificate
MDS	Multi-Dimensional Scaling
NCCA	National Council for Curriculum and Assessment
NSW	New South Wales
OCV	Organic Chemistry through Visualisation
OED	Oxford English Dictionary
PIN-Concept	Phenomena-oriented Inquiry-Based Network Concept
PSVT:R	Revised Purdue Spatial Visualisation Test
SAC	Salter's Advanced Chemistry
SM	Student Manual
SQA	Scottish Qualification Authority
TM	Teacher Manual
TRS	Teacher Reflection Sheet

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Abstract

Organic Chemistry through Visualisation

Laura Rice

This research aimed to develop and evaluate a visualization approach for teaching Organic Chemistry at Senior Cycle in Ireland. The Organic Chemistry through Visualisation (OCV) programme was designed to promote students' (i) understanding of the inter-relation between different representations of organic molecules and (ii) their ability to predict the physical properties and reactivity of organic molecules. The use of physical models to promote accurate mental models of organic structures and development of student argumentation are core elements of the approach. Organic chemistry forms the basis of pharmaceutical chemistry, green chemistry, biochemistry and nanotechnology. However, in second-level teaching, this area of chemistry is often reduced to simply the rote learning of functional groups and their reactivity without development of understanding of the nature of this reactivity. Many organic molecules that students use in their everyday life are considered too complex in structure for second level students, for example vanillin. The approach adopted in this research 'reduces' complex molecules to 'simply' looking at each bond and asking where the electrons are located and how the molecule is constructed. By locating areas of high and low electron density in a molecule, it is possible to suggest reactive centres in the molecule and hence predict its reactivity. The findings of this research study indicate that while the majority of students were successful in translating between different representations, some still held 2-dimensional mental models of organic structures. The OCV approach was particularly successful in enabling students to predict and critically compare the physical properties of a range of organic molecules. Students were not only able to identify multiple reactive centres within organic molecules but also able to suggest the most likely reactive centre in the presence of electrophiles and nucleophiles. Following a full evaluation of the OCV approach, a suggested sequence for learning organic chemistry through the use of physical models has emerged. The results of this research have implications for the ongoing review of the current Leaving Certificate chemistry syllabus in Ireland.

Introduction

This research study aimed to explore whether students' learning in organic chemistry could be enhanced through the integration of visualization and pedagogic processes, focused on fostering meaningful understanding of molecular structures and chemical reactivity. The inspiration for this study emerged from my experiences as a pre-service teacher, teaching organic chemistry to a fifth year chemistry class, where I encountered large numbers of students struggling with the core organic chemistry curriculum. It became apparent through a deep review of the organic chemistry curricula and scientific literature that the root of these problems most likely resulted from difficulties in understanding organic/ molecular structures and in identifying areas of high and low electron density (thus, contributing to a lack of understanding in chemical reactivity). I applied for postgraduate funding from the Irish Research Council during my final undergraduate year, and was awarded the Embark Initiative scholarship, which enabled me to pursue full-time this research study of organic chemistry education (through visualization).

This research took place in the context of a syllabus review of Senior Cycle Chemistry which is currently ongoing in Ireland. In order to understand why a new syllabus is required, we must look at the purpose of the LC in Ireland. Following a review of the Senior Cycle as a whole, the National Council for Curriculum and Assessment (NCCA) has outlined a key skills framework which highlights five key skills as central to teaching and learning across the curriculum at Senior Cycle (NCCA, 2009). These are: Information Processing, Communicating, Being Personally Effective, Working with Others, and Critical and Creative Thinking. However, when we look at the nature of questioning in the organic chemistry questions of the LC chemistry exam, they are primarily content-knowledge based lower order (Walshe, 2015). There is no evidence of the development or assessment of any of the key skills identified by the key skills framework within the context fo chemistry. Thus, there is a need to not only rethink the syllabus but the assessment practises, to ensure students are being encouraged to think conceptually and at a higher order.

The objective of this research is to examine organic chemistry at second level in Ireland, and develop an alternative approach to the teaching and assessment of organic chemistry which is focused on students' scientific predictions and understanding. This approach, entitled Organic Chemistry through Visualisation (OCV), has been developed with an aim to move students away from a rote – learning system of studying organic chemistry towards an ability to problem solve and apply their knowledge, particularly to unfamiliar problems.

A wide range of representations are used in organic chemistry. These can be both 2-dimensional (2D) and 3-dimensional (3D). An understanding of these representations and an ability to move seamlessly between them is a foundational skill which students require in order to successfully engage with organic molecules at a conceptual level and master all areas of organic chemistry (Treagust et al, 2010; Cheng and Gilbert, 2009; Kieg and Rubba, 1993). Research has shown that this is the first hurdle which students can fall at when studying organic chemistry (Bernholt et al, 2012; Cooper et al, 2010; Nicoll, 2003; Hassan et al, 2004). If students can not engage fully with these representations and select the required information from the structures, this can hinder their understanding of structural concepts such as isomerism and classifying organic compounds (Domin et al, 2008; Schmidt, 1997). Without a clear understanding of structures, the development of alternative conceptions and misunderstandings of structure-property relations, organic reactions and organic mechanisms can arise.

The substantial number of difficulties experienced by students when studying organic chemistry has led to the perception of organic chemistry as a difficult subject, with many students avoiding it if possible. Students in upper second level education in Ireland are not operating at the cognitive level required to engage in the abstract and multi-dimensional nature of organic chemistry (McCormack, 2009). A culture of rote learning has emerged as a result.

The structure-related difficulties and need to develop higher order thinking in students led to the development of the research question that will guide this project:

> **Can students learn organic chemistry through an approach where the focus is on meaningful understanding of (a) molecular structure, and (b) the basis of chemical reactivity?**

This thesis comprises 8 chapters. Chapter 1 addresses the key difficulties experienced by students studying organic chemistry and examines several theories of learnings to suggest why these difficulties arise. Various approaches that have been developed to address these difficulties will also be discussed.

Chapter 2 describes organic chemistry in an Irish context. This chapter establishes the link between learning outcomes and assessment. Organic chemistry questions which have appeared on LC chemistry exams in previous years are examined to show the low cognitive demand required to successfully answer them. Several international comparisons are made. A brief snapshot of how 1st year undergraduate science students engage with representations of organic chemistry is also given.

Having placed this project in a clear context in Chapters 1 and 2, an overview of the methodology for the research is described in Chapter 3. The thinking which led to the development of the research question is described. A theoretical framework for the research is described, along with the timeline of the research project, the participants of the research and the data sources collected during implementation of the OCV programme.

This research follows the action research cycle with a case study design. It is cyclic in nature which allows for the OCV approach to be evaluated in an iterative manner. The OCV approach underwent a 4-week pilot and two trial implementations. Participants in the OCV evaluation were primarily second level students in their fifth year. Two exploratory studies at third level were also conducted. The first was a representational exploratory study involving first year third level students whose purpose was to compare students' ability to engage with representations of organic structures with the literature. The second was a process modelling exploratory study with second year pre-service teachers using a virtual modelling environment with animation tool.

Chapter 4 describes the development of the OCV approach and materials. Development of the OCV programme went through three main cycles. The first cycle involved the development of preliminary activities which were piloted with a single 5th Year chemistry class. The second cycle involved evaluation of feedback from this pilot, redevelopment of resources and assessment materials and full development of the OCV programme. Implementation 1 took place during cycle 2 and involved six chemistry classes.

The data collected during Implementation 1 was analysed to identify areas of student achievement and student difficulties. The effectiveness of assessment materials was also examined. This is discussed in Chapter 5.

Feedback from and evaluation of Implementation 1 identified a need to redevelop the student assessment to include more 3D assessment. A 3D form of assessment was developed during cycle 3. A second implementation took place to evaluate the effectiveness of the redeveloped student assessment. Chapter 6 will describe the evaluation of Implementation 2.

The OCV programme focuses on the use of physical models to aid students' creation of accurate mental models. Comparison of student tasks in Implementation 2 allowed for a suggested sequence for teaching organic chemistry using physical models. This will be described and compared with an existing sequence in the literature in Chapter 6.

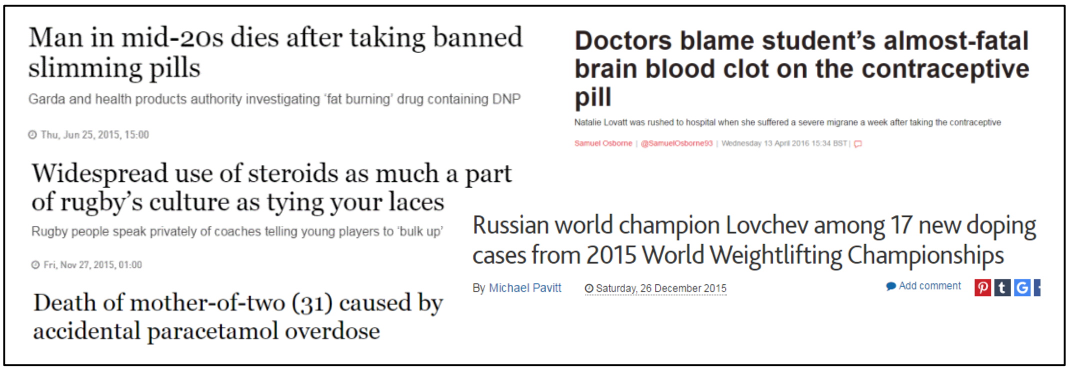
The process-modelling exploratory study which examines the use of virtual modelling using animation software to examine students' understanding of chemical phenomena at a process level will be described in Chapter 7.

The implications of the use of a visualisation approach like OCV for teaching organic chemistry and the significance of the findings from this project will be discussed in Chapter 8.

Chapter 1

Teaching and Learning Organic Chemistry

Organic chemistry is an important part of senior cycle chemistry. It has particular relevance to us in our everyday lives. From the food we eat, to the dye used in our hair colour, to the medication used to battle our illnesses, our everyday lives are rooted in core organic chemical processes. Newspapers often contain headlines which can, really, only be explained or engaged with using a level of chemical or organic chemical understanding, see Figure 1.1.



Man in mid-20s dies after taking banned slimming pills

Garda and health products authority investigating 'fat burning' drug containing DNP

Thu, Jun 25, 2015, 15:00

Doctors blame student's almost-fatal brain blood clot on the contraceptive pill

Natalie Lovatt was rushed to hospital when she suffered a severe migrane a week after taking the contraceptive

Samuel Osborne | @SamuelOsborne93 | Wednesday 13 April 2016 15:34 BST |

Widespread use of steroids as much a part of rugby's culture as tying your laces

Rugby people speak privately of coaches telling young players to 'bulk up'

Fri, Nov 27, 2015, 01:00

Russian world champion Lovchev among 17 new doping cases from 2015 World Weightlifting Championships

By Michael Pavitt Saturday, 26 December 2015 Add comment

Death of mother-of-two (31) caused by accidental paracetamol overdose

Figure 1.1: Newspaper headlines: Cullen (2015), Howell (2015), O'Hara (2015), Osbourne (2016), Pavitt (2016).

Despite the plethora of examples of the relevance of organic chemistry, the subject has gained a 'killer course' reputation and is consistently identified in the literature as one of the most difficult topics in chemistry, both at second and third level, both internationally and in Ireland (Ratcliffe, 2002; Jimoh, 2005; Schroder and Greenbowe, 2008; O'Dwyer and Childs, 2011).

The aim of this research project is to develop an alternative approach to the teaching and assessment of organic chemistry which focuses on students' scientific predictions and understanding. The purpose of this chapter is to inform this research. The particular difficulties experienced by students when studying organic chemistry are summarised. Theories regarding how students learn are next examined to identify why these difficulties may arise. Approaches that have been taken by researchers and teachers to address these difficulties and aid students' study of organic chemistry are considered. Finally, international assessment practises are examined and compared.

1.1 Areas of Difficulty for Students Studying Organic Chemistry

Following a review of the literature, the difficulties experienced by students when studying organic chemistry can be categorised under five main headings, as shown in Figure 1.2. Each of these categories will now be discussed.

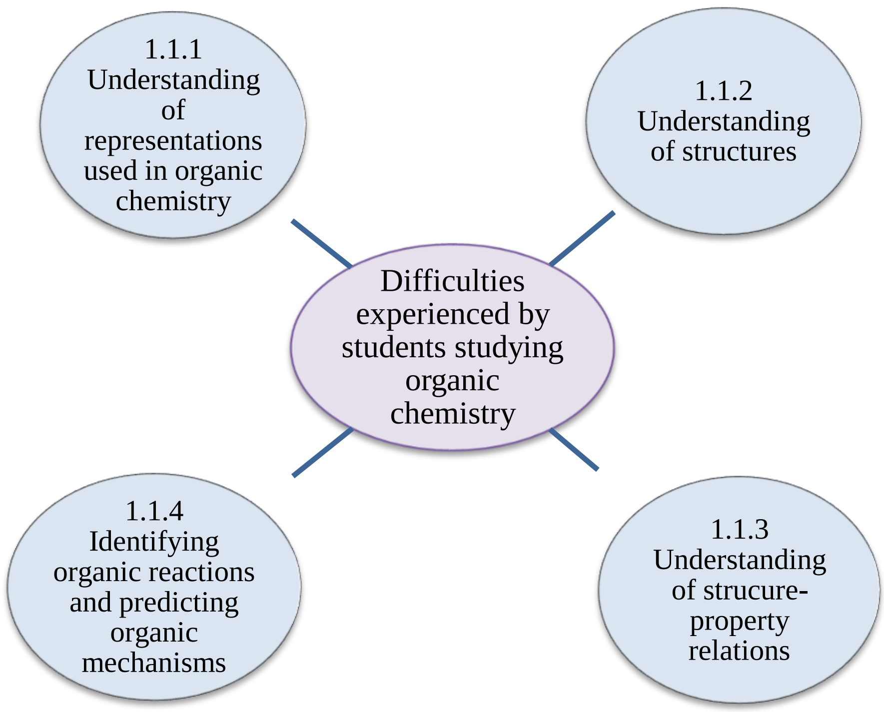


Figure 1.2: Categories of difficulties experienced by students when studying organic chemistry.

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1.1.1 Understanding of Representations used in Organic Chemistry

Chemists use three different levels of representation to refer to chemical phenomena- the macroscopic, the symbolic and the sub-microscopic (molecular), all of which are directly related to each other (Treagust, Chittleborough and Mamalia, 2003). The relationship between these levels was first represented by Johnstone (1991) as a 'Triangle of Chemistry' and has become a cornerstone in chemistry education.

Mahaffy (2006) has since proposed the addition of a fourth vertex to this triangle to emphasise the 'human element' of chemistry, thus creating a Tetrahedron of Chemistry, see Figure 1.3 (a).

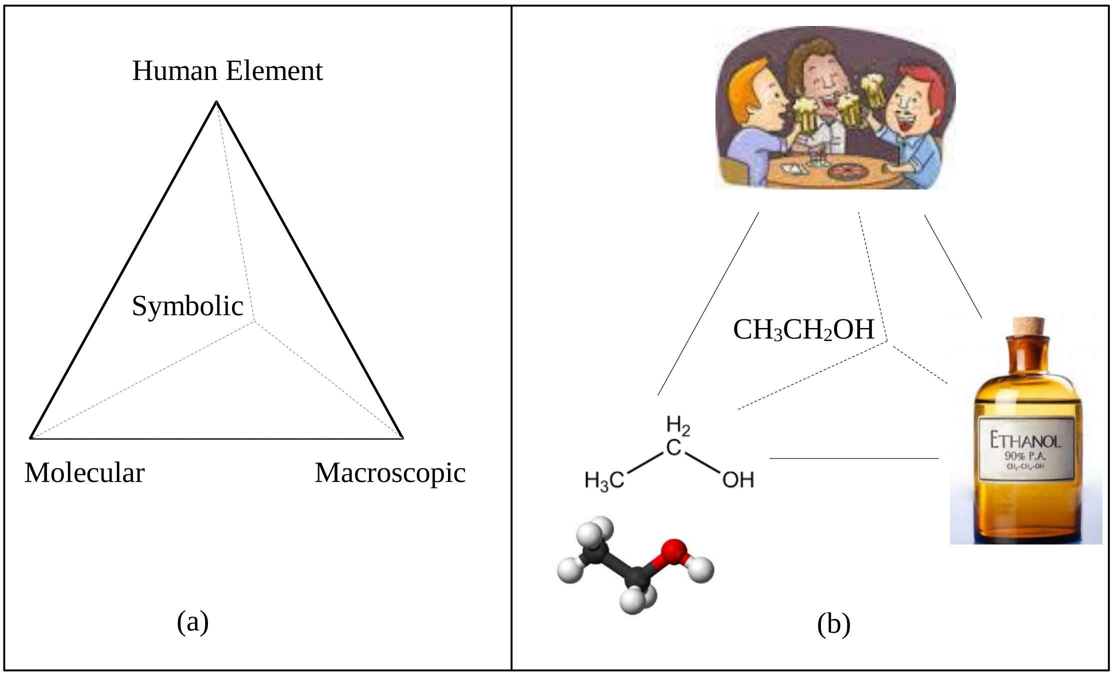


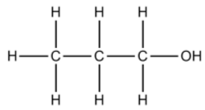
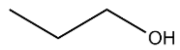
Figure 1.3: (a) Mahaffy's Tetrahedron of Chemistry (Mahaffy, 2006)
(b) Ethanol as an example

The human element focuses on the human learner and the human context for learning chemistry; it focuses on the relevance of chemistry to students and their everyday lives. The macroscopic level refers to what is observable and tangible. Chemists use the symbolic level of representation to communicate and represent the macroscopic level. This can include structural and molecular formula, chemical equations and reaction mechanisms. The molecular level, based on the particulate nature of matter, is what is molecular and invisible. It is used to explain the phenomena observed on a macroscopic level in terms of the movement and behaviour of particles such as molecules, atoms and electrons (Talanquer, 2011; Treagust, Chittleborough and Mamalia, 2003; Johnstone, 2000a).

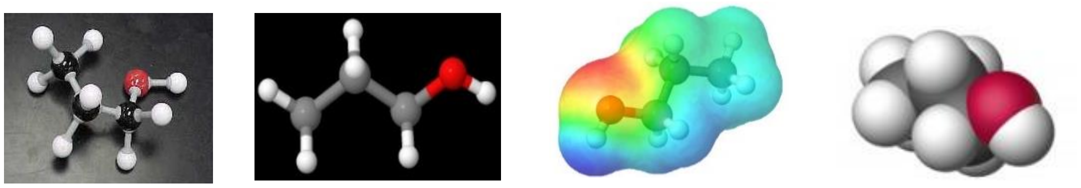
Ethanol is used as an example to demonstrate the multiple levels of chemistry, as shown in Figure 1.3 (b). The human element which students can most relate to is the social situation of drinking in a pub with friends but also relates to the human interactions, e.g. communication between teacher/student or student/student in teaching and learning of chemistry. Ethanol is viewed at the macroscopic level as a colourless liquid. It is represented at the molecular/sub-microscopic level by its structural formula and 3-dimensional (3D) molecular structure. The molecular formula of CH_3CH_2OH represents ethanol at the symbolic level.

Particular issues arise in organic chemistry due to the multitude of representations used in organic chemistry. Figure 1.3 demonstrates the variety of levels of representation used in chemistry, and indeed organic chemistry. Within the molecular/sub-microscopic level there is a further multitude of representations used in organic chemistry. These can be categorised as either 2-dimensional (2D) or 3D. There are five key formulae used to represent organic compounds in 2 dimensions; structural formula, condensed structural formula, extended (or expanded) structural formula, skeletal structure and a compound's IUPAC name. Examples of these can be found in Table 1.1.

Table 1.1: Examples of 2D formulae used to represent organic compounds

IUPAC name	Structural Formula	Condensed Structural Formula	Extended Structural Formula	Skeletal Structure
Propanol	$CH_3CH_2CH_2OH$ or H_3C-CH_2-CH_2-OH	$CH_3(CH_2)_2OH$		

In addition to these 2D representations, 3D representations (both physical and computer generated) can be used to represent the structures of these molecules. These are shown in Figure 1.4.



(a) Physical ball-and-stick 3D model

(b) Computer generated 3D model

(c) Computer generated electrostatic potential map

(d) Computer generated space-filling model

Figure 1.4: 3D models for representing molecules

Students need to be able to move seamlessly between all types of representations of organic molecules in order to master all areas of organic chemistry (Treagust et al, 2011; Cheng and Gilbert, 2009; Kieg and Rubba, 1993). This skill has been described in the literature under several different names. Gilbert (2005) described it as 'meta-visualization' capabilities, that is, the metacognition in respect to visualisation. He argues that this is central in the process of learning science. This involves at least the capability to:

- Demonstrate an *understanding* of the 'convention' for different levels (i.e. macroscopic, sub-microscopic and symbolic) and dimensionality of representations;
- Demonstrate the capacity to *translate* between different levels and modes of representation;
- Demonstrate a capacity to be able to *construct* a representation within any level and dimensionality for a given purpose.

Students need to be able to use a variety of representations to aid their explanations of chemical phenomena. Kozma and Russell (1997) defined a set of representational competencies which students require to be able to do this. Students should be able to:

- Generate representations that express their understanding of underlying entities and processes;
- Use these representations to explain chemical phenomena at the observable, physical level in terms of chemistry at the particulate level (molecular and structural);
- Identify and analyse features of representations and use them to explain, draw inferences, and make predictions about chemical phenomena or concepts;
- Take the epistemological position that representations correspond to but are distinct from the phenomena they observe and their understanding of them;
- Use different representations that are appropriate for different purposes;
- Use language in a social context to communicate chemical understanding and make explicit connections across representations that convey relationships between different representations and between symbolic expressions and the phenomena they represent. (Kozma et al, 2000; p. 136)

Thus, Johnstone's triangle and Mahaffy's tetrahedron are too simplistic a view of the multi-level nature of chemistry; it should not be seen as a static image with the levels of representation at each apex of the triangle or tetrahedron but should be viewed as fluid and dynamic, in which movement between each level of representation is shown.

The main issues that have been identified with regard to students' understanding of these representations used in organic chemistry can be summarised as: (a) difficulty interpreting 2D formulae, (b) difficulty translating between 2D and 3D representations and (c) an inability to perform mental rotations on organic molecules. These will now be discussed.

a) Difficulty interpreting 2D formulae

The simplest representations available to chemists for representing molecules are 2D formulae. Bernholt et al (2012) detected upper second level (Classes 9, 10 and 11) students' difficulties in identifying the neighbouring constituents of a marked carbon atom in chemical formulae like CH_3-CH_2-Cl, see Figure 1.5 (a) for an example question. Between 40 and 50% of the 135 students surveyed in this study were successful in this question, as can be seen in Figure 1.5 (b). Even when H_3C- was used instead of CH_3- in an effort to clarify bonding relations, students' performance did not improve (see molecule b and c in Figure 1.5 (a)). The age range of students in this study did not appear to significantly influence students' performance in these tasks. While these results do indicate that students struggle with reading these structural formulae, the mistakes made by the unsuccessful students are not detailed.

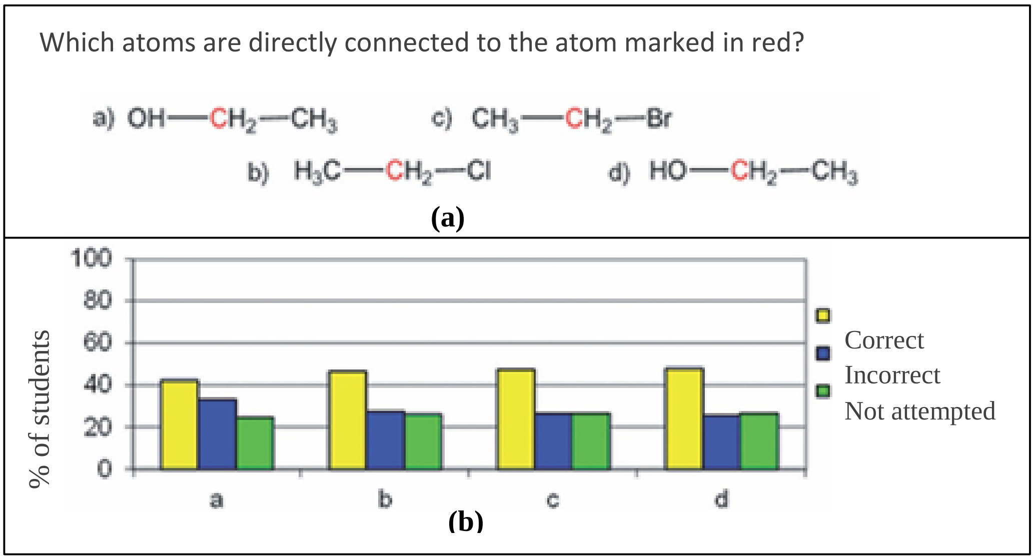


Figure 1.5: Example question (a) and results (b) from Bernholt et al (2012)
Note: This question and results are translated from Bernholt et al (2012)

Another 2D representation used in organic chemistry that has not been mentioned is the Lewis-Dot structure. Drawing Lewis-Dot structures is an important skill for a student studying organic chemistry, as it will allow them to identify areas of high and low electron density, and thus, predict physical properties and possible reactive centres within a molecule. Cooper et al (2010) used OrganicPad, a tablet PC-based structure drawing programme, to investigate university organic chemistry students' (N=70) representational competence when drawing Lewis-Dot structures of organic molecules. The students in this study were enrolled in a common organic chemistry module. Students were given a range of molecular formulae, including CH_4O, CH_3COOH, CH_2O, HCN, CH_3OH, and asked to construct valid Lewis-Dot structures for each. This required students to be able to elucidate the correct arrangement of atoms before finishing the Lewis-Dot arrangement. In total, 527 Lewis-Dot structures were collected and analysed.

A number of revealing trends arose from this research that will have implications for teaching organic chemistry. It was found that as the number of atoms in the structure increased from six to seven and above (species with more than one carbon), the percent of students constructing correct representations fell significantly from around 80% (one carbon atom) to around 30% (two or more carbon atoms).

Similar to the work of Kellet and Johnstone (1980), the presentation of formulae influenced students' success; over 90% of students could produce the required correct structure for CH_3OH, while a significantly lower percentage (60%) drew the correct structure for CH_4O.

These studies demonstrate the need for educators to emphasise to students the variety of 2D representations of organic molecules. Students need to be trained explicitly in reading these and translating from one to another.

Not only do students struggle with translating between these 2D representations, they also have difficulty moving between 2D and 3D representations.

b) Difficulty translating between 2D and 3D representations

Difficulties and misconceptions in organic chemistry, and chemistry in general, result from inadequate and inaccurate mental models at the molecular level (Tasker and Dalton, 2006).

A study carried out by Nicoll (2003) investigated undergraduates' translation between the symbolic and molecular/sub-microscopic representations of molecules by asking them to build free-form models when they were given the molecular formula for formaldehyde, COH_2 Students were asked to represent the Lewis-Dot structure and molecular model of formaldehyde, a compound which they were familiar with. Students were given different coloured clay and different sized sticks. Four examples of students' Lewis-Dot structures and their corresponding models are shown in Figure 1.6.

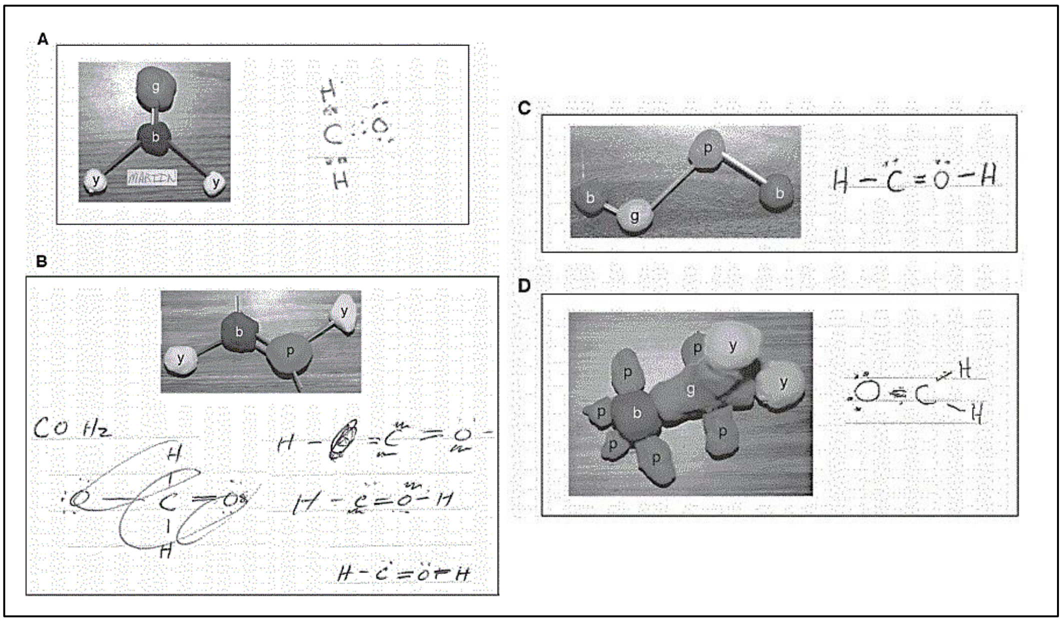


Figure 1.6 : Examples of the types of models and Lewis-Dot structures of formaldehyde from Nicoll (2003; p. 208). A, a junior taking organic; B, a sophomre taking organic; C a freshman in general chemistry for science and engineering majors; D, a freshman in general chemistry for chemistry majors. The colours of the clay are represented by the following letters: g-green, b-blue, y-yellow and p-pink.

All students differentiated the atoms by colour. Students A and D were considered to have the correct arrangement of atoms. Student A differentiated with size also, however incorrectly constructed oxygen bigger than carbon.

The results of this study suggest that students do not necessarily have a developed or accurate mental image of how atoms are arranged in a specific molecule. Of the

56 students surveyed in this study, 39% of students built their models with oxygen as the central atom, a common explanation for this being that students started with a water molecule and added atoms to it to build up the structure of formaldehyde, see student B in Figure 1.6.

Confusion arose over the size of the atoms; only 21% of students made the carbon the largest, while 37% incorrectly made the oxygen the largest, explaining ‘it has more electrons’. As students came from a variety of chemistry courses, both minoring and majoring in chemistry, it is interesting to note that these difficulties were distributed across all groups; indicating that students’ mental models are rather resistant to change, despite increased educational level in chemistry.

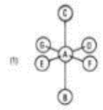
Students need an understanding of the 3D nature of organic molecules in order to fully understand their 2D representations. As students advance through their studies of organic chemistry, they are required to not only translate between these representations, but also perform mental operations, such as rotation, on 3D structures.

c) Inability to perform mental rotations on organic molecules

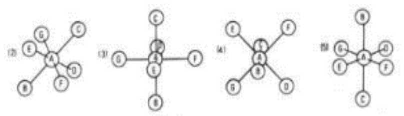
The ability to visualise a 2D representation as a 3D structure and mentally rotate it has been identified as a key skill for students in understanding key organic chemistry concepts, particularly when they meet organic mechanisms (Bodner and Domin, 2000).

Tuckey and Selvaratnam (1991) tested second year undergraduate students’ ability to rotate and reflect ball and stick representations of molecular structures. In order to avoid student failure due to a misunderstanding of the terms ‘rotation’, ‘reflection’ and ‘axis’, the test items included a dashed line to represent the axis being referred to in the question. An example of a rotation task and a reflection task from this study can be found in Figure 1.7 (a) and (b) respectively.

Consider the octahedral molecule represented in diagram 1 below:

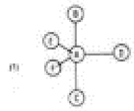


Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like it were turned around the axis corresponding to the dashed line MN?

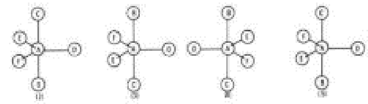


(a)

Consider the trigonal bipyramidal molecule represented in diagram 1 below:



Which one of the diagrams (2, 3, 4 or 5) shows what the mirror image of the molecule would look like?



(b)

Figure 1.7: Examples of a (a) rotational task and (b) reflectional task **(**adapted from Tuckey and Selvaratnam, 1991)

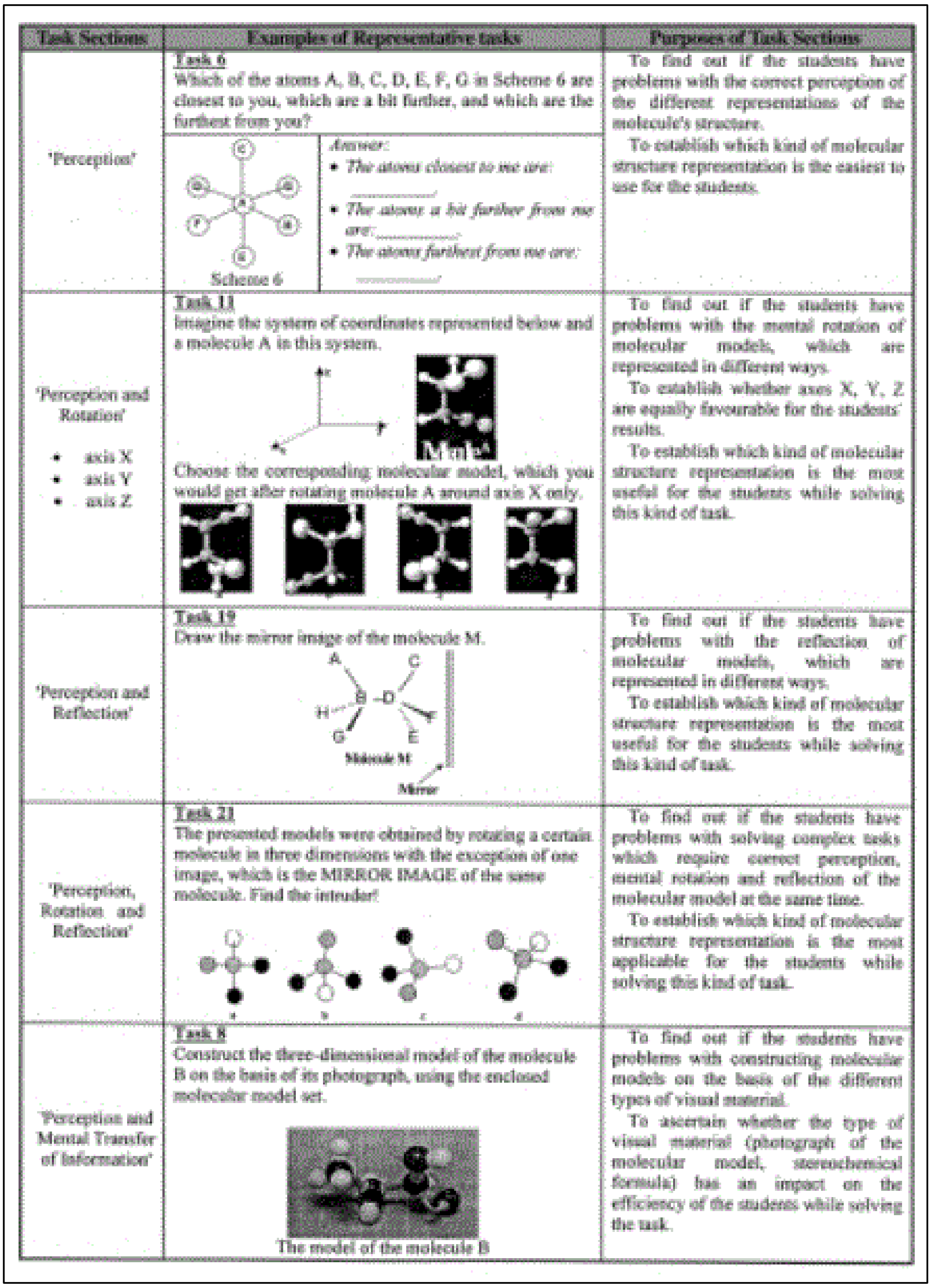
The majority of students in the study (N=31) had difficulty visualising the position of atoms after rotation or reflection. In the examples given in Figure 1.7, 40 % of students were unsuccessful in (a) and 30% of students were unsuccessful in (b).

Following on from this research, Ferk et al (2003) devised a ‘Chemical Visualisation Test’ (CVT) to examine students’ success at mental tasks on a variety of 3D representations of organic molecules. Five main tasks were examined, examples of which are shown in Figure 1.8; namely, Perception (can students perceive the 3D nature of the structure; Perception and Rotation (can students mentally rotate a 3D structure), Perception and Reflection; Perception, Rotation and Reflection; Perception and Mental Transfer of Information.

In total, 124 students were involved in this study; 42 primary school students (13-14 years old), 55 secondary school students (17-18 years old) and 27 fourth year undergraduate students (21-25 years old). As would be expected, the students’ age contributed to the students’ success in the given tasks. However, regardless of the students’ age or educational level, their success decreased when the number of incorporated processes increased. When only the correct perception of the molecules’ 3D structure was required for solving the task, 71.4% of the primary school students, 89.1% of secondary school students, and 96.3% of university students were successful. When a combination of two mental process was required (Perception and Rotation or Perception and Reflection) for solving the task the students' success decreased by about 25%, and when a combination of three mental processes (Perception, Rotation and Reflection) was required the students' success further dropped by about 25%.

Students who are unable to mentally rotate structures have been shown to have a lower spatial ability and perform worse in organic chemistry tasks that involve mental visualisation or rotation of structures.

Students who were most successful in the CVT test were shown to have a superior spatial ability by Ferk et al (2003). Likewise, students with the lowest spatial ability performed the least successfully on the CVT task. Students' spatial ability was tested using the 'Rotations Test' (Pogacnik 1998). This is a spatial relations test which focuses on mental rotation of a given visual representation. The tasks consist of three non-symbolic visual objects. Some of them are rotated versions of the model and some of them are its mirror projections or other objects. Students are required to identify the rotated representations of the model and also check that the other objects do not resemble the model.



Task Sections	Examples of Representative tasks	Purposes of Task Sections
'Perception'	Task 6 Which of the atoms A, B, C, D, E, F, G in Scheme 6 are closest to you, which are a bit further, and which are the furthest from you? Scheme 6 *Answer:* • *The atoms closest to me are:* ________ • *The atoms a bit further from me are:* ________ • *The atoms furthest from me are:* ________	To find out if the students have problems with the correct perception of the different representations of the molecule's structure. To establish which kind of molecular structure representation is the easiest to use for the students.
'Perception and Rotation' • axis X • axis Y • axis Z	Task 11 Imagine the system of coordinates represented below and a molecule A in this system. Choose the corresponding molecular model, which you would get after rotating molecule A around axis X only.	To find out if the students have problems with the mental rotation of molecular models, which are represented in different ways. To establish whether axes X, Y, Z are equally favourable for the students' results. To establish which kind of molecular structure representation is the most useful for the students while solving this kind of task.
'Perception and Reflection'	Task 19 Draw the mirror image of the molecule M. Molecule M Mirror	To find out if the students have problems with the reflection of molecular models, which are represented in different ways. To establish which kind of molecular structure representation is the most useful for the students while solving this kind of task.
'Perception, Rotation and Reflection'	Task 21 The presented models were obtained by rotating a certain molecule in three dimensions with the exception of one image, which is the MIRROR IMAGE of the same molecule. Find the intruder!	To find out if the students have problems with solving complex tasks which require correct perception, mental rotation and reflection of the molecular model at the same time. To establish which kind of molecular structure representation is the most applicable for the students while solving this kind of task.
'Perception and Mental Transfer of Information'	Task 8 Construct the three-dimensional model of the molecule B on the basis of its photograph, using the enclosed molecular model set. The model of the molecule B	To find out if the students have problems with constructing molecular models on the basis of the different types of visual material. To ascertain whether the type of visual material (photograph of the molecular model, stereochemical formula) has an impact on the efficiency of the students while solving the task.

Figure 1.8: Examples of tasks in the CVT test (adapted from Ferk et al, 2003)

The link between spatial ability and success in organic chemistry, particularly spatial tasks, has been well documented. Studies have shown that students with high spatial ability scores performed better on organic chemistry questions requiring problem-solving skills at third level (Pribyl and Bodner, 1987; Small and Morton, 1983). This appeared particularly true for questions that involved drawing or manipulating molecular representations; it was found that students with a higher spatial ability were more likely to draw correct structures and diagrams than those with lower spatial skills. Both studies also found that spatial ability had little impact on those questions that could be answered using memorised material or simple numerical procedures. Pribyl and Bodner (1987) found a significant correlation between two spatial ability tests (Purdue Visualisation of Rotation Test and the Find-a-Shape Puzzle, see Figure 1.9 for examples) and performance on organic chemistry exam questions that required students to carry out one of the following tasks: use, draw or name structural formulas or transform between representations of molecules (either projections, names or structural formulas); identify what is missing or wrong in a particular molecular structure or formula; complete a synthesis either by specifying reactants and reagents, or by proposing an entire multistep synthetic route; analyse the 3D structure of a molecule.

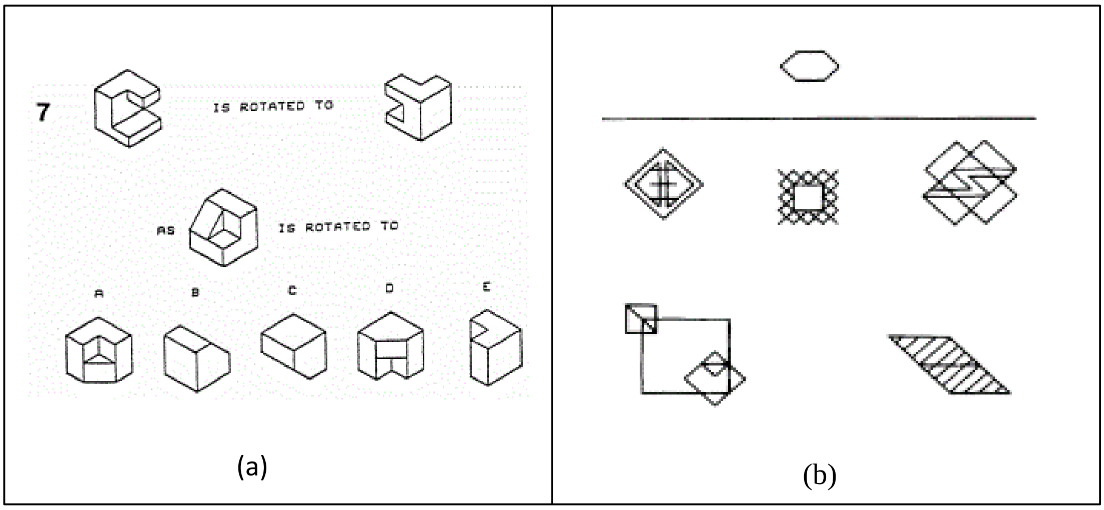


Figure 1.9: Examples of questions from spatial ability tests; (a) the Purdue Visualisation of Rotation Test and (b) the Find-a-Shape Puzzle.

The ability to diagnose students' who may at risk of difficulty at second level and third level due to their spatial ability is a valuable tool. Bodner and Guay (1997) recently validated the Purdue Visualisation of Rotation Test as a predictor of students who may experience difficulty when studying organic chemistry and/or biochemistry. One of the problems students face when taking a course that requires the use of spatial skills is that instruction may not directly help them learn how to use the spatial skills required to solve problems (Harle and Towns, 2011). Thus, if educators are able to identify students who may be at risk of experiencing difficulty, they can tailor their instruction to include activities that will aid their students' development of the required spatial skills.

Students who are not able to move between the various types of 2D and 3D representations of structures and form mental models of these structures, may go on to struggle with core concepts of organic chemistry, such as isomerism, functional groups, organic reactions and organic mechanisms.

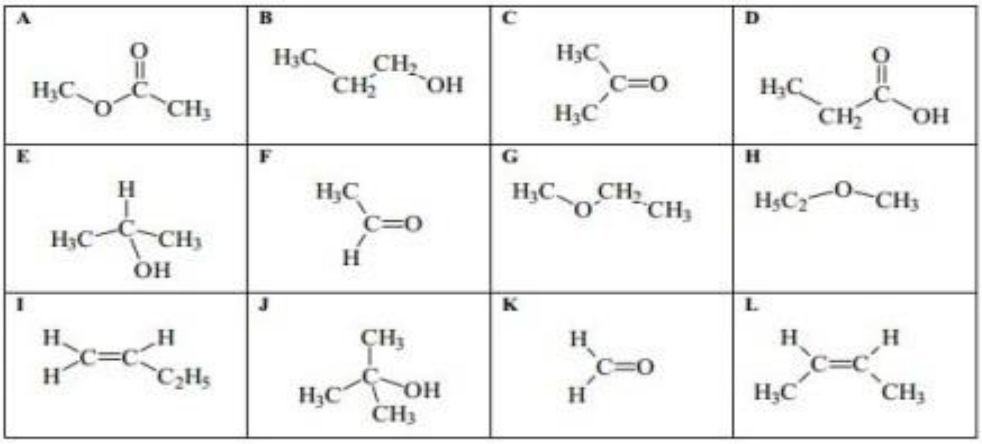
1.1.2 Understanding of Structural Problems

Structure is absolutely critical to the study of organic chemistry. It forms the basis for predicting and rationalising reactivity on the molecular scale and physical properties at the macroscopic level (Hassan et al, 2004). Difficulties experienced by students related to the representation of organic compounds can lead to difficulties recognising isomers of organic compounds. Without an understanding of the structural representations of organic compounds, students find it difficult to recognise isomers, and often resort to selecting compounds that have the same shape (branched or straight) as isomers (Schmidt, 1997).

Schmidt (1997) identified an 'alternative framework' which students can hold around isomers, i.e. that compounds can only be isomers if they belong to the same organic family. The term, *alternative framework*, as opposed to *alternative conceptions*, describes a set of students' ideas that can be seen as a meaningful and logically coherent alternative to a science concept (Kuiper, 1994):

'The observed error apparently resulted from a meaningful reasoning process, showing at the same time that there was an ordered understanding of the concept.'

Hassan et al (2004) used structural communication grids to identify incoming first year undergraduate chemistry students' conceptual understanding of organic chemistry concepts in a Scottish university. An example of a communication grid and the questions which accompanied the grid are shown in Figure 1.10. Structural communication grids are highly recommended for insights into conceptual understanding (Reid, 2003). Structural communication grids present data in the form of a numbered grid, students are given questions and asked to select appropriate boxes in response to these questions. Use of these grids gives an insight into sub-concepts and linkages between ideas held by students, so that understanding can be assessed. Students are not told how many correct responses there are. In this way, the wrong answers selected by students can reveal misunderstandings and misconceptions held by students.



		Correct responses
(a)	An isomer of the compound shown in box G	B, E
(b)	A secondary alcohol	E
(c)	An aldehyde (alkanal)	F, K
(d)	A compound which reacts with bromine to form 1,2-dibromobutane	I
(e)	An ester	A

Figure 1.10: Example of communication grid (from Hassan et al, 2004)

In part (a) of this particular question, 33% of students correctly identified both isomers, while a further 14% identified one of the two. Another 30% identified both but added a third option, with many selecting an identical molecule in box H that was shown in a different way. The molecule in box H is a mirror image of the molecule in box G, with the CH_2-CH_3 condensed to C_2H_5. Similar results were found in other questions examining isomer understanding.

This study demonstrates students' difficulties with the concepts of isomers; in identifying all possible isomers and also differentiating between structures of the same molecules with different orientations/presentations. Students need to have a good foundation of understanding structures and how to extract the appropriate information from the various representations of structures in order to successfully classify organic compounds. This will in turn inform structure-property relations and the ability to engage with organic reaction mechanisms

Domin et al (2008) described two methods of categorisation that may be used in organic chemistry: rule-based and similarity based. The rule-based method is strict and rigid, involving procedural knowledge to make a clear yes or no decision. In rule-based categorizations, items are grouped together on the basis of whether they satisfy a particular abstract proposition. The similarity-based method is dependent on the students' own perception of a common characteristic.

There are a number of significant features presented to students when they are asked to categorise a given organic compound. Domin et al (2008) listed seven of these features:

- Number of carbons
- Types of heteroatoms present
- Connectivity of parent compound
- Presence of multiple bonds between atoms
- Presence of chiral centres
- Stereochemistry associated with a chiral centre
- Different types of functional groups (Domin et al, 2008)

As can be seen from this list, categorisation can be a complex and intricate process. It can be difficult for students to identify the most prominent feature that could lead to a correct categorisation. Domin et al (2008) found that the critical feature used by students to categorise organic compounds actually changes as they progress through studying organic chemistry. Functional group has been found to be the most common feature used by both higher and lower ability students for categorisation (Domin et al, 2008; Hassan et al, 2004).

Categorisation using functional group has been shown to cause difficulty for students. A study by Strickland et al (2010) found that many organic chemistry students were unable to clearly explain or define what a functional group was. To the novice student, all organic compounds may appear very similar, as a molecule composed of carbon, hydrogen and oxygen. The most common functional groups in introductory organic chemistry courses, both at second and third level are:

alcohols (-OH); aldehydes (-CHO); ketones (>C=O); carboxylic acids (-COOH); esters (-COO-); aliphatic and aromatic hydrocarbons; haloalkanes

The presence of oxygen, hydrogen and carbon in most of these functional groups can cause difficulty for students when trying to differentiate between functional groups (Hassan et al, 2004), especially aldehydes and ketones as both contain the carbonyl group (>C=O). Difficulties classifying organic compounds can lead to difficulties when understanding physical properties of organic compounds, organic reactions and organic mechanisms.

1.1.3 Understanding of Structure-Property Relations

The relationship between the molecular-level structure of a substance and its properties is a core concept of chemistry and a key skill for understanding a subject like organic chemistry. The foundational idea that the arrangement of atoms in a substance directly affects the macroscopic, observable properties and reactivity of that substance is important and can provide students with a scaffold on which to build their understanding of a wide range of chemical phenomena.

Without a robust understanding of the underlying ideas that allow the structure-property relationship, students, out of necessity, resort to memorisation (Cooper et al, 2013). This is particularly relevant to organic chemistry, in which large numbers of different reactions can be introduced within the one course. If students are unable to use structural cues to determine how and why molecules interact, it is not surprising that organic chemistry is thought to be all about memorization.

There are many studies documenting students' difficulties in this area. A common misconception that has been identified in the literature is that during the processes of boiling and melting, covalent bonds (intramolecular bonds) are broken, rather than intermolecular forces being overcome (Smith and Nakhleh, 2011; Schmidt et al, 2009; Othmann et al, 2008; Taagepera and Noori, 2000).

Schmidt et al (2009) investigated upper secondary school students' difficulties in predicting the relative boiling points of organic compounds. While students were able to arrive at both correct and incorrect predictions by assuming that boiling involved breaking bonds, the information gathered did not allow the researchers to identify students' alternative models of boiling. They were, however, able to identify a variety of ideas around hydrogen bonding, including: hydrogen bonding only occurs between molecules containing an –OH group; a hydrogen bond is formed if dipolar molecules line up so that the positive end of one molecule is close to the negative end of another; dimethyl ether forms hydrogen bonds because water molecules do so.

Taagepera and Noori (2000) used a pre- and post-test method to construct a knowledge structure for novice organic chemistry students at university. In doing so, they identified four key problem areas that can arise during the study of organic chemistry:

- Bond polarities depend on absolute electronegativities of atoms only, regardless of what they are connected to, i.e. hydrogen will always be positively charged, chlorine will always be negatively charged;
- Confusion around intermolecular bonds, intramolecular bonds and boiling, i.e.: intramolecular bonds are broken on boiling;
- Inability to recognise reaction types, such as a simple proton transfer reaction;
- Belief that hydrogen bonding involves a covalent bond between molecules.

Cooper et al (2013) investigated the understanding of structure-property relationships of college chemistry students' (N=17), with varying majors. A semi-structured interview protocol was used that also required students to draw structures of compounds to aid their verbal responses. Students were required to have completed one semester of organic chemistry to participate in this study. While much of the literature identifies individual misconceptions, their results suggested that student difficulties in this area arise from a complex interplay of problems from different sources, some of which have already been discussed here. These difficulties were classified under the following headings:

<u>Mental models of phases/phase change</u>: Eight of the seventeen students interviewed did not possess a coherent model of the structure of solid, liquid and gaseous simple molecular compounds, which typically emerged when students were asked to draw structures representing the different phases.

<u>Use of representations</u>: Nine of the seventeen students interviewed experienced difficulty when trying to represent their thoughts on paper, for example; translating

from a 2D Lewis structure to a 3D structure or representing bonds breaking during phase change.

Language and terminology: The majority (fourteen) of the students interviewed struggled with scientific terms such as hydrogen bonding, intermolecular bonds, intramolecular bonds and covalent bonds.

Use of heuristics in student reasoning: All students employed some sort of heuristic or 'rule' in prediction tasks. While some of these resulted in a correct prediction, many of them did not and several were complicated by problems with representations and terminology, demonstrating the inter-linked nature of these difficulties. Examples of heuristics that students used include; a molecule with oxygen will have a higher boiling point than a similar hydrocarbon; an alcohol will have a higher boiling point than an ether; heavier molecules have a higher boiling point as heavy molecules are harder to get into the gas phase ("more means more").

For every student in this study, each of these problematic areas combined with others in slightly different ways, making each student's response unique. This indicates that student difficulties in this area should not considered as individual misconceptions or difficulties but a result of interactions between understandings of what words mean, what structures mean and their models of how phase changes occur.

1.1.4 Identifying Organic Reactions and Predicting Organic Mechanisms

Classification of a reaction "*adds an additional cognitive demand, which does not automatically bring the benefits that accrue to the expert"* (Taber 2002, p. 142).

There is much research highlighting the misunderstandings and misconceptions related to the reactivity of compounds due to bonding and electron density that make organic reactions difficult for students. Huat Bryan (2007) identified a number of conceptual questions put forward by A-Level students in Singapore, including:

Why are alkenes more reactive than alkanes, in spite of the fact that double bonds are "stronger" than single bonds?

How does the delocalization of π-electrons in the benzene ring make it more stable than expected?

If the benzene ring is stable, why do arenes still undergo reactions such as halogenation and nitration?

Why does OH activate, and Cl deactivate the aromatic ring towards electrophilic substitution? Aren't both groups highly electronegative and electron-withdrawing?

'Curly arrows', 'electron pushing', 'arrow-pushing' and 'curved arrows' are all names used to describe the methods of electron book-keeping used to keep track of electrons in chemical reactions. Hassan et al (2004) likened learning of organic chemistry to learning a foreign language:

> *"Students must learn the vocabulary (names, functional group) and the grammar (reactions, mechanisms) in order ultimately to develop a rudimentary style of comparison (mechanistic explanations, evidence of structures)".*
>
> (Hassan et al, 2004; p. 40)

A study by Rushton et al (2008) demonstrated how the improper assimilation of discipline-specific terms such as chirality, stereochemistry and aromaticity can result in students' confusion of concepts to which these terms are central. Ultimately, the misapplication of these terms hinders students' success in organic chemistry. A 'think-aloud' protocol was used to unearth misconceptions held by fourth year undergraduate chemistry or biochemistry majors while they solved multiple choice questions from an American Chemical Society (ACS) Organic Chemistry Examination. Questions that assessed fundamental organic chemistry concepts were chosen. Nineteen students volunteered to take part in the study. An example of the misapplication of terms was shown by a student attributing the term 'aromaticity' to six-membered rings with only one double bond to explain a resonance-stabilized, non-aromatic molecule.

Reaction mechanisms also caused confusion in this study: in a question which asked students to determine the correct reaction mechanism, several opted to 'ignore' the curved arrow notation and instead evaluated the proposed products. The question, of course, required students to actually evaluate the curved arrow notation to determine the correct bond formation and breaking.

This mis-understanding of the curved arrow notation for reaction mechanisms was also identified in a study by Bhattacharyya and Bodner (2005). A ‘think-aloud’ protocol was also used to assess students’ predictions of mechanisms. It was found that the curved arrows used in electron pushing mechanisms held no meaning for the students involved; students did not understand the function of the mechanism to explain the ‘how’ and ‘why’ of the reaction. Their use of curly arrows was shown to be useless by the justification that their use was ‘to get to the product’. When asked to explain each step, it was clear that students had simply reproduced memorised material. Students were able to produce correct answers without an understanding of the concepts on which their solutions are based.

Further to this study, Anderson and Bodner (2008) explored the experiences of a student who was very successful in general chemistry but was unsuccessful in organic chemistry. They showed that the student had difficulty in moving between various representations used in organic chemistry. In particular, the student struggled to explain the chemical symbols (Lewis-Dot structures, condensed and skeletal structures and reaction mechanism) that compose the subject.

Bhattacharyya and Bodner (2005) concluded that the reason students cannot understand curved arrows is because their cognitive understanding of organic chemistry is not yet at a formal operational stage. Taber (2002) also acknowledged the link between an understanding of how and why reactions occur with a complete background knowledge. If students do not have a strong foundational knowledge of organic chemistry concepts, they will not be able to understand, predict and classify reactions and mechanisms.

Ferguson and Bodner (2008) outlined the steps that students must be able to do in order to draw a correct mechanism:

- Understand chemical principles;
- Apply complex and abstract theories and facts;
- Look at the problem from different perspectives;
- Selectively apply chemical and physical concepts;
- Correctly draw starting intermediate.

While practising chemists (experts) use mechanisms to explain reactions and understand new reactions, there are a number of conditions which can hinder students' ability to engage with these mechanisms.

Ferguson and Bodner (2008) used the 'Constructivist Theory' to highlight the importance of the students' prior knowledge to difficulties with writing reaction mechanisms. They described the factors which limit students' ability to make sense of mechanisms, including:

<u>Inability to recall</u>: poor understanding of the rules, concepts and theories and only applying them sparingly. Too much reliance on memorisation to solve the problem;

<u>Inability to apply or understand</u>: confusion of reactions that look similar on the surface. Students fail to make a link between what happens in the laboratory and drawing curly arrows on paper;

<u>Poorly understood content</u>: poor application and linking of general chemistry concepts with organic chemistry;

<u>Non-content-specific barriers</u>: spatial reasoning abilities, e.g.: linear reactant and cyclical products. (Ferguson and Bodner, 2008)

This section has addressed the difficulties which students experience when studying organic chemistry. It has shown that student difficulties should not be considered as individual difficulties but a result of interactions between a students' understandings of what words mean, what structures mean and their mental models of chemical processes.

An understanding of representations, both 2D and 3D, and an ability to translate between these is a foundational skill which students require to successfully engage with organic molecules at a conceptual level. It has been shown that this is also the first hurdle which students can fall at when studying organic chemistry. If students cannot engage fully with these representations and pick out the 'important' information required from the structures, they can struggle with structural concepts such as isomerism and how to classify organic compounds.

Finally, without a strong understanding of structures, alternative conceptions and misunderstandings of structure-property relations can arise. Without clear and established mental models and mental process (rotation, reflection, etc.), the prediction of organic mechanisms and the ability to ‘follow’ the electrons through the use of curved arrows becomes very difficult.

Having addressed how students’ difficulties are influenced by their previous knowledge and experiences with organic chemistry, Section 1.2 will now consider why these difficulties arise, in relation to how students learn and assimilate information.

1.2 How Do Students Learn?

A significant proportion of the difficulties identified in the literature involve students’ abilities to engage with representations and translate between them. To further understand why these difficulties occur, we need to examine how students process and internalise these representations. The processes which result in meaningful learning are examined and compared with those which result in rote learning of information. The terms *mental model*, *internal representation* and *visualisations* have been used in the literature to describe how students engage with and process their surroundings, including molecular representations. The creation of mental models and development of visualisation skills will be discussed.

1.2.1 Rote Learning vs Meaningful Learning

The Information Processing Model shown below (Figure 1.11), depicts how students perceive, understand and learn information. This model presented by Johnstone (1997) was originally proposed by Greene and Hicks (1984).

The key factors which this model identifies as affecting learning are: perception filter, working space and long-term memory.

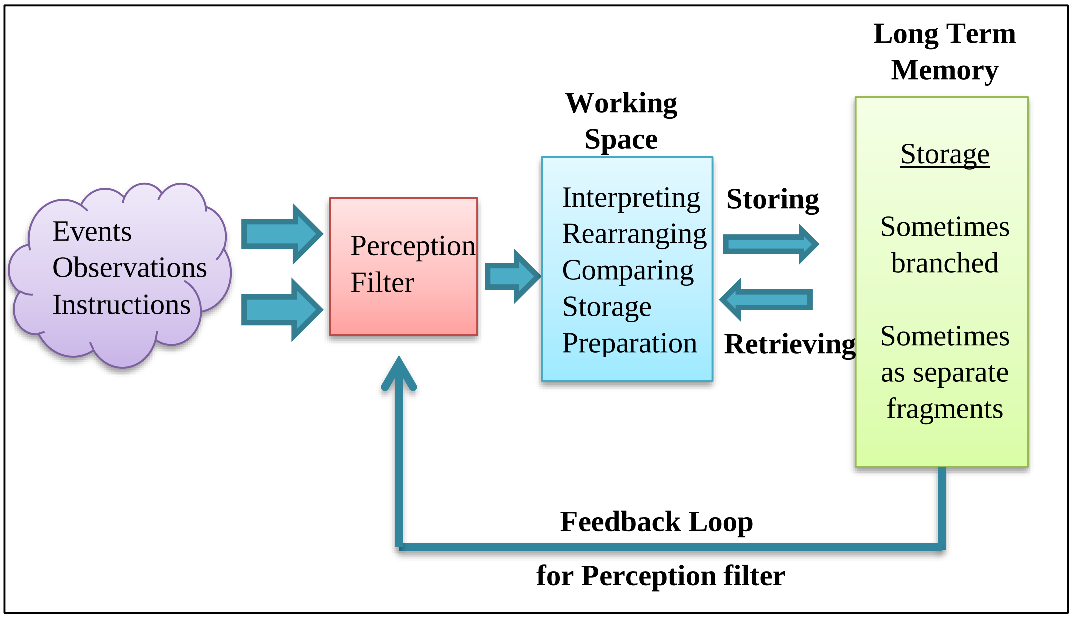


Figure 1.11: The Information Processing Model (from Johnstone, 1997)

The perception filter is a fundamental component of the Information Processing Model. The perception of new information is dependent on what students already know: the perception filter is thus controlled by the long term memory (Ausubel, 1968). Ausubel (1968) explained how our prior knowledge and experiences depict what we can learn in the future. Students can only perceive what is familiar to them, thus, if a new concept is rejected at this stage, it may never pass through the working memory space to the long term memory and understanding. When there is no attachment to established frameworks in the long term memory, students are often forced to turn to rote learning. Perceiving information which is familiar or known to students facilitates understanding. Many chemistry students cannot see any link between what they learn in the classroom or the investigations carried out in the laboratory with their everyday lives and the world that they live in. While, in fact, there are many examples of organic compounds in every aspect of the students' lives, such as foods, clothes, materials, pharmaceuticals, etc., teachers often struggle to or don't make students aware of these due to their complexities (O'Dwyer, 2012). This is, perhaps, a contributing factor for the multitude of studies which identify students' and teachers' perception of organic chemistry as one of the most difficult areas of chemistry (Ratcliffe, 2002; Jimoh, 2005; Schroeder and Greenbowe, 2008; Childs and Sheehan, 2009; O'Dwyer and Childs, 2011). Context-based approaches to teaching chemistry will be discussed in Section 3.3.

Grove and Bretz (2012) reported how prior knowledge, as it relates to the nature and scope of chemistry, impacted students' learning of organic chemistry. A significant theme which emerged from their research was the perceived 'straightforwardness of organic chemistry'. Students found it difficult to accept that *one* starting compound treated with only *one* set of reagents could lead to *more than one* correct product.

If the perception filter works efficiently, information overload of the working memory space is less likely (Reid, 2008). The working memory space has two main functions; temporary storage for incoming information (short term memory), as well as processing and making sense of the filtered (perceived) information (Johnstone, 1997). The working memory space has a limit to the quantity of information that it can hold and process (Johnstone, 1997). If the working memory space is overloaded, learning will cease. It is understandable that the manner in which a problem or new information is presented to students can limit their working memory space available, if it is not in an approachable format. Working memory overload can occur for two reasons:

- The working memory space is shared between processing, short term storage and sometimes translations;
- New incoming ideas can displace old ideas if they are not organised. (Johnstone and El-Banna, 1986)

Miller (1956) identified the average number of pieces of information that one can hold within the short term memory as seven. Considering the multi-dimensional nature of chemistry, it is easy to understand how a students' working memory space may become overloaded when studying chemistry. Indeed, Johnstone (1991) found that the reason for much difficulty in science and chemistry is due to information overload and the students' limited working memory space.

Johnstone and El- Banna (1989) suggested that due to the difficult nature of science and the method by which it is taught, the average number of pieces of information that can stored in the short term memory is just five. They proposed the use of working-memory capacity as a predictor of student performance in chemistry. This model was verified by Stamovlasis and Tsaparlis (2000) and Danili and Reid (2004). Stamovlasis and Tsaparlis (2000) showed that the working-memory capacity of university students correlated with the relative achievement scores in organic-synthesis problem solving.

Danili and Reid (2004) measured both the working memory capacity and field dependency (the ability to 'see the message from the noise') of 105 Greek students aged 15 – 16 years. These were both compared with performance in chemistry. As expected, those with higher working memory capacity and those who were field independent (could select information efficiently from questions) performed better. Their results showed that average performance increases as working memory capacity increases. This makes complete sense in that working memory overload is less likely with a higher working memory capacity and those who can select the 'message' from the 'noise' are less likely to take in extra unnecessary information to their working memories, thus causing possible overloads.

Reid (2008) highlighted the importance of setting questions for students to ensure that the question itself does not overload the working memory space before students can even begin to perceive what is being asked and to answer the question. The multi-dimensional nature of organic chemistry, and the multitude of representations used to represent organic molecules hold 'the potential for gross overload of working memory space' (Johnstone, 2006, p 59). This can result in students resorting to rote learning and information being stored incorrectly in the long term memory or not even making it that far.

Hassan et al (2004) used the 'simple' molecule of methyl propanoate as an example to illustrate this, see Figure 1.12 below. They suggested that if this structure was presented to a student with little or no organic chemistry for ten seconds and they were then asked to reproduce what they saw, the task could be beyond their capabilities. Hassan et al (2004) suggested that this is simply because the amount of information in the structure is well beyond the capacity of the working memory space of the student.

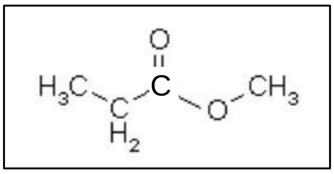


Figure 1.12: Structure of methyl propanoate

However, a student with some knowledge of organic chemistry may be able to ’chunk’ the information from this structure to reduce working load; the CH_3CH_2 group could be the first ‘chunk’ (with or without the name ‘ethyl’), followed by the ester functional group (COO) as the next’ chunk’ and the final methyl group as a third ‘chunk’.

Unless there is systematic organisation of information from the working memory space to long term memory, any new ideas can replace older ideas. The long term memory can be described using the analogy of a ‘filing cabinet’ of information (Johnstone, 1997): the ability to recall and retrieve information from the long term memory influences both students’ perception of new information and how they process this information and is dependent on how the knowledge has been stored. If stored in an ordered and organised manner, information will be easily retrievable. However, if it is stored without order and understanding, information will not be retrieved or recalled easily. If knowledge is stored in a linked fashion, it will be more easily recalled (Reid, 2008). Very often, students cannot make sense of information processed in the working memory space because they cannot link it to anything in the long term memory. Thus, the accuracy of how prior knowledge is stored and understood can affect how we learn.

Johnstone (1997) referred to Ausubel’s Spectrum of Learning (1968) in order to describe the difference between how meaningful learning, the development of misconceptions and rote learning takes place. This spectrum, which ranges from meaningful learning to rote learning, is illustrated in Figure 1.13.

This illustrates the different ways in which information can be stored in the long term memory (Johnstone, 1997). Meaningful learning can only take place if new knowledge is correctly linked with previous knowledge that is stored in the long term memory.

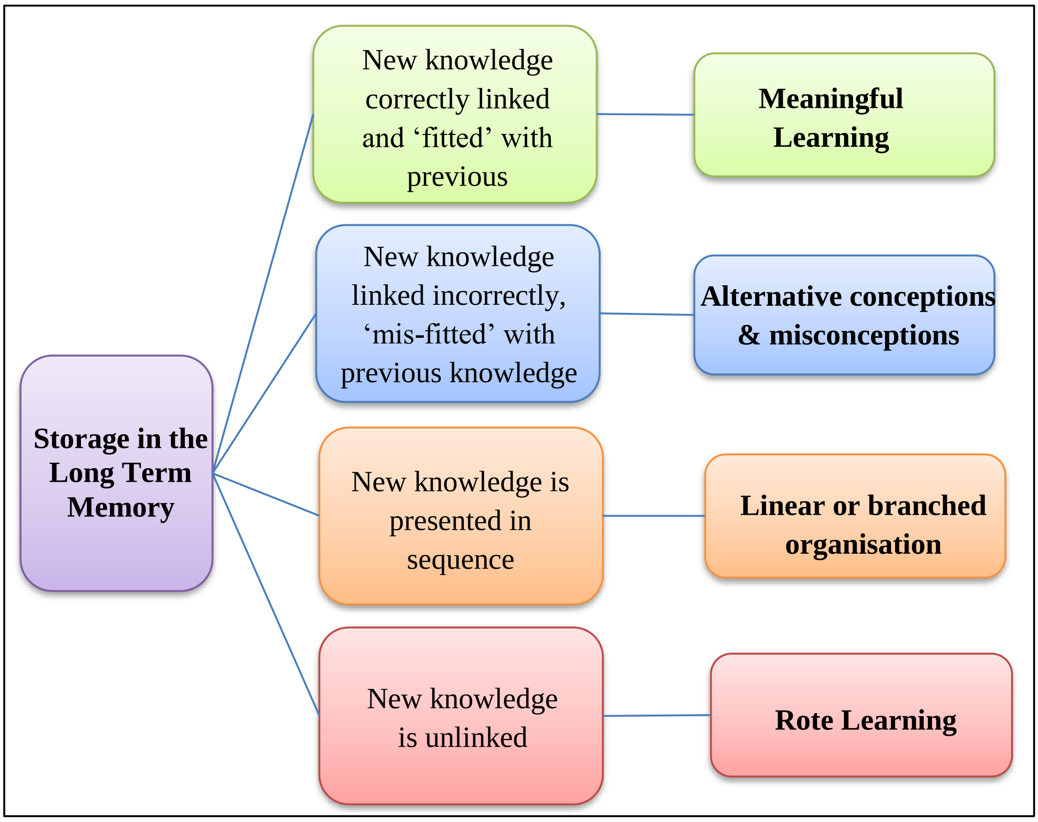


Figure 1.13: Ausubel's Spectrum of Learning (adapted from Johnstone, 1997)

Alternative conceptions and misconceptions are developed when new knowledge is incorrectly linked with that already existing in the long term memory. If new knowledge is presented in a sequence, it can be stored in the long term memory in a linear or branched organisation without a link to other knowledge in the long term memory. However, if the new knowledge presented is unlinked to anything in the long term memory, a student must resort to rote learning in order to store it in the long term memory.

Based on this spectrum and the information processing model, Grove and Bretz (2012) summarised the three key requirements for meaningful learning to occur:

1. students must first possess relevant prior knowledge with which to situate and anchor new knowledge;
2. the knowledge to be learned in and of itself must be perceived by the student as 'relevant to other knowledge and must contain significant concepts and propositions';

3. the student must chose to learn meaningfully. That is, the students must 'consciously and deliberately choose to relate new knowledge to knowledge the student already knows in some nontrivial way' (Novak, 1998)

In cases where one or more of these conditions is not met, students may use rote learning techniques (Grove and Bretz, 2012). Information which is rote learned is mostly unattached and is difficult to recall later (Johnstone, 2006). Incorrectly linked knowledge or separate fragments of knowledge in the long term memory are stored by memorisation without any clear understanding. Alternative frameworks lead to the development of alternative conceptions or misconceptions.

Students' ability to accurately perceive knowledge presented to them influences their ability to store this knowledge. The creation of mental models is an important element of storing representational and structural information with regards to organic chemistry. The creation of mental models and the process of visualisation will now be discussed.

1.2.2 Mental Models and Visualisation

Gilbert (2010) used Paivio's Dual Coding Theory, proposed in 1986, to describe the process of visualisation. Paivio's dual coding theory suggests two types of stimuli exist, verbal and non-verbal, which are processed in different ways by sensory systems that are common to both (Paivio, 1986). Verbal stimuli come in the form of speech while non-verbal stimuli comes through as touch, sight, sound and taste. In this theory, the pieces of verbal information, called 'logogens', are stored separately but are capable of cross-reference to form 'associative structures'. Similarly, the pieces of non-verbal information are stored separately with the capability of forming their own associative structures. The two types of associative structures can then be linked to form 'referential connections'. See Figure 1.14 for a pictorial representation of this theory.

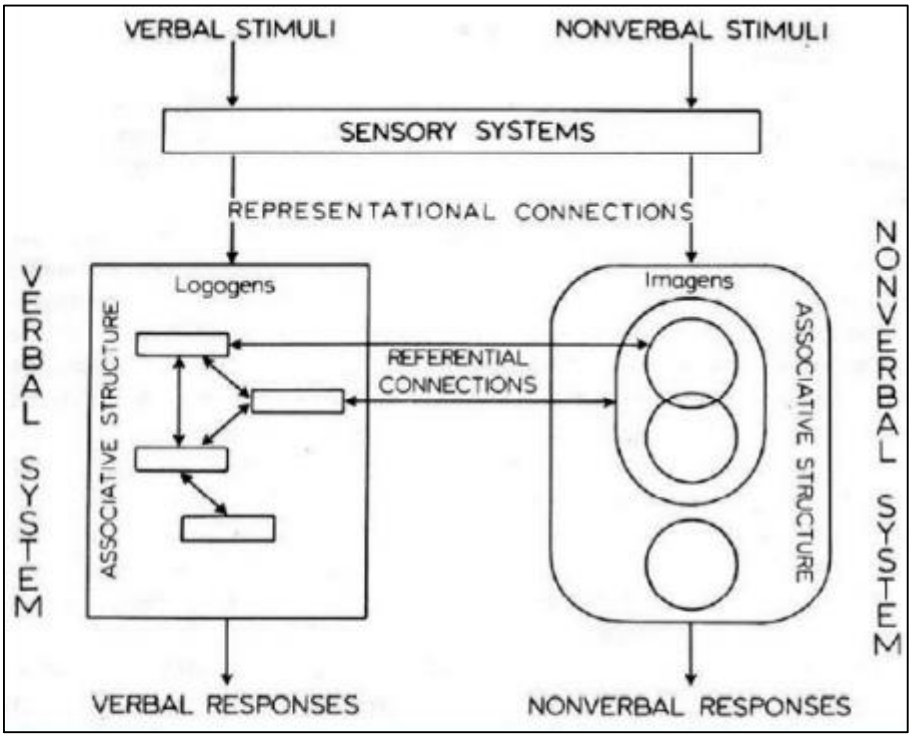


Figure 1.14: Paivio’s Dual Coding Theory (Paivio, 1986)

Depending on the referential connections and associative structures that have been developed, an individual will produce either a verbal or non-verbal output. This activity is visualisation and it operates on models (Gilbert, 2010).

The existence of mental models has been discussed as far back as 1983; Johnson-Laird (1983) proposed the existence of three types of mental constructs: mental images, mental models and propositional representations. Propositional representations are essentially abstract, for example, definitions, symbols and formulae. Mental models are functional representations of the real world which are constructed by a student through perception or acts of imagination. Finally, mental images are mental views of mental models which are dynamic and contain more visual-spatial information than the models themselves (Buffler et al, 2008). Johnson-Laird suggested that mental models allow students to work between mental images and propositional representations. It is then the dynamic interplay between these 3 mental constructs that enables conceptual understanding (Geelan et al, 2014).

Since it is primarily propositional representations that students are actually tested on, Geelan et al (2014) suggest the use of external images and visualisations to aid students’ development of mental models that then allow them to develop an understanding of propositional representations (see Figure 1.15). The use of external representations will be fully examined in Section 1.3.1.

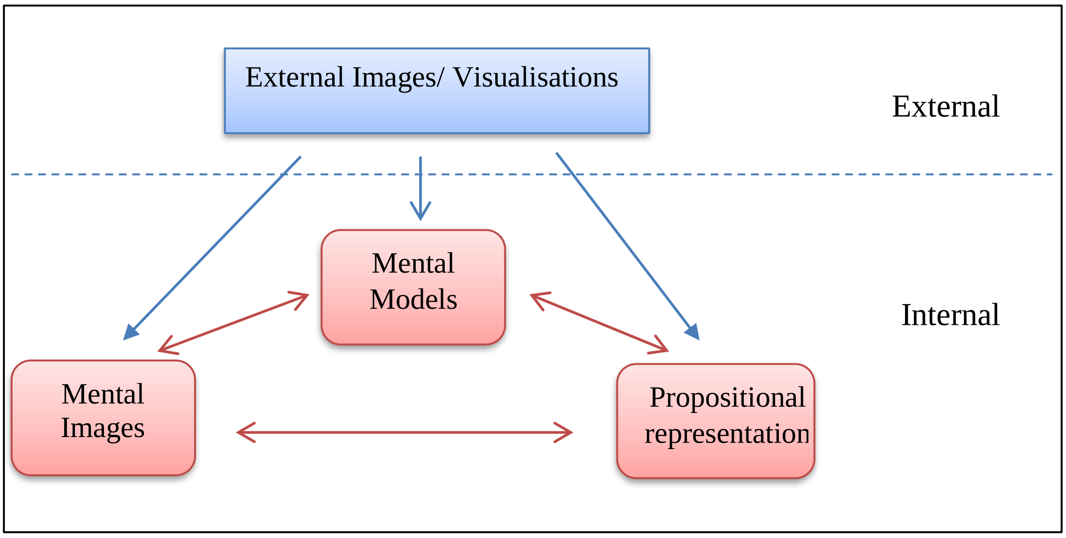


Figure 1.15: Representation of the link between mental constructs and external representations

Greca and Moreira (2000) attempted to distinguish between mental models and conceptual models. They describe mental models as internal representations constructed by students to enable them to understand and explain their surrounding world and its phenomena. Thus, mental models are personal constructs that are incomplete and qualitative. According to Greca and Moreira conceptual models are introduced to students in the classroom and are generally external representations that have been created by researchers and teachers to facilitate comprehension. Mental models are fluid and open to change, while conceptual models are precise, complete and coherent with scientifically accepted knowledge.

Bodner and Briggs (2005) describe five components of a mental model. The five components, referent, relation, rules/syntax, operation and result, are a mixture of static and dynamic components, as follows:

<u>Referents</u>*:* physical objects, labels for objects and mental representations.

<u>Relations:</u> this involves the spatial relationship between referents.

<u>Rules/syntax:</u> a set of rules and syntax by which to order a mental representation. A 'rule' is defined as a concept and the 'syntax' is how the rule is implemented. Bodner and Briggs (2005) suggest that the creation of mental models is not a random set of mental images but is an ordered operation.

<u>Operation:</u> this is the dynamic component of the mental model. It is defined as 'the process of transforming a representation from one form to another'. Bodner and Briggs describe this process as 'visualisation' and the result of this is a 'representation'.

<u>Result:</u> the product of operating on a referent.

Bodner and Briggs go on to describe a model for molecular visualisation as a process of mental modelling that uses both representations and operations. They used a 'think-aloud' protocol to study the mental structure and processes involved in mental model construction and visualisation of five second year undergraduate organic chemistry students. Students were given two-dimensional molecular representations on paper, asked to perform a mental rotation and produce a drawn representation of the rotated molecule. An example of a task molecule can be found in Figure 1.16. The compounds whose molecular representations were used in this study were composed primarily of carbon and hydrogen atoms, with at least one oxygen or nitrogen atom as a reference for the rotation instruction. The various tasks in this study were of increasing difficulty and were categorised based on three criteria: the number of atoms in the molecule, the extent of branching of the carbon chains, and the degree of rotation about each axis.

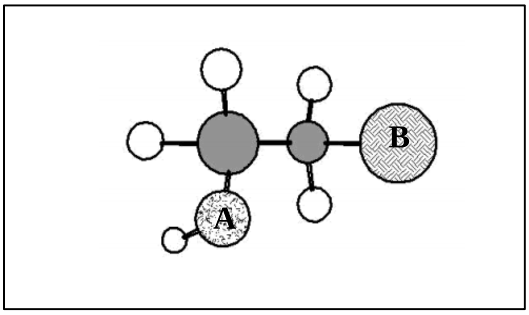


Figure 1.16: Example of a task molecule given to students, taken from Bodner and Briggs (2005). The grey filled circles represent carbon atoms, the unfilled circles represent hydrogen atoms, circle marked A represents an oxygen atom; and circle marked B represents a halogen atom.

A number of key points in relation to mental model construction and visualisation arose during this study, which have significance for organic chemistry instruction:

- Being able to distinguish one atom from another is crucial to completing the task of visualisation and rotation. The inability to do this may indicate a defective or missing visualization operation and would prevent a student from constructing a useful mental model of the task molecule;

- Students need to be able to recognise spatial and sequential relations between components in molecules;
- An understanding of the 'rules' in relation to organic molecules, such as the number of bonds formed by carbon and the tetrahedral shape of single-bonded carbon, is needed for students recognise spatial cues from drawings and to check for the reality of 'correctness' of a student's result. Students without rules and syntax were unable to make sense of the task molecule and visualise it;
- Some students with a deficiency in their ability to mentally rotate a molecule attempted to invent an alternative operation to replace rotation.

(Bonder and Briggs, 2005)

An important insight from this study suggests that the process of visualisation, or the creation of a mental model, precedes the operation of rotation in a mental molecular rotation task. Improper visualisation can result in a flawed representation and an incorrect result when asked to perform a mental rotation task. Visualisation is an operation of dual media; it acts upon both physical and mental objects.

The process of mental model construction is complex and relies on a student's ability to process external representations efficiently. Dori and Kabermann (2012) broke the process of visualisation into a set of modelling sub-skills. These sub-skills were split into 2 types; Type A and Type B. Type A sub-skills are related to drawing and transferring between a molecular formula, a structural formula, and a model. Type B modelling sub-skills deal with transferring between symbols and/or models on the one hand and the microscopic, macroscopic, and process chemistry understanding levels on the other hand.

Dori and Kabermann assessed six hundred 12^{th} grade students' modelling sub-skills following participation in an organic chemistry Computerised Molecular Modelling (CMM) unit. In this unit, students explored daily life organic molecules through assignments and two CMM software packages. This modelling environment will be discussed further in Section 1.3. Students' modelling sub-skills were assessed through the use of five questions, which can be found in Figure 1.17. Despite learning to model via the CMM, these questions were asked via and pen-and-paper test.

These sub-skills were arranged in a hierarchy of difficulty, according to students' success in the questions detailed above. This hierarchy was represented as a set of stairs, as shown in Figure 1.18; as the student climbs the steps, they are required to master increasingly higher level modelling sub-skills, starting with transferring from molecular to structural formula at the bottom, all the way to transferring from the symbol to the process level. Each stair contains the modelling sub-skill definition, while the vertical face of the stair has an example of the sub-skill taken from the questionnaire used in this study.

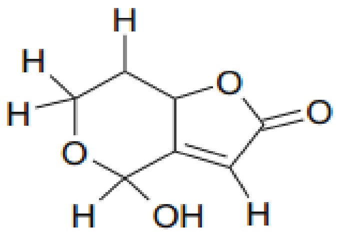
The two modelling sub-skill types were found to be intertwined, with sub-skills of Type A being in general lower than those of Type B. Depending on how high up the hierarchy of modelling sub-skills a student has reached, students will be more or less successful at solving organic chemistry problems which require these modelling sub-skills. It can be assumed that expert chemists are operating at a higher level than the novice chemist and thus, will make use of their skills in a different manner to visualise organic molecules. The differences between expert and novice visualisation will now be discussed.

1. The molecular formula of isoprene is C_5H_8. Write a possible acyclic structural formula for the molecule. [Transfer from molecular formula to structural formula—a sub-skill of type A.]
2. Draw a model for the structural formula of C_5H_8 you suggested. [Transfer from structural formula to a 3D model drawing—a sub-skill of type A.]
3. Many organic compounds are considered as air pollutants. One of them is propylene (propene), which reacts with water and $KMnO_4$ to produce propylene glycol (3D model is given).

a. Write the molecular and structural formula of propylene glycol. [Transfer from a 3D model to molecular and structural formula—a sub-skill of type A.]

b. Draw a model for propylene. [Transfer from molecular formula to a 3D model drawing—a sub-skill of type A.]

4. The structural formula of patulin is described below. Explain in bonding and structure terms why the patulin is solid in room temperature. [Transfer from symbols to macroscopic and microscopic level—a sub-skill of type B.]



5. NaI is a white solid substance, whose molar mass is 150 g/mol with melting temperature of 662°C, while the molar mass of patulin is 154 g/mol, with melting temperature of 110°C. Describe the melting processes of NaI and patulin. Explain the difference between these two processes. [Transfer from the symbol level (structural formula and ionic formula) to the process level expressed as verbal explanations—a sub-skill of type B.]

Figure 1.17: Questions used by Dori and Kabermann (2012) to assess students' modelling sub-skills.

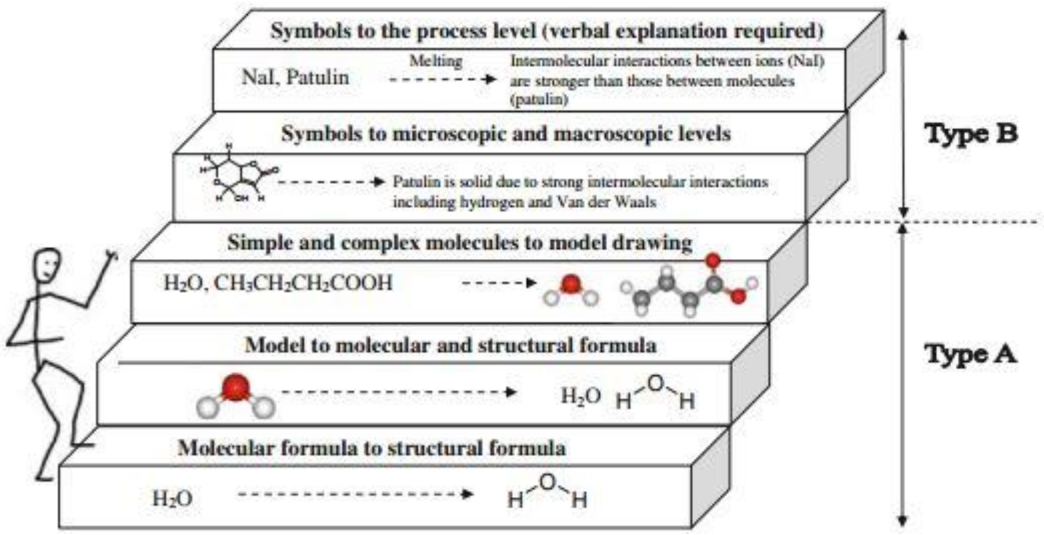


Figure 1.18: Hierarchy of modelling sub-skills for visualisation as proposed by Dori and Kaberman (2012).

1.2.3 Expert vs Novice Visualisation

Kozma and Russell (1997) examined how experts and novice chemists use various chemical visualisations such as graphs, equations, videos and animations of chemical phenomena. The visualisations were a mixture of dynamic and static. The novice participants consisted of eleven first year undergraduate chemistry students in their first semester, while the expert participants consisted of five doctoral students of the same university, five chemists from a pharmaceutical company and one community college instructor.

Participants were shown 14 visualisations and then given a card corresponding to each representation, with the dynamic representations being represented by a single still frame, examples of these are shown in Figure 1.19.

Participants were asked to sort the cards into logical groups, give a name to each group and explain the meaning of the name. Both experts and novices created chemically meaningful groups, however, novices used a smaller number of cards to form their groups and they were from the same media type (e.g., all graphs, all equations, etc.). Meanwhile, experts used larger groups composed of multiple media forms.

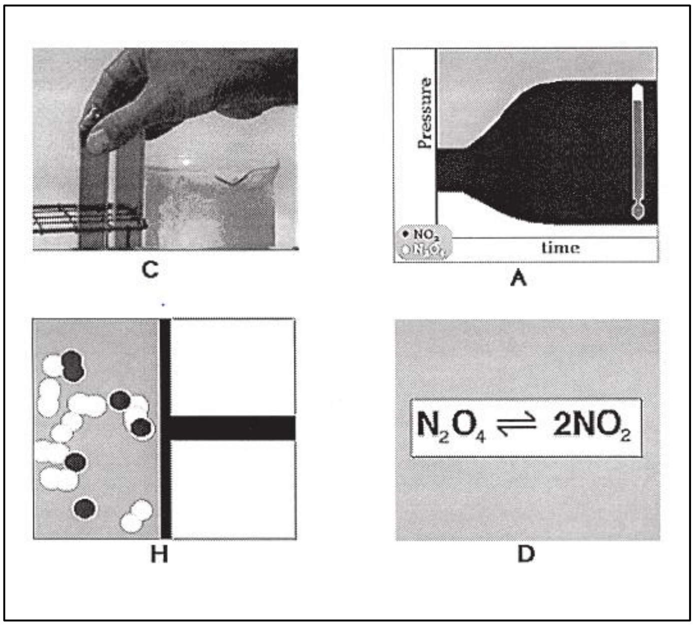


Figure 1.19: Examples of cards and the labels for each of the types of media taken from computer displays and used in the sorting task: videos (C), graphs (A), animations (H) and equations (D)

Experts also gave largely conceptual explanations for the formation of their groups while novices' reasons often were based upon surface features. For example, a similar grouping was created by both a novice and expert participant, however, the explanation provided by the expert was 'collision theory' while the explanation provided by the novice participant was 'molecules moving about'. This demonstrates the differing levels of understanding between expert and novice chemists.

This section has demonstrated the critical influence that the previous knowledge of students, the method in which organic chemistry is presented to students and the processes that students are trained in to handle the information given to them can have on students' success in engaging with organic chemistry. Educators must take steps to avoid working memory overload, both during teaching and assessing. Students need clear external representations to aid their mental model construction. Dori and Kabermann's hierarchy of modelling sub-skills indicates that students need to be introduced to translations between different representations at different stages of their studies and that not all students will be at the same level of visualisation at any given time. The translations necessary for visualisation and mental model creation need to be explicitly demonstrated to students. Approaches that educators and researchers have devised to aid these modelling skills and address the difficulties identified in Section 1.1 will now be discussed in Section 1.3.

1.3 Methods of Addressing Student Difficulties

The studies discussed in the previous sections have shown that students experience difficulties in both understanding of how multimodal representations are used to represent organic chemistry concepts and how to represesnt their knowledge using multimodal representations.

Researchers suggest that instruction emphasizing the level of particles would help students learn chemistry conceptually (Gabel, 1993; Davidowitz and Chittleborough, 2009; Williamson, 2014). This conceptual teaching puts an emphasis on students' ability to explain relationships, to predict outcomes, to visualize and explain particle behaviour, and to understand the macroscopic, particulate and symbolic levels.

Various methods and tools have been developed by chemistry instructors to help students visualize particles and understand chemical phenomena on these different levels (Williamson, 2014). This section will discuss the variety of visualizations which are available for this purpose and conceptual pedagogies which have been developed to improve students' conceptual learning:

1. Visualisations:
    a. Macroscopic representations;
    b. Particulate representations: physical models, student generated drawings;
    c. Virtual environments; animations, molecular modelling software, drawing tools with animation;
2. Conceptual pedagogies: context based approaches, phenomena-oriented inquiry-based network concept (PIN-Concept).

1.3.1 Visualisations

Visualisation has been previously discussed in terms of a mental process undertaken by students. However, the term visualisation can also be used as a noun. Visualisations can be used to help students *visualise* a particular phenomenon. Visualisations which can aid students' ability to visualise particles will now be discussed.

(a) Macroscopic Representations

Macroscopic representations show students' views of the phenomena that can be seen with their eyes. These include practical sessions/experiments, demonstrations, videos and computer simulations of actual laboratories. The use of macroscopic representations can aid students' conceptual understanding by promoting the formation of macroscopic mental models in the students' minds (Abrahams and Millar, 2004).

The amount of student activity may vary with the type of practical sessions; practical sessions can be categorized as verification, guided-inquiry, or open-inquiry (Abrahams and Millar, 2004). A verification practical sessions is the traditional format, in which students have already attended the lecture on the topic and often know the expected outcome of the session. Students take a more active role in the inquiry-based practical sessions. In guided inquiry sessions, students collect data on an unknown phenomenon, and then are asked to identify patterns or relationships in their own data. Open-inquiry practical sessions involve students designing their own procedures Abrahams and Millar (2004) suggest the use of a guided-inquiry laboratory to develop achievements in science, enhance retention of concepts and improve reasoning ability.

Johnstone (1997) does warn, however, that the laboratory is the place for information overload: most students may only be aware of and able to comprehend the macroscopic level of thought, for example: being able to set up the reflux apparatus without an understanding of the process itself. While the manipulation of laboratory apparatus is a necessary skill to be learned in a practical session, caution has to be taken to ensure the other dimensions of chemistry are not forgotten, for example: not recognising what the aim of the experiment actually is. Johnstone (1991) identified the difficulty that students experience in distinguishing the 'signal' from the 'noise' in the laboratory. She refers to the 'signal' as the aim of the practical work, while the 'noise' refers to the numerous other observations that students will make during an investigation. There is often very little cognitive gain in formal laboratory work as instructions, manipulation of equipment, recording of observations, etc. can take up most of the students' working memory space, reducing the space available for cognitive processing. Thus, it is important for educators to emphasise and create links for students between what they are viewing at a macroscopic level and what is taking place at a molecular level during practical sessions. The use of particulate representations to aid students' understanding at the molecular level will now be discussed.

(b) Particulate Representations

The Oxford English Dictionary (OED) notes that the word model can be used as a noun, adjective or verb. As a noun by the OED, the term model means '*a simplified or idealised description or conception of a particular system, situation or process, often in mathematical terms, that is put forward as a basis for theoretical or empirical understanding, or for calculations, predictions, etc.; a conceptual or mental representation of something'*.

The term model can also be used as a verb: '*To devise a (usually mathematical) model or simplified description of a phenomenon, system, etc.'* For the purpose of this literature review, the term *modelling* will be used to describe the construction of a physical model of a system.

Bodner and Briggs (2005) suggest that the meaning of the term *model* changes for students as they progress through their study of chemistry; organic chemistry students are exposed to models as nouns or adjectives that are explicit in their nature, such as models that demonstrate collision theory, gas laws, and molecular models. However, they are rarely asked to take an active role in the physical process of *modelling,* i.e. creating physical models.

Gilbert (2005) offers a categorisation of the types of models used in science teaching:

<u>Mental model</u>: a private and personal representation formed by an individual either alone or in a group. It is formed by an individual's thought process;

<u>Expressed model</u>: a version of a mental model that is placed in the public domain;

<u>Consensus model</u>: an expressed model that has been generally accepted by a group;

<u>Scientific model</u>: a consensus model being worked on by a group of scientists at the cutting edge of their science;

<u>Historical model</u>: a superseded scientific model;

Curricular model: a simplified version of a scientific or historical model that is produced to aid learning of these models;

Teaching model: a model specially developed to support the learning of curricular models;

Hybrid model: curricular models which merge the characteristics of several historical models.

A complication with the models used in science teaching is the variety of the representational modes that can be used any of these model types are placed in the public domain. Gilbert (2005) identifies five modes of representation, which are often combined during instruction (Gobert and Buckley, 2000):

Concrete: three-dimensional and made of resistant materials, e.g.: a plastic ball-and-stick model of an organic compound;

Verbal: consists of a description of the entities and the relationships between them in a representation, e.g.: the nature of the balls and sticks in a ball-and-stick representation;

Symbolic: consists of chemical symbols and formulas;

Visual: two-dimensional representations of chemical structures; diagrams and virtual computer-based models;

Gestural: makes use of the body or its parts.

Particulate models and representations help students to visualise the nature of matter at the sub-microscopic level of Johnstone's triangle. Williamson (2014) suggested the use of the term 'particulate' instead of 'sub-microscopic' in Johnstone's triangle in order to include atoms, molecules, etc. As already discussed, the abstract nature of organic chemistry makes it difficult for students to visualise the processes that occur at a particulate level. Thus, instructors should use techniques to promote the formation of mental models of particles in their students. Williamson and Jose (2009) suggest the use of (i) physical models and (ii) student generated drawings to promote visualisation at a particulate level.

(i) Physical models

Physical models are *concrete, tangible* objects that can be used to illustrate the chemical structures and processes at the particulate level, for example, MolyMod Kits (Taber, 2012). They are, however, limited in quantity, variety of colours and sizes, and are not amenable to any computational operations (Dori and Barak, 2001).

Toon (2012) identified molecular models as props that guide students' 'imaginings'. These include imagining the balls and sticks of the models to be atoms and bonds; users of molecular models also imagine themselves looking at molecules, picking them up and twisting them around. It can be argued that this 'imagining' is students visualising and performing mental tasks on the structures.

Baker et al (1998) designed a molecular model workshop using MolyMod kits to teach the concepts of isomers and stereoisomers to first year undergraduate chemistry students. Students were encouraged to think of molecules and construct models of their own. While they do not present any data, they suggest that this hands-on approach using molecular models helped considerably in teaching the relationship between different isomers and the importance of symmetry and structure. They reported a good response from their students, who found it helpful in understanding the difference between isomers.

Jones et al (2005) discussed the value of allowing students to measure the bond angle in alkanes and alkenes, the bond length, etc. to gain a better understanding of the structure of the molecules. Although, care should be taken when measuring the bond length as the flexi-bonds used to represent double bonds in traditional molecular modelling kits are actually longer than those used to represent single bonds. There is a danger that this could cause more misconceptions rather than aiding understanding.

Nicoll (2003) identified a number of issues with the conventional molecular model kits:

- Conventional model kits tend to lead students towards the correct answer; with a fixed number of holes and a fixed geometry inherent in each piece of the kit;

- Conventional model kits do not allow students the freedom to represent different types of models;
- Despite using these kits, students still appear to build their own, potentially unconventional, representations of molecules; not all students are positively affected by the use of these kits.

Tasker and Dalton (2006) also acknowledged that molecular models can create new misconceptions, and that the teacher needs to be aware of these. Teachers need to integrate molecular modelling (using model kits, computerised models or animations) into their lessons in a manner that will not overload students' working memory space. Thus, instruction using molecular model kits need to be designed and presented with great care to encourage students to focus on the intended 'key features' and to avoid generating or reinforcing misconceptions.

Nicoll (2003) highlighted two key advantages of using alternative materials, like the clay and sticks instead of conventional molecular modelling kits. Some students in this study tried to bring more to their models than traditionally included in model kits; for example, one student used clay to include lone pairs in their model, while another used colour intensity to represent increasing electronegativity of atoms.

The use of alternative materials also means students can build their own, potentially unconventional albeit correct representations of molecules (Nicoll, 2003). Another student in this study used sticks of a particular length to indicate the presence of lone pairs. One student in this study opted not to use sticks at all, but created a space-filling model made only of clay.

Some educators wish their students to have a common sub-microscopic representation of molecules, which may be achieved by molecular model kits. However, Nicoll's findings indicate that '*while some students produced something that represented traditional model kits, there were those students who had perfectly correct representations…*[that] *appear to have exceeded the expectations of the model kit and built more creative and potentially useful representations'* (Nicoll, 2003, p.212).

While the use of physical models has been shown to improve student understanding at the molecular level, they are not widely used in chemistry instructions. A survey by Dori and Barak (2001) of 51 science and chemistry teachers regarding the use of models, revealed that only a minority (17%) indicated the use of models in individualized active learning while most teachers use models in cooperative learning (32%) and demonstrations (51%). The teachers who used models in demonstration mode only, attributed this to budgetary and time constraints. Unfortunately, this is an issue facing all chemistry teachers, both in Ireland and internationally.

Treagust et al (2004) investigated students' understanding of the descriptive and predictve nature of teaching models used to represent organic compounds in an introductory organic chemistry course (structural formulae, ball-and-stick models, computer generated structures and space-filling models). Thirty six students between 16 and 17 years of age were observed, interviewed and surveyed using a questionnaire. The questionnaire examined students' perceptions of the role of the types of models used in this study while the observations and interviews examined students' use of them.

The dialogue observed indicated that students were confirming and consolidating their understanding of structures and nomenclature using the ball-and-stick models. Students were observed using the ball-and-stick models as explanations for possible structures and differences between isomers and then relating these to other representational formats, such as the structural formula. The dialogue collected in this study indicates the potential for model-based explanations in expanding students' understanding of organic chemistry structures and ability to relate different representations. Students could also make predictions about the reactivity of a compound, for example, by identifying the site of double bonds, and making predictions about a compound's stability by looking at bond angles. However, the result from their questionnaire indicate that students did not realise that they were using these models in a predictive manner.

An important recommendation from Treagust et al (2004) is not just the incorporation of models in chemical instruction and explanation but that teachers need to teach modelling skills and encourage students to use multiple representations within their explanations. It also suggested that working in pairs was an effective way for students to both help and challenge each other.

Harrison and Treagust (2000) suggested: '*learning to model should be overtly social and involve discussion and negotiation of learning'*. Boulter and Gilbert (2000) highlighted the importance of student discourse when using models constructively and emphasises the social aspect of the process of modelling. The use of teaching models can encourage discussion and the articulation of explanations that encourages students to evaluate and assess the logic of their thinking (Raghavan and Glaser, 1995).

In this manner, the use of models in teaching and learning, places it within the social constructivism theory of learning. In the classroom, conceptual understanding is '*dependent on the opportunity to socially construct, and reconstruct, one's own personal knowledge through a process of dialogic argument'* (Driver et al, 2000, p. 298). Thus, understanding develops through the course of communicating ideas and interacting with others.

Another method that has been identified to aid students' communcation of their ideas at a particulate level are student generated drawings, which will now be discussed

(ii) Student generated drawing

Quillin and Thomas (2015) define a drawing as:

'a learner-generated external visual representation depicting any type of content, whether structure, relationship or process, created in static two-dimensions in any medium' (p. 2).

While experts use drawings to imagine new relationships, test ideas and elaborate knowledge, the science classroom is mainly focused on interpreting others' visualisations. When drawing does occur, it is rare that students are systematically encouraged to create their own visual forms to develop and show understanding (Ainsworth et al, 2011).

Ainsworth et al (2011) suggest five important reasons to encourage students to draw in the science classroom:

<u>Drawing to enhance student engagement:</u> to create more interactive, inquiry learning. The aim is to move students' role in the classroom from passive to active;

Drawing to learn to represent in science: generating their own representations can deepen students' understanding of the specific conventions of representations (e.g. "this is how a line graph works") and their purposes (e.g. the effectiveness of line graphs for showing continuous quantitative information);

Drawing to reason in science: to show conceptual understanding, students must learn how to reason with multiple, often visual, modes;

Drawing as a learning strategy: drawing as a learning strategy can help students overcome limitations in presented material, organize their knowledge more effectively, and integrate new and existing understanding; ultimately, they can be transformative by generating new inferences;

Drawing to communicate: through drawing, students make their thinking explicit and specific, which leads to opportunities to exchange and clarify meanings between peers.

Quillin and Thomas (2015) provide a visual framework for the generative theory of drawing construction, as shown in Figure 1.20. This model demonstrates that a drawing may be an end-point, developed after the creation of a mental model, or a means to creating a mental model; thus creation of internal and external models can be linear or iterative.

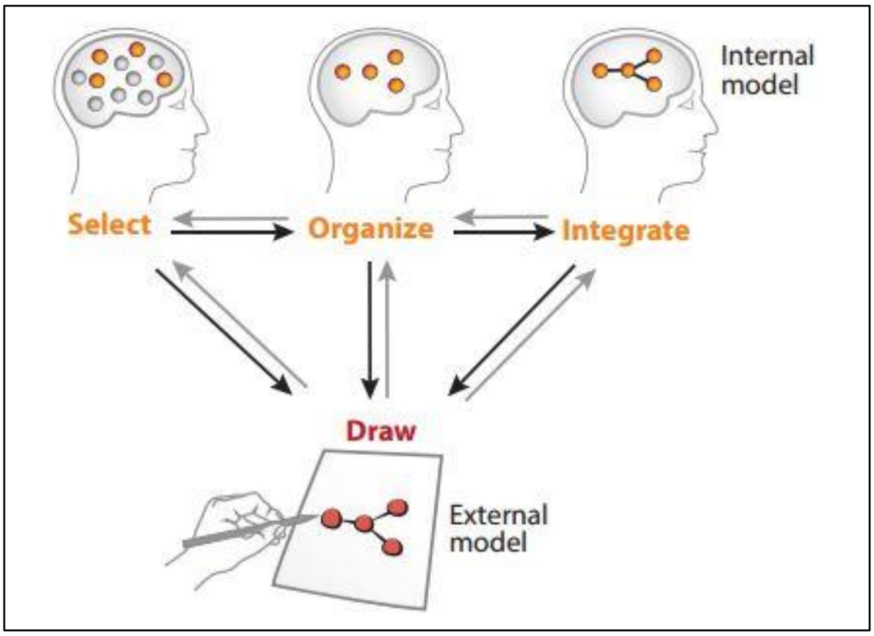


Figure 1.20: Framework for the generate theory of drawing construction (from Quillin and Thomas, 2015). In this model the circles represent verbal and/or visual information.

Quillin and Thomas do warn however, that an ability to draw effectively in one medium, for example, using pen and paper, does not necessarily mean an ability to draw equally effectively in another medium, for example, computer drawing software. The main barrier to this effective translation of skill is experience; thus, students need to be trained, not just in drawing, but in drawing in different media.

(c) Virtual Environments

There are three main types of virtual environments from which students can learn from: (i) animations, (ii) molecular modelling software and (iii) molecular modelling software with animation tool.

(i) Animations

In contrast to drawings, physical models and textbook illustrations, animations can show the dynamic, interactive and multi-particulate nature of chemical reactions explicitly (Tasker and Dalton, 2006). Students can benefit from the three-dimensional computer representations of chemical events and gain a better mental image of the course of a reaction (Fleming et al, 2000).

A computer animation is *'a series of visual images displayed in rapid succession on a computer screen, providing the illusion of motion'* (Burke et al, 1998)

Fleming et al (2000) investigated how computerized models can be useful in facilitating students understanding of chemical reactions and mechanisms, which have often been identified as the most difficult topics of organic chemistry for students. They designed computerised representations that showed a ball and stick perspective and the space filling representation. The goal of the animations was to '*facilitate visualisation and understanding* [of]*…electronegativity differences, bond polarisation, delocalisation of charges and partial charges….and electron distribution within* molecules' (Fleming et al, 2000, p.790). Being able to see molecular orbital interactions helps in understanding the electron flow in a reaction and why certain molecules react the way they do (Fleming et al, 2000).

Molecular Workbench provides a variety of real-time, interactive simulations of chemical phenomena by adding sets of rules describing chemical reactions to a molecular dynamics modelling system (Xie and Tinker, 2008). The goal of *Molecular Workbench* is to use advanced computational techniques and visualizations to help students develop appropriate mental models of different chemical systems and concepts. All simulations are calculated and displayed for a two-dimensional molecular dynamics model with the potential energy for forming molecules at 0 K taken as the sum of electronic energies for each bond and adjacent pair of bonds with the total potential energy the sum of two- and three- center terms. Added to the potential energy are terms for intermolecular forces for van der Waals, electrostatic, bond stretching, and bond angle bending. The software has the flexibility to allow users to set most initial parameters including the atoms, their positions, velocities, and bonds as well as all potential energies parameters. To simplify use, an initial simulation with preset values for these parameters is provided for each topic. Many topics allow users to add or subtract thermal energy and rerun the simulations.

Pallant and Tinker (2004) found that when students used *Molecular Workbench* they accurately recalled arrangements of the different states of matter, and could reason about atomic interactions. The results were independent of gender and they held for a number of different classroom contexts. Additionally, a close evaluation of students' responses about the bulk properties of atoms and molecules revealed that fewer students had misconceptions following the intervention as compared to their responses on the pre-test. Follow-up interviews indicated that students were able to transfer their understanding of phases of matter to new contexts, suggesting that the knowledge they had acquired was robust. Xie and Tinker (2004) claim their work with other simulation systems (Pallant and Tinker, 2004) indicates maximum learning occurs when students experiment with the simulations with some instructor guidance. Kozma and Russell (2005) suggest that instructors might ask students to determine if products will form if any one of the four activation energies is set to its upper limit with the other three set low, perform the simulations and explain what they observe.

Fleming et al (2000) identified how the use of computerised molecular animations not only has learning benefits for students beginning their study of organic chemistry by '*seeing the molecules undergoing the reactions in the ball and stick movie'* (p. 792) but can also aid advanced undergraduates to '*observe stereo-electronic effect….reaction reversibility and the role of orbital symmetry*' (p.792).

The *VisChem* project was funded to produce a suite of molecular animations depicting the structures of substances and selected chemical and physical changes (Tasker and Dalton, 2006). The work of Tasker and Dalton (2006) in the *VisChem* project indicates that animations and simulations can communicate many key features about the molecular level effectively, and these ideas can further link the laboratory macroscopic level to the symbolic level.

Tasker and Dalton (2006) identified specific learning benefits of computerised animations of molecules for students:

- Animations encourage a student with low prior knowledge to develop new ideas in long term memory to create their mental models;
- High prior knowledge in the long term memory allows a student to perceive subtle but relevant features in an animation enabling development of more sophisticated mental models;
- High prior knowledge also enables comparison of an image in working memory from viewing an animation, with an existing mental model in long term memory, leading to confirmation or modification of the existing mental models;
- High dis-embedding ability allows a student to perceive the desired key features in a 'busy' animation;
- High working memory space ensures a student is able to manage information from complex animations effectively, and construct and manipulate mental models of the phenomena;
- Adoption of deep-learning strategies and not surface learning approaches enables a student to relate 'key features' in animations to models in the long term memory for deep understanding

(Tasker and Dalton, 2006, p. 150)

Geelan et al (2014) investigated the effect of visualisations on students' conceptual development in seven Australian chemistry classrooms; a total of 129 students. Students completed one teaching sequence with and without the use of scientific visualisations in at least two of the following subject areas; Le Chatelier's Principle, Intermolecular Forces and Thermochemistry. One or two visualisations for each subject were chosen from free online sources, which were intended to model ways in which classroom teachers use visualisations. Students' conceptual development was measured using conceptual knowledge tests based on the Chemistry Concept Inventory (CCI) (Mulford and Robinson, 2002). The tests were designed to distinguish the extent to which students developed the 'correct' scientific concept in relation to a topic, rather than a number of possible 'misconceptions'. This study found no significant difference in students' conceptual understanding following the use of visualisations. It did, however, identify serious flaws in the visualisations used. This demonstrates that it is important for teachers to consider the type of visualisations used in their teaching.

With that in mind, Burke et al (1998) summarised some characteristics of effective instructional animation sequences:

- Short: 20-60 seconds per concept seem to work best;
- Accurate chemistry content;
- Option for accompanying text or audio narration explanation;
- Panel with pause forward, reverse and exit control buttons;
- Non-linear navigation;
- Addresses a misconception reported in the literature;
- Interactivity, decision making, and prediction incorporated for active learning;
- Appropriate assessment and feedback;
- Provides an opportunity to construct knowledge;
- Faculty testes, student tested and classroom tested. (Burke et al, p. 1658)

Viewing dynamic 3D animations can improve students' incomplete mental models of the dynamic nature of chemical reactions (Sanger and Badger, 2001). However, it has also been shown that engaging students in creating their own representations can be an effective instructional tool to foster their conceptual understanding and representational skills (Ainsworth et al, 2011; Gilbert, 2010). Thus, engaging students in molecular modelling software can be an effective tool to further aid students' mental models.

(ii) Molecular Modelling Software

Molecular modelling software enables students to interactively construct a range of models, such as ball-and-stick, space-filling, and electron density models, even for large molecules. Interactive modelling programs provide for the construction of molecules from atoms, measure bond lengths and angles for this structure, and manipulate and rotate the model to be viewed from different angles (Dori and Kabermann, 2012; Kozma and Russell, 2005).

Asking students to draw or visualise their conceptions can also help to probe their understanding (Cheng and Gilbert, 2009). There are a number of molecular modelling software programmes that can be incorporated into organic chemistry instruction for these purposes. Several free version are available online and will now be discussed.

As already discussed in Section 1.2.2, Dori and Kaberman (2012) assessed students modelling sub-skills following the use of a computerised molecular modelling (CMM) environment. The environment included two CMM software packages, which the students downloaded from the Internet: the ISIS/Draw from MDL (2000) and the WebLab Viewer from MSI (2000). The ISIS/Draw software enables students to construct molecules by determining the type and number of atoms and the covalent bonds between them according to the bonding rules. It is also possible to draw carbon chains, sugar rings and amino acid molecules, as well as to add different functional groups to the drawn molecules. After constructing the molecule, students are shown its three-dimensional structure. For example, given the formula of lactic acid, $CH_3CH(OH)COOH$, students are asked to construct the molecule using ISIS/Draw. They then view the molecule in 3D using WebLab Viewer (see Figure 1.21).

The software enables the transfer of the 2D drawing between three molecular representation forms (line, ball-and-stick and space-filling), the rotation of the molecules, and measuring bond length and angle size between different atoms (Barnea and Dori, 1999).

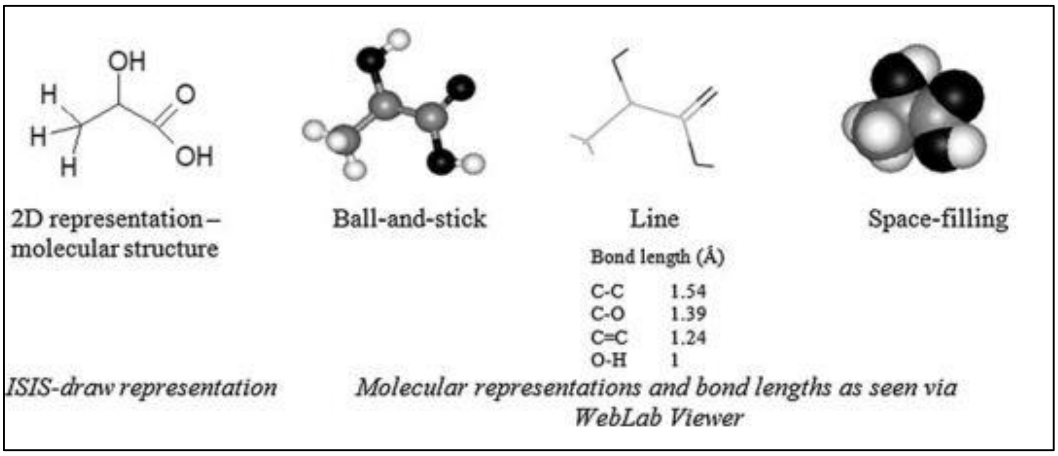


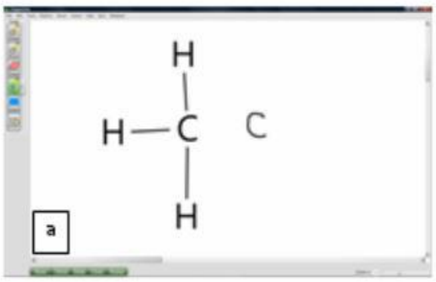
Figure 1.21: Four molecular representations of lactic acid in the CMM (Dori and Kaberman, 2012). The 2-D representation is created by students and it is then translated by WebLab Viewer into other types of representations

The assessment used in the study by Dori and Kabermann has been discussed in Section 1.2.2, see also Figure 1.18. Their pre/post-test design showed an improvement in students' overall modelling skills and performance in the assessment. Following learning through the CMM unit, approximately 80% of students were able to complete the transfer from molecular to structural formula and 3D model to structural formula of propylene glycol.

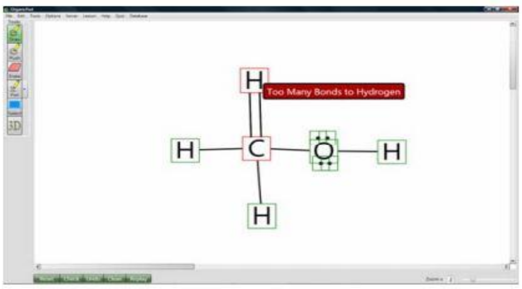
Wu et al (2001) reported similar improvements in translations by students, following the use of a computer-based visualisation tool called eChem. eChem provides three tasks: Construct, Visualize and Analyse. In Construct, students create organic molecular structures, view them from all possible angles, and manipulate them. In Visualize, students are provided with multiple views of different compounds and various representations such as ball-and-stick, wire-frame and space-fill simultaneously. In Analyse, students can make connections between molecular models at the microscopic level (molecular structures) and their collective behaviours at the macroscopic level (chemical and physical properties). This software provides students with direct training for creating structures, translating between different representations and using the structure to explain physical properties. Additionally, the analysis of interviews suggested that using eChem enabled students to reason with chemical representations either mentally or on a computer screen.

An element that the CMM and eChem are missing is the provision of immediate feedback to students on their success in drawing an accurate structure. An example of a programme which does this is OrganicPad. This is an interactive freehand drawing application for tablet PCs for drawing Lewis structures of organic molecules (Cooper et al, 2009). OrganicPad has a number of key features for its use as a teaching tool for organic chemistry; the Draw tool allows students to use the tablet PC stylus to draw atomic symbols, bonds, electron dots and charges and the software will recognise these and convert them to parts of the structure. This allows students to draw as they would on paper. In Figure 1.22 (a) the letter 'C' that has been drawn is about to be converted into a second carbon atom.

The Tutorial Mode allows students to receive individual feedback on the structures that they draw; by selecting the 'Check' button, their structures are compared against a series of rules that define valid Lewis structures. In instances where the students' drawing does not conform to these rules, OrganicPad flags the problematic areas of the structure and provides immediate feedback for students on how to fix it. An example of this can be seen in Figure 1.22 (b).



(a)



(b)

Figure 1.22: OrganicPad screenshots: (a) A hand-drawn C about to converted into a carbon atom (b) A structure which has been flagged by the 'Check' tool as containing an error

If students' structures are drawn correctly, the 3D tool will convert it into a 3D structure, see Figure 1.23. There are three 3D options for students to view; ball-and-stick, space filling and electrostatic potential map. Students can also rotate their molecule using this tool.

Figure 1.23: Example of ball and stick model from OrganicPad

The CMM, eChem and OrganicPad are all examples of molecular modelling software which have been shown to improve students' translation between representations and modelling sub-skills. However, this drawing of structures is a static process and does not address students' understanding of the dynamic processes which molecules undergo. Thus, molecular modelling software with additional animation tools have been created.

(iii) Drawing Tools with Animation

A drawing tool with animation function allows students to express their ideas or externalise their dynamic mental images about chemical processes (Chang et al, 2014). Chemation allows students to construct simple 2D molecular models and flip-book-style dynamic animations on handheld computers. Chemation has three types of objects: atoms (or particles), links, and labels. Objects are created using the toolbar which can be seen in the first frame of Figure 1.24. Flipbook-style animations are created through a simple process of copying and modifying frames, as shown in Figure 1.24. The frame is copied and can be slightly modified by adding, deleting or moving atoms and adding or deleting links. Continuing this process of copying and modifying frames creates a series of frames that can then be played back by clicking the "Play" button next to the label tool.

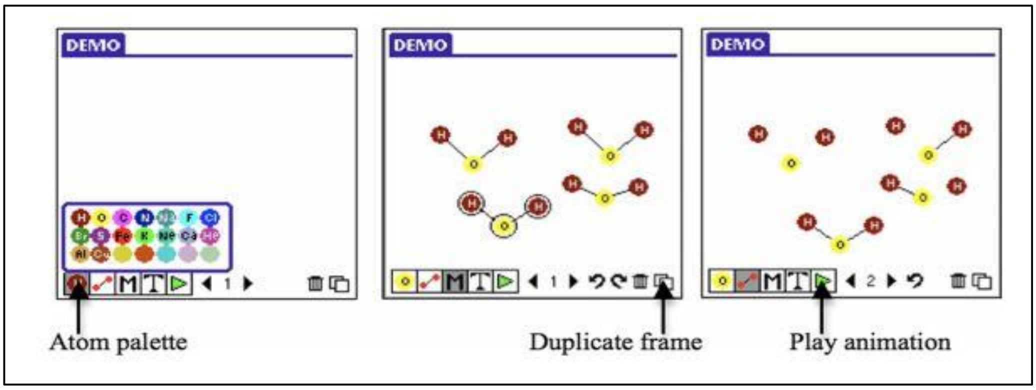


Figure 1.24: Examples of creating a flip-book style animation using Chemation

Chang et al (2014) used Chemation and think-aloud interviews to examine students' understanding of chemical reaction processes. Their study identified four types of connections that students made as they used Chemation, these are shown in Figure 1.25.

Chang et al (2014) compared students who were able to create dynamic visualisations with those who only created static visualisations; they found that students who were unable to generate dynamic visualisations were more likely to show incoherent understanding of chemical reaction processes. Their study had three key implications for assessment of student understanding:

- Engaging students in constructing visualisations can help to assess gaps in their conceptual understanding;
- Asking students to interpret the visualisation they generate can reveal how well they reconstruct their chemistry knowledge or what alternative conceptions they might have;
- Requiring students to visualize the intermediate process of a chemical reaction at the molecular level (i.e. the dynamic visualization of chemical reactions) can indicate how well they develop an integrated understanding of chemical reactions.

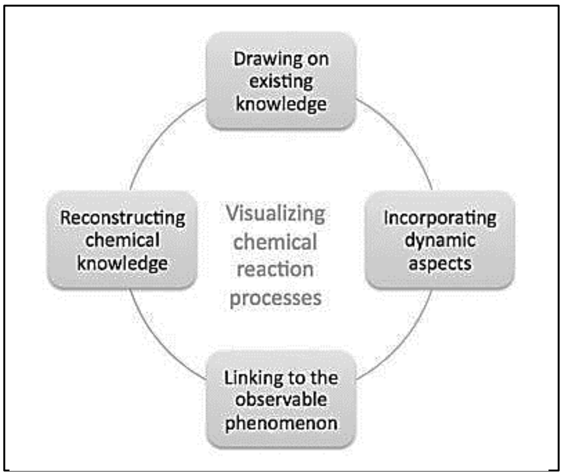


Figure 1.25: Four types of connections made around visualisations of chemical processes (from Chang et al, 2014)

Very similar to Chemation, the ChemSense Animator enables students to create drawings and animations of chemistry concepts (Schank and Kozma, 2002). Schank and Kozma found that enabling students to create ChemSense drawings and animations helped them to develop representational competence such as the ability to construct and use representations to think about and explain chemical phenomena (Kozma and Russell, 2005).

A key element of both ChemSense and Chemation is that there are no pre-constructed molecules from which to choose. This forces students to make critical design decisions as to how they are going to use these building blocks to represent the molecule and the phenomenon in their task: What atoms do I need? How many are there? What type of bonds are there? Which atoms are bonded? The ChemSense Animator has an advantage over Chemation, in that it can be used on any laptop/ PC while Chemation is made specifically for handheld devices.

While virtual molecular modelling has been shown to improve students' understanding and ability to translate between representations, teachers require an expertise in modelling and the particular software in order to facilitate this (Aksela and Lundell, 2008). Dori and Kaberman (2012) did note that their CMM included an additional element: well trained teachers.

While both physical and virtual models have shown to increase student understanding, studies have shown the largest gain to occur when both physical and virtual models are used. Dori and Barak (2001) recommend incorporating a combination of virtual and physical models in chemistry learning. Their study investigated the effect that teaching organic chemistry using virtual and physical models had on students' understanding of both new concepts and the spatial structure of new molecules. It was found that experimental students who worked with both physical and virtual models gained a better understanding of the model concept. These students were more capable of defining and implementing new concepts and were able to transfer between the different levels of understanding (symbolic, macroscopic and microscopic). Similar results were found by Copolo and Hounshell (1995) in the study of organic structures and isomerism. This study also showed that students who used both physical and virtual models had greater retention of information, indicating better storage in the long term memory

The studies discussed thus far have involved students actively engaging in the molecular modelling process through virtual environments. There is disagreement in the literature as to whether viewing 3D computer models of structures is enough, or if students need to actually interact with them. Stull et al (2012) found that students who simply viewed a 3D model but did not interact with it performed no better on a test to measure representational translation than students who did not see the models at all. Similar results were found by Barak and Hussein-Farraj (2013); students who did not learn via hands-on exploration of web-based models did not improve their ability to transfer across different modes of molecular representation.

Springer (2014) suggested that students may not necessarily need to perform specific manipulations themselves and that simply viewing the appropriate manipulations being performed by an instructor may be enough to improve understanding. Computer models were presented alongside standard 2D representations of organic structures in lectures of an introductory organic chemistry course for non-chemistry major undergraduates. Although in doing so the amount of information presented to the student increased, their study showed that viewing the appropriate rotational manipulations with a verbal explanation of how to interpret the models significantly improved a students' understanding of molecular structure.

This study was of pre/post-test design with both an experimental group, who received lectures with computer models and 2D representations and control group, who received lectures with just 2D representations. Although the experimental group students performed significantly better than the control group students on the post-test, it is unclear from this study *why* they benefitted from the experimental treatment; their study cannot say anything about *why* the experimental design was effective just that is was. The researcher suggested that it was possible to assume the experimental group students performed better on the post-test because they were better at performing mental representational translations; they could create 3D mental models from 2D images presented to them. However, without qualitative data, it is not possible to tell what the students were thinking.

An understanding of the particulate level, both the representations and the process which occur, is an important element of a students' success when studying organic chemistry. Whether physical or virtual, static or dynamic, particulate models and representations have been shown to be successful aids in developing students' conceptual understanding at a particulate level.

1.3.2 Conceptual Pedagogies

The aids which have been effective in helping students engage with molecular level and particulate representation have been discussed. Over the past 20 years, different approaches aimed improving students' engagement and conceptual understanding have been discussed in the literature. The approaches which have particular relevance to this study are a Social Constructivist Approach, Context-Based Learning and Phenomena-oriented Inquiry-Based Network Concept (PIN-Concept). These will now be discussed

(a) Social Constructivist Approach

According to Vygotsky, cognitive development is largely a social process and language plays an essential role in the organization of 'higher psychological functions' (Vygotsky, 1978). He maintained that language and action are equally important in development and that they are components of the same complex psychological function. Vygotsky believed that the most significant moment in intellectual development occurred '*when speech and practical activity, two completely independent lines of development, converge'* (1978, p. 24).

Vygotsky challenged the traditional 'static' testing used to predict children's ability to make progress in school learning. He developed what he called 'dynamic' testing to gain a deeper insight into the child's potential to learn which involves individual interviews between the child and a psychologist. The psychologist compares the child's unassisted responses with their final responses following a discussion about possible solutions to the test item. This gives an indication of the child's ability to learn. Vygotsky showed quantitatively that the information derived from this mode of testing lead to better predictions of children's progress in school learning over the next two years than the previously used 'static' tests did (Adey and Shayer, 1994).

Vygotsky believed that with help, a child could perform tasks which would normally be considered out of their mental capabilities. Thus, learning is a social construct.

Krajcik (1991) outlined the social constructivist model as shown in Figure 1.26. By this model, students only construct new information when they have to reconsider their current understanding. Students have to reconsider their understanding when asked to communicate it or when exposed to conflict situations that create dissatisfaction with their current views.

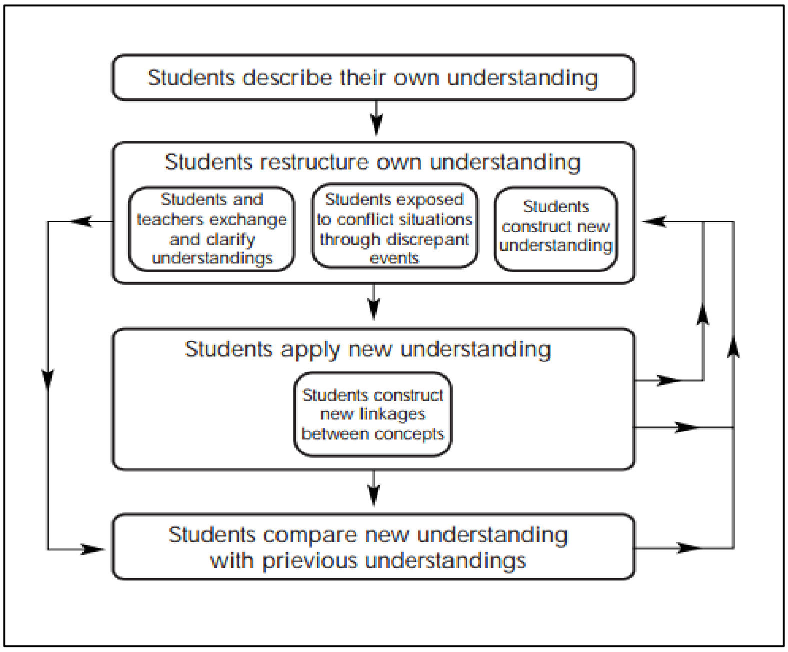


Figure 1.26: Model of social constructivism (from Krajcik, 1991).

Treagust et al (2003) provided a number of examples of student discourse being used to reinforce their understanding of the bonding structure of carbon and the general formula for an alkane and compare the symbols used to represent them (p. 1365).

The relevance of organic chemistry to a students' everyday life makes context-based learning a particularly pertinent pedagogy to the teaching of organic chemistry. The importance of linking the macroscopic and observable phenomena with processes at the particulate level to succeed in organic chemistry has already been discussed. Thus, the PIN Concept also has particular relevance to the teachinf of organic chemistry. These will now be discussed context based learning and the PIN-Concept.

(b) Context Based Learning

Students often find conventional chemistry curricula quite abstract, challenging to learn and unrelated to the world that they live in. As a result, students can become disconnected from the information that they are learning. A 'context-based' approach to teaching chemistry is where a topic is introduced by showing the students how the chemistry is relevant to today's world in research, industry, etc. Learning chemistry through context and applications helps students to make sense of the world around them and understand the relevance of what they are learning. Some chemistry curricula only 'tag on' applications of chemistry at the end of a chapter or topic '*with applications of chemistry only added as a footnote'* (Reid, 2000, p.381). Reid (2000) suggested many possible application areas: clothes, washing, dyeing, food and drink, cooking and cleaning, cosmetics and cleanliness, drugs and medicine, and colours. Of course, different applications will be more appropriate for different societies and cultures, which is something both teachers and curriculum developers need to be aware of.

The Salter's Advanced Chemistry Course (SAC) is a two-year course which leads to the A-Level examinations (aged 18) in the U.K. This course and examination has been nationally validated and qualifies candidates for third level courses. The examination consists of both written and practical elements. The main aims of the SAC are:

- To show the ways chemistry is used in the world and in the work that chemists do;
- To broaden the appeal of chemistry by showing how it relates to people's lives;
- To broaden the range of teaching and learning activities used;
- To provide a rigorous treatment of chemistry to stimulate and challenge a wider range of students, laying the foundations for future studies yet providing a satisfying course for those who will take the study of chemistry no further.

(Bennet and Lubben, 2006, p. 1003)

The SAC has three core resources: Chemical Storylines book, a Chemical Ideas book, and an Activities folder. The Storylines provide the "backbone" of the course, introducing the contexts within which chemical ideas and skills are developed. As students' progress through the stories, at pertinent points they are directed to sections of the Chemical Ideas book. The Chemical Ideas book is more like a standard textbook; it systematically draws together the chemical principles from the individual units and the different parts of the course.

A key element of the context-based approach in this course is that scientific ideas are introduced on a "need to know" basis. In other words, the science ideas are used when they are needed to help develop understanding of features of the particular context being studied.

Because students taking the SAC course undertake a different examination to those following more conventional A-Level courses, direct comparisons of achievement are not possible. However, students involved in the SAC course reported greater enjoyment and interest in what they were learning (Reid, 2000, Bennet and Lubben, 2006). A greater proportion of SAC students go on to study chemistry or chemistry-related courses at University (Bennet and Lubben, 2006).

Following the ideas of the Salter's course, 'Chemie im Kontext' (ChiK) is a context-based chemistry curriculum which has been developed in Germany by chemistry teachers, school authorities and science educators for all grades and types of schools. ChiK links three conceptual principles with a four-phase lesson structure. The three contextual principles are:

Context orientation: introducing topics using personally or socially relevant topics, e.g.: hydrogen fuel cell cars;

Cross-linking knowledge to basic concepts: offers students a structure for the systematic and cumulative development of knowledge and understanding;

Methodological diversity: more active role of the students.

The four phases of the lesson structure are:

1. Contact Phase: students become familiar with the new context;
2. Curiosity and Planning Phase: students participate in planning and structuring future work;
3. Elaboration Phase: Independent student activity supported by the teacher as little as possible;
4. Final Phase: freshly acquired chemical subject knowledge is extracted from the original context and applied to new contexts.

(Parchmann et al, 2006)

Similar to the SAC, students taking part in the ChiK curriculum have been shown to have improved motivation (Parchmann et al, 2006)

(c) Phenomena-oriented Inquiry-Based Network Concept (PIN-Concept)

The PIN-Concept programme for teaching organic chemistry in universities and second level grammar schools in Germany (Barke et al, 2012) places a focus on the macroscopic before the sub-microscopic.

An example of an experiment from this approach can be seen in Figure 1.27. Homologous alcohols are mixed with water in petri dishes on an overhead projector. The purpose of the demonstration is to visualise the graded water solubility of homologous alcohols. A graded movement during the solution process can be observed for the short-chained alcohols while the long-chained alcohols are 'sluggish' to move. This is due to the difference in water solubility. Students view this demonstration and then have to explain their observations (macroscopic) using what they know about the structures of the alcohols (molecular/sub-microscopic).

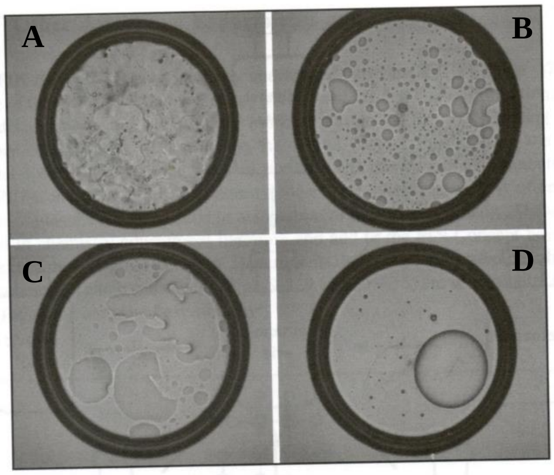


Figure 1.27: Mixing alcohols with water (PIN-Concept). A = butanol, B = pentanol, C = hexanol, D = octanol

The PIN-Concept has been shown to be 'motivating and effective' for trainee teachers and chemistry classes aged 16-17 years of age (Barke et al, 2012).

1.4 Summary

This chapter has addressed the inter-linked difficulties which students experience when studying organic chemistry and has discussed the possible reasons for these difficulties using theories of learning. Methods of addressing these difficulties using aids and pedagogies have also been examined. The findings from this chapter will inform the development of the OCV approach and resources. In the next chapter, organic chemistry will be placed within the context of the Irish Senior Cycle education system.

Chapter 2

The Irish Education System and Organic Chemistry

Chapter 1 addressed the range of difficulties that students may experience when studying organic chemistry, reasons why these occur and what has been done by researchers and educators to address these. Students in Ireland will first meet organic chemistry if they chose to study chemistry as part of the Senior Cycle at second level. Both the senior cycle as a whole and the chemistry curriculum have come under criticism in recent years and are currently undergoing review. This chapter will outline these criticisms and new developments which are currently being undertaken. The link between learning outcomes and assessment will be established within senior cycle chemistry and the cognitive demand of current LC organic chemistry questions will be identified. International comparisons will also be made.

2.1 Senior Cycle in Ireland

At the end of their second level education, the LC is the set of final exams taken by students in Ireland. From 16-17 years of age, follow the LC senior cycle, over 2 years and take 6-7 subjects. Points are allocated to students based on the grades received in these exams and these points determine students' entry into third level courses. In 2015, 2014 and 2013 the numbers of students sitting the LC were 55,044, 54,025 and 52,767, respectively. This year, 56,595 students sat the LC exams (SEC, 2016).

2.1.1 Senior Cycle Chemistry

The number of students studying chemistry at LC level is relatively small, only 15-16% of the cohort. Of the three main science subjects at LC (physics, chemistry and biology), biology has remained the most popular with 33,865 students taking the subject in 2015, compared to 8,938 taking chemistry and 7,508 taking physics (SEC 2015)

Trends of LC performances in chemistry over the last three years are shown in Table 2.1. The percentage of LC students taking chemistry is shown as % Total, with % HL as the percentage of students taking Higher Level (HL). The % Hons in HL is the percentage of these students achieving an Honours grade (Hons), A1-C3. The percentages of students achieving each of the honours grades are also shown (%A1-%C3).

It is noteworthy that there are small changes from year to year but the pattern remains similar. Over 80% of those students who take chemistry are taking the higher level paper. Of these students taking the higher level paper, over 70% are achieving an honours grade and almost 20% achieving A grades. These figures give an indication of the type of student taking chemistry for Leaving Certificate. The perception of chemistry as a difficult subject appears to have resulted in only 'good' students who are capable of achieving high grades taking the subject and they are taking it at higher level.

Table 2.1: Performances in Leaving Certificate Chemistry in 2015, 2014 and 2013

	2015	2014	2013
% Total	16.24	15.93	15.46
% HL	84.28	83.98	82.85
% Hons in HL	73.5	72.8	73.5
% A1	12.8	9.7	9.6
% A2	9.2	10.9	10.9
% B1	10.2	10.6	8.2
% B2	9.1	9.5	9.7
% B3	9.1	9	10
% C1	7.8	7.8	8.3
% C2	8	7.5	7.9
% C3	7.3	7.8	8.9

2.1.2 Chemistry Curriculum Change

The current LC chemistry syllabus has been in place since 2000 and was first examined in 2002. The vision for this new curriculum was to allow for a better balance between knowledge and skills in the educational experience of senior cycle students, and the promotion of the kinds of learning strategies associated with participation in the knowledge society (Walshe, 2015). The stated objectives of this syllabus are shown in Figure 2.1. The main changes that this syllabus brought to LC chemistry were a move towards a practical assessment, an emphasis on basic analytical instrumentation and an emphasis on the relevant social and applied aspects of chemistry.

Higher Level Syllabus Objectives

The objectives of the syllabus are:

1. Knowledge

Students should have a knowledge of

- basic chemical terminology, facts, principles and methods
- scientific theories and their limitations
- social, historical, environmental, technological and economic aspects of chemistry.

2. Understanding

Students should understand

- how chemistry relates to everyday life
- scientific information in verbal, graphical and mathematical form
- basic chemical principles
- how chemical problems can be solved
- how the scientific method applies to chemistry.

3. Skills

Students should be able to

- follow instructions given in a suitable form
- perform experiments safely and co-operatively
- select and manipulate suitable apparatus to perform specified tasks
- make accurate observations and measurements
- interpret experimental data and assess the accuracy of experimental results.

4. Competence

Students should be able to

- translate scientific information in verbal, graphical and mathematical form
- organise chemical ideas and statements and write clearly about chemical concepts and theories
- report experimental procedures and results in a concise, accurate and comprehensible manner
- explain both familiar and unfamiliar phenomena by applying known laws and principles
- use chemical facts and principles to make chemical predictions
- perform simple chemical calculations
- identify public issues and misconceptions relating to chemistry and analyse them critically.

5. Attitudes

Students should appreciate

- advances in chemistry and their influence on our lives
- that the understanding of chemistry contributes to the social and economic development of society
- the range of vocational opportunities that use chemistry, and how chemists work.

Figure 2.1: Objectives of Higher Level Chemistry Syllabus (NCCA, 1999)

A number of mandatory experiments (28) are specified in the current syllabus, which are divided between all sections of the syllabus. A note on assessment at the beginning of the syllabus can be found in Figure 2.2. The written assessment of the practical work takes the form of Section A on the LC chemistry exam. Section A contains 3 questions which are all based entirely on the mandatory experiments. One question assesses volumetric analysis, one assesses organic chemistry and the other can be from any of the other experiments on the syllabus.

Assessment

The syllabus will be assessed in relation to its objectives. All material within the syllabus is examinable. Practical work is an integral part of the study of chemistry; it will initially be assessed through the medium of the written examination paper. An element of the practical assessment may be included as part of the overall assessment at a later stage.

Figure 2.2: Note on assessment in Leaving Certificate Chemistry syllabus (DES, 1999; p. 3)

The inclusion of basic analytical instrumentation demonstrated the move towards real-life applications of chemistry. The instrumentation included mass spectrometry, thin layer chromatography (TLC), gas chromatography (GC) and high performance liquid chromatography (HPLC) with an emphasis on forensic work as a practical application.

The social and applied aspects of chemistry amount to 30% of the syllabus and are specifically highlighted in this syllabus using a separate column. An example is shown in Figure 2.3.

Content	Depth of Treatment	Activities	Social and Applied Aspects
5.6 Other Chemical Fuels (Time needed: 3 class periods)	Ethyne: preparation, combustion, tests for unsaturation	Mandatory experiment 5.2 (equations and structures of products not required for the tests for unsaturation	Oxyacetylene welding and cutting

Figure 2.3: Social and Applied Aspects of chemistry are detailed in their own column of the syllabus (DES, 1999).

Despite these intended changes in senior cycle chemistry, the Senior Cycle itself and the LC chemistry syllabus have come under criticism.

2.1.3 Criticisms of Senior Cycle in Ireland

The Leaving Certificate process itself has come under criticism in recent years (Walshe, 2015). The report *Commission on the Points System: final report and recommendations* (Ireland, 1999) suggested that a substantial review of the LC as an educational programme was overdue. It recommended that this review be fundamental, addressing matters such as the nature of the senior cycle experience, issues of narrow curricula and assessment approaches, and the establishing of provisions that would contribute to social cohesion. It highlighted several key reasons for the need for reform of the LC, including the points system and the adverse effects of students' experiences during the senior cycle.

(a) The Points System

The LC examination supports the selection process for entry into further and third level education, known as the 'points system'. This was developed and run by the Central Applications Office (CAO). The CAO allocates points to students based on the grades they achieve in the LC examination. Places within higher education institutes are allocated based on points achieved; the point allocations have been collectively agreed by the third-level institutions involved in the CAO scheme.

The points system has now turned into a 'points-race' for places in third level education. This has resulted in the development of a grinds-school culture, where the focus of teaching has shifted to preparing for the LC examinations and attaining as many points as possible. Students are often provided with notes which summarise 'what is needed for the examination' and 'predictions' of what topics are going to be examined based on previous years' examinations; in some cases, this results in very little practical work being carried out and some sections of the curricula being left out.

(b) Experiences of LC Students

The ESRI research report, From LC to Leaving School: A Longitudinal Study of Sixth Year Students (Smyth et al, 2011) reported that the current LC model impacts significantly on teaching and learning in sixth year and earlier years. Key findings from these reports show that the current LC model tends to narrow the range of student learning experiences and to focus both teachers and students on covering the course. Sixth year students also report teacher-centred classes, which focus on practicing previous exam papers with very heavy workload.

Many students contrast what happens in their classes with the kinds of active learning which engage them. Others, especially high-aspiring students, become more tactical, focusing on what is likely to come up on the exam paper, and expressing frustration with teachers who do not focus on exam preparation. Almost half of sixth year students take private tuition (grinds) to prepare for the exam.

A consultation with fifty 5th and 6th year students identified the perceptions held by students of the LC (McEvoy, 2013). Students viewed the system as one that is entirely exam-focused rather than focused on learning or knowledge and dominated and driven by a tactical and competitive points game and CAO process. Students identified the imposition of a rote-learning system that stunted creative learning and teaching and made the transition from second to third level difficult. They also felt the heavy curriculum resulted in time-pressured teaching and cramming of material.

The system has resulted in students making subject choices based on what is easier to rote learn and making career choices based on points rather than what they are passionate about (Hyland, 2013). This rote learning results in a lack of development in skills that students should be learning before they leave second level education and move into third level education. This lack of skill development has also been a topic of criticism of senior cycle chemistry.

2.1.4 Criticisms of Senior Cycle Chemistry

Despite the note at the beginning of the syllabus regarding assessment, see Figure 2.2, and the heavy emphasis of mandatory experiments both in the exam and in the syllabus, there has been no development of a practical assessment for senior cycle chemistry. Thus the skills identified as part of the aims of the syllabus are not assessed and there is no need for students to actually perform the practical work at all; as long as they can learn the theory relating to each experiment and answer exam questions related to them, there is no requirement for practising practical skills.

Along with a lack of skill support and development within senior cycle chemistry, the questions asked in the examination have been shown to be of lower order and not cognitively demanding. McCrudden (2009) applied Bloom's Taxonomy to questions on the LC Chemistry exam between the years of 2000 and 2008 to determine the percentage that were higher and lower order questions. Bloom's Taxonomy categorises cognitive objects into six areas of increasing complexity and higher learning skills; knowledge (K), comprehension (C), application (Ap), analysis (A), synthesis (S) and evaluation (E). These categories can be used to identify the level of questioning employed, the type of skill a student must possess in order to correctly answer a question and thus, the cognitive demand of a question.

The first three categories; knowledge, comprehension and application are grouped as lower order questions. Knowledge is the most basic level and requires recall or the ability to state a fact without any need to understand what it means, e.g. definitions. Comprehension requires students to display an understanding beyond simply stating facts. Application is where students use their accumulated knowledge of concepts to solve problems on an analytical basis.

Higher order questions, categorised as analysis, synthesis and evaluation, require more critical thinking and skill. Analysis requires students to break down a complex idea, evaluate it critically and formulate an answer. Synthesis involves students making predictions and identifying links between difference concepts and ideas. Evaluation, the category of highest cognitive demand, requires students to make judgements about the quality of ideas or solutions to problems.

McCrudden (2009) categorised the questions on the LC chemistry exams by the verb used. The rubric for this is presented in Table 2.2. Using this rubric, it was found that the majority of questions (between 74% and 82%) on each of the examination papers from 2000 to 2008 were of lower order; knowledge, comprehension or application. No questions were identified as synthesis or evaluation. The only higher order questions that appeared on any of the papers analysed were of analysis type, with the percentage of these questions varying from 17-20%.

Table 2.2: Rubric for question analysis according to Bloom's Taxonomy (from McCrudden, 2009)

Knowledge		**Comprehension**		**Application**	
Tell List Relate Define Recall	Label Select Locate Find State Name	Explain Estimate Interpret Outline Discuss Identify	Distinguish Predict Restate Translate Describe Explain Draw	Solve Show Use Write Demonstrate Give	Illustrate Construct Complete Examine Classify
Analysis		**Synthesis**		**Evaluation**	
Analyse Distinguish Compare Contrast Investigate Categorise	Separate Calculate Diagrams Differentiate Advertise Devise	Create Invent Compose Plan Construct Design	Imagine Propose Formulate Compile Relate Summarise	Choose Decide Debate Prioritise Critique	Verify Argue Recommend Assess Rate Evaluate

Assessment drives teaching and learning. Examinations need to be less predictable and more diverse; include more 'why' questions that assess understanding as opposed to questions based on students' ability to recall and memorise material without an understanding, which are typical of the LC chemistry examination. The inclusion of higher order questions is important to examine students' understanding of a topic and their ability to apply their understanding to new situations, however, state examinations are dominated by lower order questions (McCrudden, 2009).

Another criticism of the current chemistry syllabus is the narrow and limiting learning outcomes that are specified. These will be discussed further in Section 2.2.1. Following the criticisms of the current senior cycle and the individual subject syllabi, consultation has been undertaken by the NCCA in recent years. New developments in the senior cycle itself and the individual syllabi are currently ongoing.

2.1.5 New Developments in Senior Cycle

Following an extensive consultation during the early part of the 2000s the NCCA set out its overview of a 'new' senior cycle, informed by a vision of creative, confident and actively involved young people who are prepared for the future of learning in Towards Learning: an overview of Senior Cycle Education (NCCA, 2009c). Within this, five key skills have been identified as being essential for all senior cycle learners to develop at this stage of their education: information processing, being personally effective, communicating, critical and creative thinking and working with others, see Figure 2.4 below.

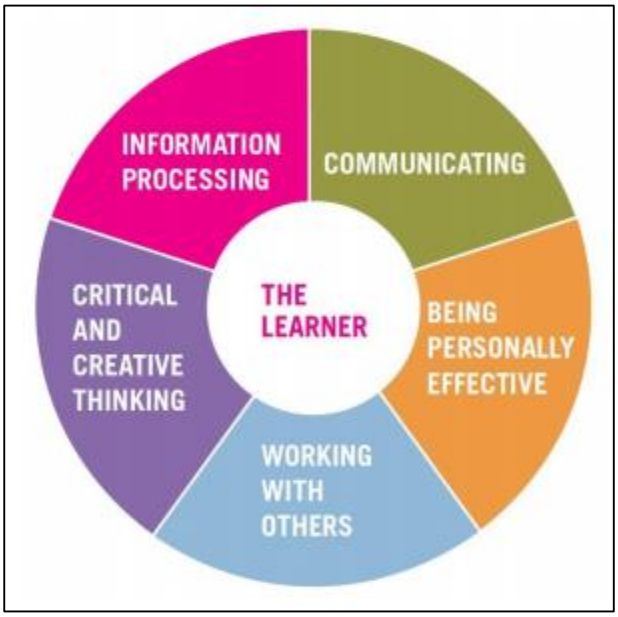


Figure 2.4: Key Skills Framework (NCCA, 2009)

Information processing involves students developing the specific skills of accessing, selecting, evaluating and recording information. An appreciation of the differences between information and knowledge and the roles that both play in making decisions and judgements is required.

By **being personally aware**, students become more self-aware and use this awareness to develop life plans and personal goals. Students are given specific strategies related to self-appraisal, goal setting and action planning. Students also require an appreciation of how to get things done, how to collect and use resources effectively and how to act autonomously according to personal values.

Communication is central to human relationships of all kinds and students will gain an appreciation of this. Students will become better communicators under both formal and informal conditions, using a variety of media while gaining competence and confidence in literacy.

To develop **critical and creative thinking,** students will develop an awareness of different forms and patterns of thinking. This will enable them to become more skilled in higher order reasoning and problem-solving.

Working with others is an important skill for all students. Students will gain an appreciation of group dynamics and the social skills needed to engage in collaborative work, while recognising the need for group work to enable social cohesion.

Taking these key skills into account, the individual science curricula (Chemistry, Physics and Biology) are also currently undergoing a revision, with a renewed emphasis on the need for a practical element of assessment (Walshe, 2015) and the development of these key skills.

2.2 Organic Chemistry in Senior Cycle Chemistry

In total, organic chemistry accounts for almost one quarter of the LC chemistry examination paper. At least one of the practical questions in Section A assesses an organic chemistry practical. There are usually two full questions on the paper in Section B dedicated to Organic Chemistry. One of these questions assesses fuels and thermochemistry, while the other usually focuses on reaction types and mechanisms. This gives a minimum of three questions on organic chemistry out of a total of 11 questions, where eight have to be answered. Questions 10 and 11 sometimes also include organic chemistry topics.

Organic chemistry is found in two sections of the current LC chemistry syllabus; Section 5: Fuels and Heats of Reaction and Section 7: Organic Chemistry. The class periods recommended by the DES (1999) to teach the total LC chemistry syllabus is 270 class periods of 40 minutes. Combining all class periods recommended for Section 5 and Section 7, organic chemistry requires approximately 23% of the class periods at HL and approximately 18% of the class periods at ordinary level.

There are eight mandatory experiments stated for organic chemistry:

5.2 Preparation and properties of ethyne;

7.1 Recrystallisation of benzoic acid and determination of its melting point;

7.2 Preparation of soap;

7.3 Preparation and properties of ethane;

7.4 Preparation and properties of ethanol;

7.5 Preparation and properties of ethanoic acid;

7.6 Extraction of clove oil from cloves by steam distillation;

7.7 Separation of a mixture of indicators using paper chromatography or thin-layer chromatography or column chromatography. (DES, 1999)

The SEC publishes a Chief Examiner's report on the chemistry exams every three years. The reports from 2002, 2005, 2008 and 2013 identify the organic question in Section A (practical question) as the least popular (SEC 2002, 2005, 2008, 2013). The Chief Examiner's reports in 2002, 2005 and 2008 have recognised a tendency for candidates to avoid organic chemistry questions, even though in doing so, their choice on the examination paper is severely restricted. In 2005, there were three and a half questions on organic chemistry topics and these were amongst the least popular questions on the examination. In general, when these questions were attempted, they were either well answered or poorly answered, with few candidates occupying a middle ground (SEC, 2005). The report in 2008 recognised an improvement in the number and quality of attempts at questions on organic chemistry, although they still had 'mixed popularity' (SEC, 2008). This improvement appeared to increase in 2013, although the report stated that organic mechanisms at higher level continue to be poorly answered (SEC, 2013).

While there appears to have been an increase in the number and quality of attempts at organic chemistry questions since the current LC Chemistry syllabus came into effect in 1999, organic chemistry questions remain some of the least popular and poorly attempted questions in the examination at both HL and ordinary level. Indeed, a study by Childs and O'Dwyer (2011) found that many students studying LC chemistry identified the organic chemistry section as the most difficult section on the course.

2.2.1 Learning Outcomes and Assessment

Another factor which contributes to the grinds-school culture in Ireland, particularly with organic chemistry, is the rigid prescription of the molecules which students must study; because there is a maximum number of compounds which students could be presented with, students need to simply 'learn off' the molecules instead of understanding them.

In both organic sections, Section 5 and Section 7, the learning outcomes clearly prescribe the compunds which students are required to study. For example, the depth of treatment of Section 5.2 Structure of Aliphatic Compounds states:

> *'Alkanes, alkenes and alkynes as homologous series. For alkynes, only ethyne to be considered. Systematic names, structural formulas and structural isomers of alkanes to C-5. Structures, but not isomers, of hexane, heptane, octane, cyclohexane and 2,2,4- trimethylpentane (iso-octane) to be considered. Systematic names, structural formulas and structural isomers of alkenes to C-4.'* (DES, 1999)

Similarly, in Section 7 Organic Chemical Reaction Types, specific reactions are specified for each reaction type, for example, under addition reactions:

> *Alkenes – reactions with hydrogen, chlorine, bromine, water and hydrogen chloride.*
>
> *Mechanisms of ionic addition (addition of HCl, Br_2, $C1_2$, only to ethene)*
>
> *Evidence for this mechanism: reaction of ethene with bromine water containing sodium chloride results in the formation of 2-bromoethanol, 1-bromo-2-chloroethane and 1,2-dibromoethane.*
>
> *Polymerisation reaction (of ethene and propene only – reaction mechanism not required).*
>
> *Unreactivity of benzene with regard to addition reactions, relative to ethene.* (DES, 1999)

The rigidity of the learning outcomes specified in the syllabus is far too limiting and has reduced the range of questions which can be asked in the LC examinations. Critics of the current model of curriculum and assessment argue that the under-development of critical skills and the narrow range of assessment methods leads to a reductionist approach to learning (Hyland, 2011).

Walshe (2015) designed a '3-axis scale of assessment item demand' framework for determining the cognitive demand of assessment questions. This framework comprises of three dimensions on which assessment items are ranked; assessment dimension, cognitive process dimension, and knowledge dimension.

The assessment dimension identifies the type of assessment being used, i.e. if students are being asked to demonstrate knowledge or analyse information. It is divided into four categories: (i) knowledge and understanding of facts, principles, concepts, and methods; (ii) application of knowledge to familiar and unseen contexts; (iii) manipulation, analysis and evaluation of data and (iv) use of arguments based on evidence.

The knowledge dimension identifies the type of knowledge required by the student: factual, conceptual, procedural or metacognitive. Factual knowledge refers to the basic elements students must know to be familiar with a topic, for example; terminology, symbols and sources of information. Conceptual knowledge refers to the interrelationships among the basic elements within a larger structure that enable them to function together; for example, classifications and categories, theories and models. Procedural knowledge is knowledge of how to do something and is generally subject-specific, i.e. techniques and methods for solving problems. Finally, metacognitive knowledge is knowledge of cognition as well as awareness and knowledge of one's cognition.

The cognitive process dimension identifies the intended cognitive process of a question and is based on Bloom's Taxonomy; the lowest cognitive processes being 'remember' and 'understand' and the highest being 'evaluate' and 'create'.

Each task within a question is treated separately. The coding used for each dimension can be found in Figure 2.5. The higher the number on the scale, the more complex the task.

Walshe (2015) applied this framework to a typical organic chemistry question found on the LC chemistry examination, as shown in Question X, Figure 2.6.

This question was considered a difficult question in the LC examination. However, when this framework is applied to Question X, it is not cognitively demanding.

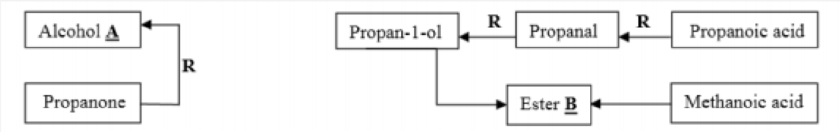
Figure 2.7 shows the task value assigned to each of the three scales. As can be seen, all parts of the question are ranked very close to the bottom of each scale. The majority of the parts of this question (6 out of 9) are ranked on the ‘remember’ level of the cognitive process dimension scale, the ‘factual’ level of the knowledge dimension scale and the ‘knowledge and understanding of facts, principles, concepts and methods’ of the assessment criteria scale. Thus, six out of nine parts of this question are of the lowest level possible in all three scales.

Assessment Criteria – written examination	Point on scale
Knowledge and understanding of facts principles concepts and methods	1
Application of knowledge to familiar and unseen contexts	2
Manipulation, analysis and evaluation of data	3
Use of arguments based on evidence	4
Knowledge Dimension	
Factual	1
Conceptual	2
Procedural	3
Metacognitive	4
Cognitive Process Dimension	
Remember	1
Understand	2
Apply	3
Analyse	4
Evaluate	5
Create	6

Figure 2.5: Coding of each scale of framework (from Walshe, 2015)

QUESTION X

Study the reaction scheme and answer the questions that follow.



i) Give the systematic (IUPAC) name for (i) the alcohol **A**, (ii) the ester **B**.

ii) Alcohol A and propan-1-ol are structural isomers. Explain the underlined term

iii) What is the structural difference between a primary alcohol and a secondary alcohol?

iv) Identify another pair of structural isomers from the reaction scheme.

v) Identify a compound in the scheme whose carbon atoms are all in tetrahedral geometry.

vi) Name the reagent and catalyst used to bring about the conversions labelled **R**.

vii) Propanol is oxidised by Fehling's reagent. Describe how this reaction is carried out.

viii) Why does propane not react with Fehling's reagent?

ix) Which compound in the scheme would you expect to have a fruity odour?

Figure 2.6: Typical question from LC organic chemistry question (higher level)

	Question	A	K	C
A i)	Give the IUPAC name	1	1	1
A ii)	Explain the underlined terms	1	1	1
A(iii)	What is the structural difference	1	2	2
	Identify another pair of structural isomers	2	2	2
	Level A	2	2	2
B(i)	Identify a compound with tetrahedral carbons	2	2	2
B (ii)	Name the reagent	1	1	1
B (iii)	Describe the oxidation reaction	1	1	1
B(iv)	Why does propanone not react with Fehling's reagent	1	1	1
B(v)	Which compound has a fruity odour	1	2	1
	Level B	2	2	2

Figure 2.7: Analysis of Question X by Walshe (2015)

The low cognitive demand of this question is typical of organic chemistry questions in the LC and places an emphasis on information that can be simply rote-learned and reproduced. This is consistent with the study by McCrudden (2009) who identified the lack of higher-order questioning across the whole of chemistry exams in the LC. There is no evidence of skill development or assessment of conceptual understanding.

The link between learning outcomes in syllabi and assessment has been well established and is evident in international contexts.

2.2.2 International Comparison

Having discussed the link between the narrow learning outcomes and the limited exam questions in LC chemistry, international syllabi and examinations will now be examined. Two countries have been selected for their broader learning outcomes and assessment of organic chemistry: (a) New South Wales, Australia and (b) Scotland. This section is not intended to be a complete overview of syllabi and high-stakes examinations but is intended to simply highlight different assessment practises for organic chemistry.

(a) New South Wales, Australia

The exit examination in New South Wales (NSW) is the Higher School Certificate (HSC). There are two years of study leading to the HSC examination, comprising a preliminary course and a Higher School Certificate (HSC). The preliminary course comprises 4 units of study: The Chemical Earth; Metals; Water; Energy. The HSC is comprised of three units: Production of Materials; The Acidic Environment; Chemical Monitoring and Management; and one option chosen from: Industrial Chemistry; Shipwrecks, Corrosion and Conservation; The Biochemistry of Movement; The Chemistry of Art; Forensic Chemistry (Board of Studies NSW, 2002). The learning outcomes of the NSW chemistry syllabus range from broad to narrow, an example of this range is found in the unit The Acidic Environment when addressing esterification. Some learning outcomes are quite prescriptive:

'describe the differences between the alkanol and alkanoic acid functional groups in carbon compounds'

'identify the IUPAC nomenclature for describing the esters produced by reactions of straight-chained alkanoic acids from C1 to C8 and straight-chained primary alkanols from C1 to C8'

Meanwhile other learning outcomes are left broad:

'outline some examples of the occurrence, production and uses of esters'

'explain the difference in melting point and boiling point caused by straight-chained alkanoic acid and straight-chained primary alkanol structures'

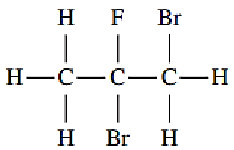
Despite a combination of broad and narrow learning outcomes, the learning outcomes are dominated by verbs which fall under the categories of comprehension and application by Bloom's Taxonomy. This is then reflected in the types of questions asked in the HSC exam. Three questions from the 2014 HSC Chemistry exam are shown in Figure 2.8.

The first question in Figure 2.8 asks students to name a given organic structure. While students' abilities to read the information in the given structure is tested, this would classify as a knowledge question by Bloom's Taxonomy.

In the second question students have to recognise a particular reaction type, which falls under the Comprehension category of Bloom's Taxonomy. The third question is composed of two parts, beginning with 'name' and 'describe', which fall under the 'knowledge' and 'comprehension' category of Bloom's Taxonomy respectively.

Examination of the NSW HSC chemistry syllabus and examinations demonstrates another influence of learning outcomes on exam questions; if the learning outcomes focus on a particular level of Bloom's Taxonomy, then the exam questions are likely to follow suit.

1 What is the IUPAC name of the following compound?



(A) 1,2-dibromo-2-fluoropropane

(B) 2,3-dibromo-2-fluoropropane

(C) 2-fluoro-2,3-dibromopropane

(D) 2-fluoro-1,2-dibromopropane

2 Which row of the table correctly matches the reactant and the product of an *addition reaction*?

	Reactant	*Product*
(A)	$CH_3-CH_2-CH_2-CH_2-OH$	$CH_3-CH_2-CH=CH_2$
(B)	$CH_3-CH_2-CH_2-CH(OH)-CH_3$	$CH_3-CH_2-CH=CH-CH_3$
(C)	$CH_3-CH=CH-CH_2-CH_3$	$CH_3-CH_2-CH(Cl)-CH_2-CH_3$
(D)	$CH_3-C(=O)-OH$	$CH_3-C(=O)-O-CH_3$

3 A first-hand investigation to produce an ester is to be carried out in a school laboratory, using an alkanol, an alkanoic acid and a suitable catalyst.

(a) Name an ester that could be produced in a school laboratory.

....

(b) Describe how potential hazards associated with the three chemicals required for this investigation could be addressed.

Figure 2.8: Example questions from HSC examination (Board of Studies NSW, 2014)

(b) Scotland

The main university entrance qualifications in Scotland are the ‘Highers’, offered by the Scottish Qualification Authority (SQA). Students sitting the Highers are typically 16-17 years of age. The Curriculum for Excellence is the national curriculum for Scottish schools for students from age 3 to 18. It was developed out of a consultation in 2002 (SQA, 2014).

The Curriculum for Excellence Higher Chemistry course covers 4 units to be completed over 2 years (S5 and S6): Chemical Changes and Structure; Nature’s Chemistry; Chemistry in Society and Researching Chemistry. Unit assessment is assessed by end of unit tests set by the SQA. A pass for each unit is required before candidates are presented for the final exam.

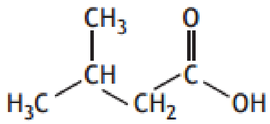
Course Assessment consists of a Question Paper (100 marks) and an Assignment (30 marks), both of which are marked externally by SQA.

The purpose of the assignment is to allow learners to apply a range of skills as they research a topic or issue, including: knowledge and understanding, research, interpreting evidence, organising and presenting findings (SQA, 2014). An example topic for the assignment is ‘Antioxidants’ in which students can investigate questions such as ‘What fruit contains the most antioxidants?’, ‘Which tea contains the most antioxidants?’ and ‘Does cooking destroy antioxidants’. Students are required to prepare a report through a medium of their choice (document, PowerPoint, poster, etc.). This assignment allows students the freedom to investigate what interests them about a particular topic and communicate their understanding following this investigation.

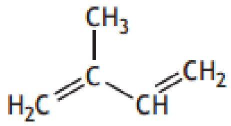
The course Question Paper is the final exam at the end of students’ studies and lasts for 2 hours and 30 minutes. The paper contains 2 sections; Section 1 is composed of multiple choice questions and accounts for 20 marks. Section 2 is composed of longer questions which require an application of knowledge and understanding. Example of questions from Section 1 and Section 2 of a Chemistry Highers paper can be found in Figure 2.9 and Figure 2.10.

The structure of isoprene is

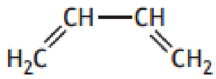
A



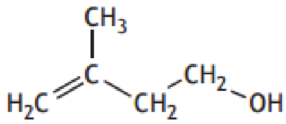
B



C

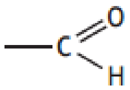


D



Which of the following statements is correct for ketones?

A They are formed by oxidation of tertiary alcohols.

B They contain the group  .

C They contain a carboxyl group.

D They will not react with Fehling's solution.

Which of the following is an isomer of 2,2-dimethylpentan-1-ol?

A $CH_3CH_2CH_2CH(CH_3)CH_2OH$

B $(CH_3)_3CCH(CH_3)CH_2OH$

C $CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2OH$

D $(CH_3)_2CHC(CH_3)_2CH_2CH_2OH$

Figure 2.9: Example questions from Section 1 of Chemistry Highers (SQA, 2014).

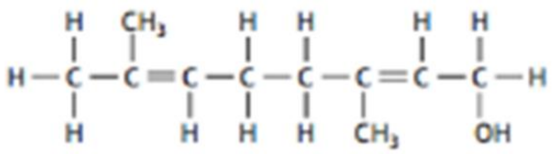
The first question in Figure 2.9 asks student to pick the structure for isoprene from four structures. There is no verb used in this question, however, as isoprene is not the IUPAC name of this molecule, the only way for students to know the structure of isoprene is from recall, thus this question classifies as a 'knowledge' question. The second question does give the IUPAC name and tests students' ability to work backward from IUPAC rules to identify the structure, therefore applying the IUPAC rules and placing this question in the 'application' category. In the final question, students have to identify a correct statement, thus is a 'comprehension' question. All of these questions in Figure 2.9 can be classified as lower order questions.

A question from Section 2 of the Chemistry Highers is shown in Figure 2.10.

Many of the compounds in perfumes are molecules consisting of joined isoprene units

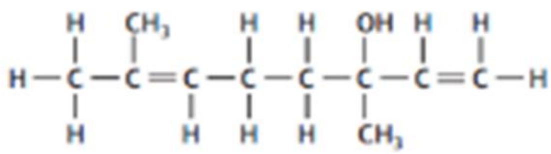
(i) State the name that is given to molecules consisting of joined isoprene units

(ii) Geraniol is one of the compounds found in perfume. It has the following structural formula and systematic name.



3.7-dimethylocta-2,6-dien-1-ol

Linalool can also be present. Its structural formula is shown below



(A) State the systematic name for linalool

(B) Explain why linalool can be classified as a tertiary alcohol

Figure 2.10: Example questions from Section 2 of Chemistry Highers (SQA, 2014)

Even though the verbs used in this question fall under the 'knowledge' and 'comprehension' categories of Bloom's Taxonomy, this question is more complex because students are asked to engage with a molecule that has not been prescribed on the syllabus and so, they probably have not seen before.

Unlike the Irish chemistry curriculum, which prescribes a set number of molecules which students have to study, the Scottish chemistry curriculum allows for a much broader range of molecules to be engaged with. This also allows for assessment to include molecules which students have not studied before, thereby testing their ability to apply their knowledge and understanding rather than reproduce learned off material.

2.3 Summary

This chapter has set organic chemistry in an Irish context. Organic chemistry makes up one quarter of the LC chemistry exam, and yet it is consistently avoided by students because of the narrow rote-learning focused questions. The link between learning outcomes and assessment has been demonstrated both in an Irish context and an international context. There is a need for a change in the assessment and learning outcomes in relation to chemistry and thus, organic chemistry in Ireland. The discussion in this chapter, and the findings in Chapter 1 will be used to inform the development of the OCV approach and the creation of OCV materials.

Chapter 3

Focus of the Project

Introduction/ Development of Research Question

The focus of this project presented itself while examining the many examples of organic chemistry that appear in our everyday lives. The following headline (Figure 3.1), which discusses the death of a man in his mid-20s due to a banned slimming pill containing dinitrophenol (DNP), appeared in the Irish Times newspaper.

Man in mid-20s dies after taking banned slimming pills

Garda and health products authority investigating 'fat burning' drug containing DNP

The man, in his mid-20s, died in May after taking a "fat burning" product that contained Dinitrophenol (DNP), a highly toxic substance marketed on the internet as a "wonder slimming aid".

Figure 3.1: Headline taken from Irish Times, Friday 26th June 2015.

We asked the question, '**How would a leaving certificate chemistry student engage with this type of headline following their study of organic chemistry?**' First of all, we would assume a student who had studied organic chemistry would engage with this headline in a different manner to a student who has not. We considered how they would visualise this compound from its name, dinitrophenol. A possible pathway for a student thinking about this molecule is shown in Figure 3.2. Would students simply see this DNP in its macroscopic form as a tablet or would students be able to break this name into two nitro groups and a phenol group? Could they draw its components in 2D or possibly visualise its 3D structure? Would they perhaps look at its molar mass or ask the question themselves; 'How did it kill this man? How does DNP react in the body?' Ideally we would like students who have studied organic chemistry for the leaving certificate to be able to follow this pathway of thinking, at least part of the way if not completely. However, from reading the literature, we suspect they cannot.

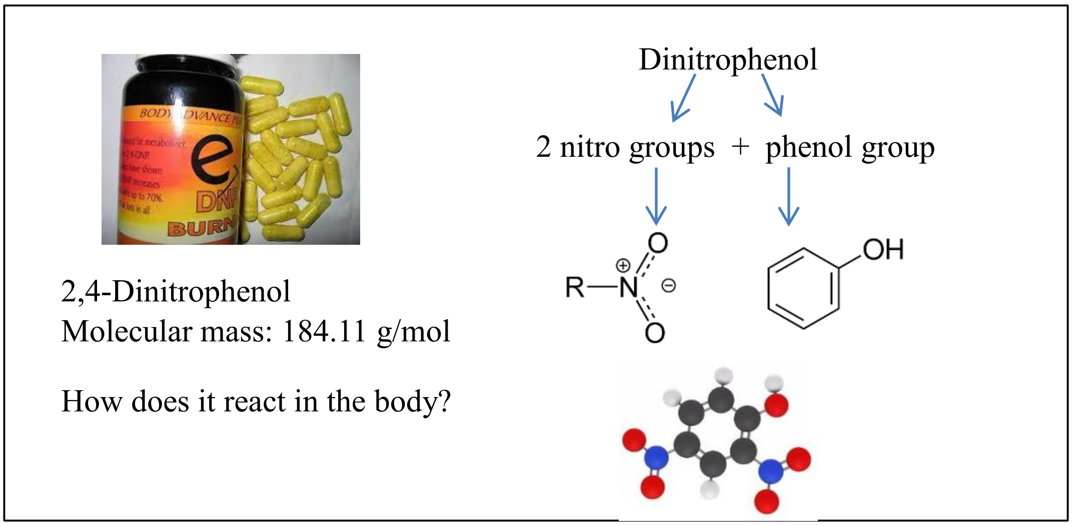


Figure 3.2: Example pathway of a student thinking about DNP

In order for a student to be able to engage with this molecule, they need to be able to understand the various forms of representations used for organic compounds. However, the literature has identified particular difficulties experienced by students which are related to the abstract nature of organic chemistry and these representations. Students have been shown to have difficulty interpreting formulae (Bernholt et al, 2012; Cooper et al, 2010), translating between different types of representations (Nicoll, 2003) and visualising and performing mental tasks on structures of organic molecules (Tuckey and Selvartnam, 1991; Ferk et al, 2003; Pribyl and Bodner, 1987; Small and Morton, 1983). These give rise to more difficulties relating to structural problems, such as isomers (Hassan et al, 2004) and structure-property relations (Taagepera and Noori, 2000; Cooper et al, 2013). In addition to these, students have to learn the 'language' of electron pushing to explain organic mechanisms (Bhattacharyya and Bodner, 2005)

The substantial difficulties experienced by students has led to organic chemistry being perceived as a difficult subject, with students avoiding it if possible. McCormack (2009) found that students in upper second level education in Ireland are only operating at the concrete cognitive level, and thus are not at the cognitive level required to engage with the abstract nature and variety of representations used in organic chemistry. Without the cognitive ability to fully understand organic chemistry, a culture of rote learning has emerged amongst LC students. What is taught in organic chemistry for the LC is anecdotally preferred by some students who find it easy to rote learn.

We have shown in Chapter 2 that students coming into third level education are able to engage somewhat with the different types of representations but are unable to translate between them. Therefore, we need to change the way that students are being taught organic chemistry.

This process led to the development of the research question for the project:

Can students learn organic chemistry through an approach where the focus is on meaningful understanding of (a) molecular structure, and (b) the basis of chemical reactivity?

This chapter describes the process undertaken to answer the above research question. The structure of the project will first be discussed, addressing the educational research methods which guided the structure. A timeline for the stages of project will be detailed. The participants involved in the project will be outlined, along with the data that will be collected to evaluate the project.

3.1 Structure of the Project

An initial representations exploratory study was conducted with incoming third level science undergraduates to determine if students leaving second level education in Ireland experience the same representational difficulties as those identified in the literature. This study indicated that students leaving second level education in Ireland can engage with three dimensional cues in representations of organic molecules but struggle to translate between them. The methodology and full results of this study can be found in Appendix A.

The next step in the project was to devise the teaching approach, which places an emphasis on 3D structures and the use of physical models. A teaching package was then created, whose key ideas related to both organic chemistry and general education, including but not limited to the use of: concrete models, large molecules, 3D structures, discussion, comparison, and the inclusion and evaluation of practical work. The actual development of the approach will be discussed further in Chapter 4.

Initial materials developed were piloted with one class group. Feedback from this pilot allowed for the re-evaluation of the approach and a finalising of the teaching package for full implementation. Following the creation of the Organic Chemistry through Visualisation (OCV) approach and teaching package, teachers were recruited to participate in a full implementation of the programme. Appropriate teacher training was provided to ensure the core values and key ideas of the approach were fully communicated to teachers. Following Implementation 1 of the package with several class groups, the approach was re-evaluated using evidence of student learning and feedback from teachers.

A second exploratory study into the use of process models as a tool to aid and examine student understanding was conducted with second year student teachers. This study will be discussed in Chapter 7.

Evaluation of Implementation 1 of the OCV programme informed the need for a second full implementation. This iterative approach took inspiration from the cyclic nature of action research, while the evaluation of individual class groups will be treated with a case study approach. These research methods will now be discussed.

3.1.1 Action Research

This study undertook research within post-primary and third level education contexts. The study drew inspiration from the Action Research model in the framing of each research phase and implementation within these contexts. In this regard, the study integrated cycle/s of 'plan, act, observe and reflect', through which the OCV programme and approaches were trialled, evaluated and redeveloped.

Action research is designed to bridge the gap between research and practise in order to improve practise and contribute to a theory of education and teaching, which can then be accessible to other teachers (Cohen et al, 2007). This research involves collaboration with practising and experienced second-level chemistry teachers.

O'Brien (1998) describes Action Research as 'learning by doing'. Alternative names for Action Research found in the literature include Emancipatory Research, Action Learning and Collaborative Learning.

The action research process has been described in the literature as cyclical. The cyclical process is intended to foster a deeper understanding of a given situation, starting with conceptualising the problem and going through several evaluations (MacIsaac, 1996). Action research is more of a holistic approach to problem-solving, rather than a single method for collecting and analysing data (O'Brien, 1998). Action research, therefore, allows for several different research tools and sources of data to be used within one project.

Kemmis and McTaggart (1988) developed a simple model to summarise the cyclical approach of Kemmis' Action Research process, see Figure 3.3. There are four main steps in each cycle of action research: planning, action, observation and reflection before revising the plan.

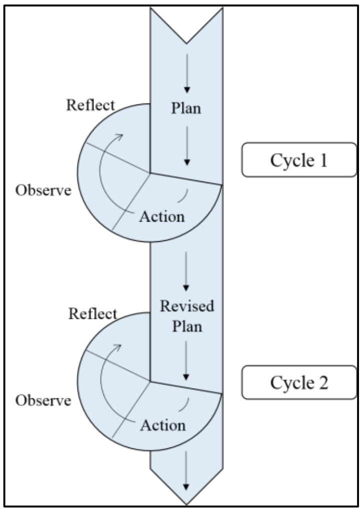


Figure 3.3: The 'action research spiral' adapted from MacIsaac (1996), based on Kemmis and McTaggart (1998)

Elliot (1991) used Kemmis' model as a starting platform but described a more detailed approach, see Figure 3.4. This approach contained some of his own elaborations, including: 'The General Idea' should be allowed to shift and 'Implementation' of an action-step is not always easy, and one should not proceed to the effects of an action until one has monitored the extent to which it has been implemented (p. 70).

As a research methodology, action research combines six key ideas:

- A straight-forward cycle of identifying a problem, planning an intervention, implementing the intervention, evaluating the outcome.
- Reflective practise
- Political emancipation
- Critical theory
- Professional development
- Participatory practitioner research (Cohen et al, 2007; p. 312)

There are however, some criticisms of action research. Hunter (2007) outlined the three main assumptions of action research:

1. Teachers introduce changes in the curriculum or in the way they teach because they perceive weakness in the current situation;
2. Any significant intervention into a practising classroom will have an effect. Action researchers ask ‘What is the effect on all participants involved?’ instead of asking ‘Was there an effect?’;
3. Changes in instruction seldom benefit all students equally. Educational research can have both positive and negative effects; while some students may benefit from the intervention, some may not.

The main criticism of action research is that the model focuses most of the attention on the action itself and changing the setting, rather than the development of research techniques and procedures (Hunter, 2007). Orlikowski and Baroudi (1991) identified some other weaknesses of action research:

- Lack of environmental control: any one variable may never be isolated in an action research study. This makes it difficult to identify how one dependant variable is influenced by other variables;
- Local utility of the research conclusions: the development of models with high external validity can be difficult from an action research project, due to the lack of generalisation. Action research projects tend to be specific, focused and localised;
- Personal Bias: Action research requires the researcher to be aware of their own bias and personal interests, as these can hinder the process and conclusions.

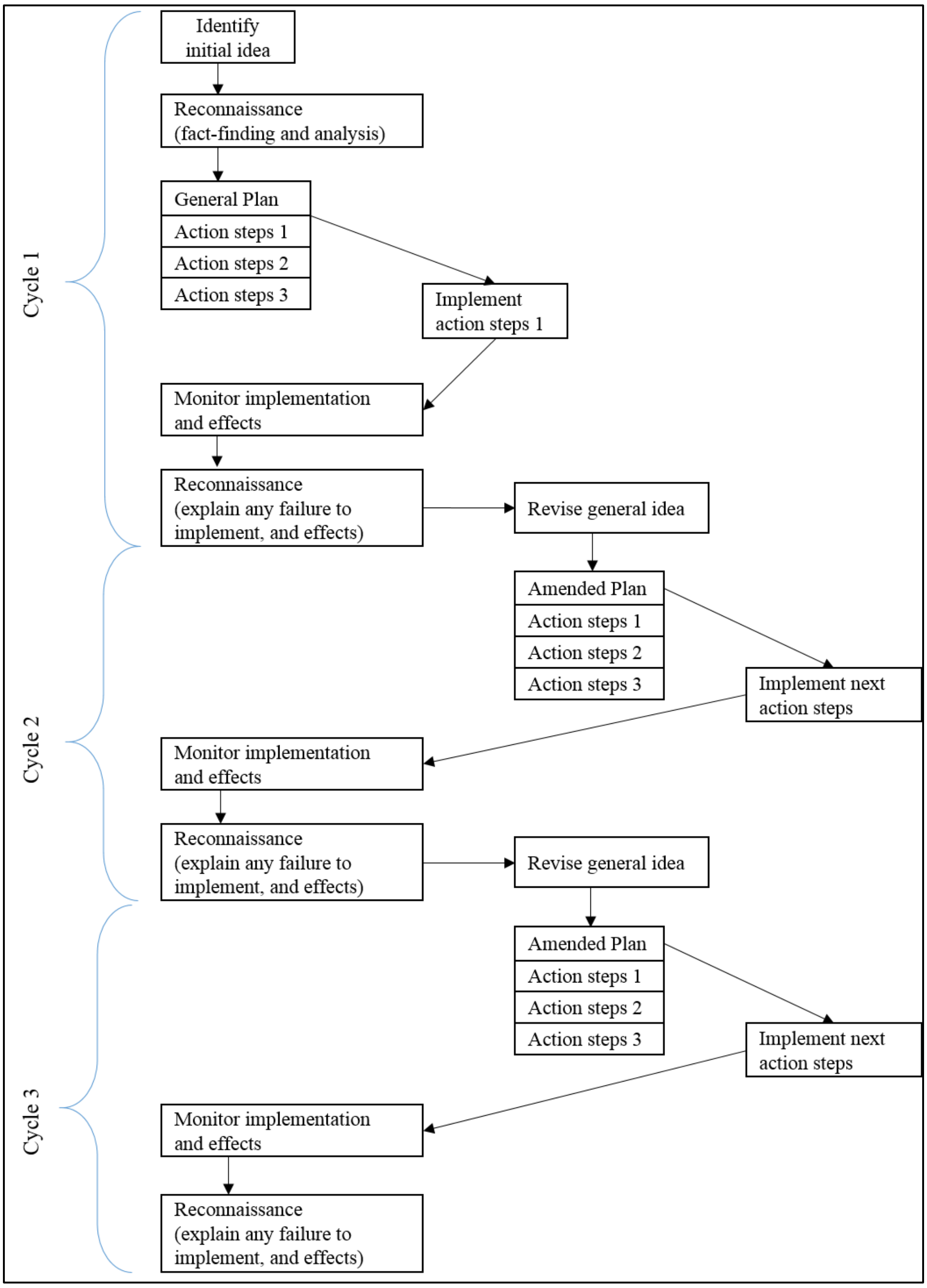


Figure 3.4: Elliot's revision of Kemmis' action research model (Elliot, 1991, p. 71)

Despite the assumptions and criticisms, action research is an effective practise for the linking of theory and practise through collaboration between researchers and teachers. The framework of this research project follows the action research model of Elliot. The general outline of the project is depicted using this model in Figure 3.5. A more detailed timeline for each of the cycles will be given in Section 3.2.

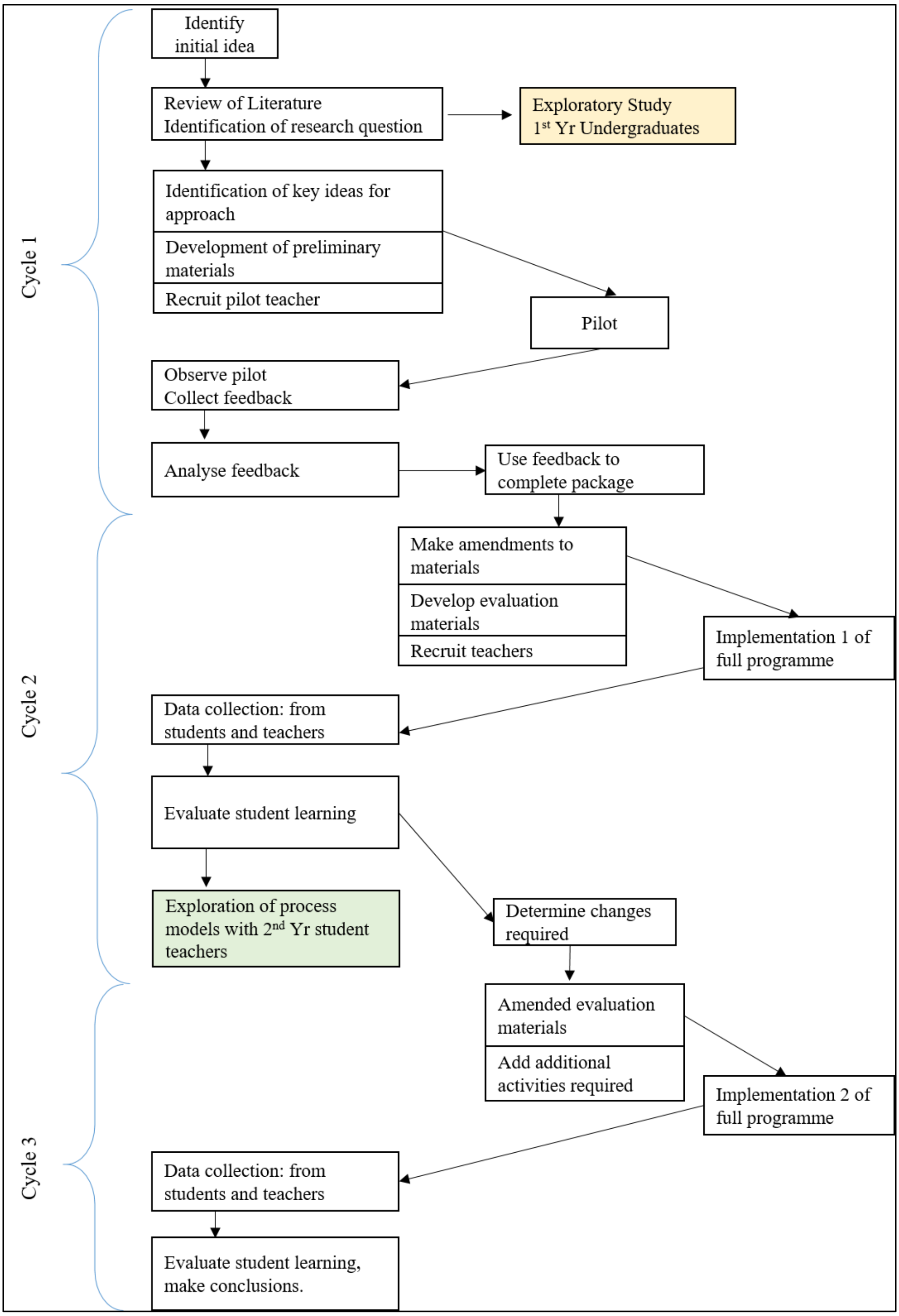


Figure 3.5: General outline of OCV project modelled on Elliot (1991)

While the general outline for the project follows the action research model, each implementation group can be considered as a case study. The case study research method will now be discussed.

3.1.2 Case Study

While action research inspires the general outline and iterative approach of this research, the individualised environment of the classroom and the nature of the implementation and evaluations of the OCV programme are guided by a case study approach. This project includes case studies from both second and third level.

A case study is a specific instance that is frequently designed to illustrate a more general principle (Nisbet and Watt, 1984), it is 'the study of an instance in action' (Cohen, 2007). A case study provides a unique example of real people in real situations, enabling readers to understand ideas more clearly than simply by presenting them with abstract theories or principles.

Hitchcock and Hughes (1995) describe several characteristics of a case study:

- It is concerned with a rich and vivid description of events relevant to the case;
- It provides a chronological narrative of events relevant to the case;
- It blends a description of events with the analysis of them;
- It focuses on individual actors or groups of actors, and seeks to understand their perceptions of events;
- It highlights specific events that are relevant to the case;
- The researcher is integrally involved in the case;
- An attempt is made to portray the richness of the case in writing up the report.

(Hitchcock and Hughes, 1995, p. 317)

Case studies can involve either single or multiple cases and numerous levels of analysis (Yin, 1984). Case studies typically combine data collection methods such as interviews, questionnaires and observations. The evidence may be qualitative (e.g. words), quantitative (e.g. numbers), or both (Eisenhardt, 1989).

Table 3.1 outlines some advantages and disadvantages of using a case study (Nisbet & Watt, 1984). Bias is identified as a potential disadvantage from the researcher as an observer. Shaughnessy and Zechmeister (2003) suggest that because case studies often lack a high degree of control, and treatments are rarely controlled systematically, it renders it difficult to make inferences to draw cause-and-effect conclusions from cases studies. Thus, there is potential for bias in some case studies as the researcher is both the participant and observer and, in that role, may overstate or understate the case.

Table 3.1: Advantages and Disadvantages of Case Study (from Nisbet & Watt, 1984)

Advantages	Disadvantages
They provide insights into other, similar situations and cases, thereby assisting interpretation of other similar cases.	The results may not be generalizable except where other readers/researchers see their application.
They can be undertaken by a single researcher without needing a full research team.	They are not easily open to cross-checking, hence they may be selective, biased, personal and subjective.
They can embrace and build in unanticipated events and uncontrolled variables	They are prone to problems of observer bias, despite attempts made to address reflexivity.

Stake (1994) classifies three main types of case study:

1. Intrinsic case study: a study that is undertaken to understand the particular case in question;
2. Instrumental case study: examining a particular case in order to gain insight into an issue or a theory;
3. Collective case study: a group of individual studies that is undertaken to gain a fuller picture.

This research can be categorised as both an instrumental and collective case study; due to the sample sizes, the project as a whole can be taken as a case study to examine the effectiveness of a model-based approach to teaching organic chemistry. Meanwhile, each individual class group can be taken as a single case study that when grouped together, provide a fuller picture for the instrumental case study.

Observation is a key element of case study, the purpose of which is to investigate deeply and examine intensively the phenomena which are being observed (Cohen, 2007). There are two main types of observation; participant observation and non-participant observation. During participant observation, the observer engages in the activities which they are investigating. while non-participant observation involves the observers standing away from the activities they are investigating.

Observation plays a key role in the evaluation of OCV programme. This will be discussed further in Section 3.5.

3.2 Case Studies

This project involved several case studies at both second and third level (Table 3.2).There were three main interventions at post-primary level; a pilot study and two implementations, in which the OCV approach was trialled, evaluated and redeveloped. The participants were a number of 5th year chemistry classes who had not yet studied organic chemistry. At third level, there were two interventions, the first of which was carried out at the outset of the research study, and which explored whether there were weaknesses in abilities to translate molecules among first year undergraduate students in Ireland. The second intervention at third level took-place at the end of the study and further examined the use of organic chemistry animations to enhance understanding of molecular structures among pre-service teachers.

Section 3.3 details the timeline along which these case studies took place and the purpose of each case study. The participants and the data collected in each case study is discussed in Section 3.3 and Section 3.4 respectively

Table 3.2: Case studies which took place at second and third level

Level	Case Study
2nd level	OCV Pilot study
	OCV Implementation 1
	OCV Implementation 2
3rd level	Representations Exploratory Study
	Process modelling Exploratory Study

3.3 Timeline of the Project

Table 3.3 describes the main phases of the project, the case studies involved, their purpose and the participants. As can be seen, there were three cycles in the project, with a total of 13 phases. Case studies which took place at second level are highlighted in green and case studies which took place at third level are highlighted in yellow.

Table 3.3: Timeline of the OCV project. Case studies highlighted in green took place at 2nd level. Case studies highlighted in yellow took place at 3rd level.
Note: TRS = Teacher Reflection Sheet

Phase		Timeline	Study	Purpose	Participants
Cycle 1	**1**	Sep-Dec '12	Reconnaissance	Identify areas where students struggle with organic chemistry, what approaches have already been taken	
			Development of approach and initial activities	Development of initial activities, resources for teachers	
	2	April '13	OCV Pilot	4-week pilot of approach, activities and resources.	Teacher: N=1 Students: N= 17
	3	May-July '13	Evaluation of pilot	Evaluation of feedback from pilot teacher.	
Cycle 2	**4**	Aug–Dec '13	Redevelopment of materials, expansion of evaluation materials	Feedback from pilot teacher used to redevelop materials Further development of materials to evaluate the approach	
	5	Sept '12	Representations Exploratory Study	Determine if students leaving second level education in Ireland experience the same representational difficulties as those identified in the literature	1st Yr undergrad. science students N=151
	6	Jan '14	Recruitment of teachers	Recruitment of teachers for Implementation 1. Meetings with teachers to familiarise with approach and resources	Teachers, N=5
	7	Feb–May '14	OCV Implementation 1	Full implementation of OCV	Teachers: N=6 (researcher included) Students: N=70
	8	May '14	Additional Case Study	Investigate student difficulty in written assessment of Implementation 1	Students from class 1B N = 3
	9	Nov '14	Process Modelling Exploratory Study	Exploring the use of process models as a tool to aid and examine student understanding	2nd Yr student science teachers N= 23
	10	June-Dec '14	Evaluation of Implementation 1	Evaluation of all feedback from Implementation 1	
Cycle 3	**11**	Jan-Feb '15	Redevelopment of evaluation	Redevelopment of evaluation technique	
	12	Feb-May '15	OCV Implementation 2	Final implementation of OCV, use of new evaluation methods	Teachers: N= 4 Students: N=45
	13	June-Dec '15	Evaluation of final implementation	Evaluation of implementation, make conclusions	

3.4 Participants

3.4.1 Second Level Case Studies

The second level classes involved in each of the pilot study, Implementation 1 and Implementation 2 are summarised in Table 3.4. The pilot study involved one class group (Teacher F), from an all-girls secondary school of 17 students. Teachers for Implementation 1 were recruited via email. Of the teachers who expressed an interest in the programme following receipt of the email, six teachers volunteered to participate in Implementation 1 of the programme. Of these teachers, one had to withdraw within two weeks of starting the programme. In total, five teachers of 5th Year chemistry classes participated in Implementation 1 and the researcher also implemented the programme with a Transition Year class group (Class G).

Table 3.4: Breakdown of participants at second level

Teacher/Class I.D	School Gender Mix	Study participated in	Number of Students
B	Girls	Implementation 1	9
		Implementation 2	6
C	Co-ed	Implementation 1	16
		Implementation 2	16
D	Boys	Implementation 1	11
E	Boys	Implementation 1	11
F	Girls	Pilot	17
		Implementation 1	5
		Implementation 2	11
G (¥)	Co-ed	Implementation 1	11
H	Girls	Implementation 2	8

¥ This class was taught by the researcher.

Three of the teachers involved in Implementation 1 also participated in Implementation 2 (Teachers B, C and F). Implementation 2 also had one additional teacher (Teacher H). Teacher E from Implementation 1 did not return to Implementation 2 as s/he believed the approach was too time consuming. It is unclear as to why Teacher D did not return. Teacher H ran the OCV programme as an after school programme once a week throughout the year with a 5th year class group.

During the initial contact with teachers via email, teachers were only given an overview of the materials that were available and were not given copies of the manuals. Two meetings were held with each teacher before they began implementation of the programme. The main reason that this was done on a one-to-one basis was the staggered start of implementation due to participating teachers' individual class plans. In the initial meeting, teachers were given an overview of the approach and the rationale behind the project itself. They were also given a copy of the Teacher Manual and the Student Manual to examine. Teachers then had the opportunity to look through these manuals and get better acquainted with the approach. The second meeting was held to address any questions that teachers had regarding the approach or the activities in the programme.

The time spent on the programme by each teacher during both Implementations will be discussed in Chapter 5. Following each teacher's execution of the programme, feedback was gathered in the form of teacher reflection sheets, informal discussions, a teacher focus group and individual teacher interviews. These, and all other feedback and data sources collected, will be discussed in Section 3.6

Following initial evaluation of the written assessment in Implementation 1, an additional study was conducted with three students from class of Teacher B. The students who were chosen for this study had particular difficulty completing Question 2 of Assessment 1 (Assessment 1 will be discussed in detail in Chapter 5). It was decided to conduct an additional study to investigate the difficulties experienced by these students in this particular question. This additional study will be discussed in Chapter 5.

3.4.2 Third Level Case Studies

This project included two case studies at third level. The first was an exploratory study into students' ability to engage with a variety of representations used in organic chemistry. The cohort selected consisted of 151 students taking a 1st Year Chemistry Laboratory module, which lasted 24 weeks (2 x 12 week semesters). These students had varying majors, from Biotechnology to Analytical Chemistry and approximately 50% (76) had studied chemistry for the Leaving Certificate. The discussion and results of this study can be found in Appendix A.

The second case study at third level involved 25 second year pre-service teachers. The purpose of this study was to investigate the potential for the inclusion of a virtual modelling environment with an animation tool in the OCV approach. At the time, these students were undertaking a module which focused on the role of ICT in science education. Thus, the purpose of selecting these students was two-fold; to use ChemSense to assess students' understanding of some core chemical concepts, and to make these student teachers aware of how to utilise this type of software for assessment of understanding and identification of misconceptions. This study will be discussed further in Chapter 7.

3.5 Ethical Consideration

Ethical behaviour is of great importance in research. As the participants in the research project included second-level students, ethical approval was sought and granted from the Dublin City University Research Ethics Committee. Ethical approval was also sought and granted for the representations exploratory study with first year third level students. The letters of approval for both studies can be found in Appendix B

The names of all schools, teachers and students are known to the researcher. This was necessary to enable the researcher to compare pre- and post- spatial ability tests with the post-assessments and other evaluation tools. Each class was coded with a letter and each student in each class was given a number. The data sources collected from students in each Implementation will now be discussed in Section 3.6.

3.6 Data Collection

The case study approach taken in this project allows for a mixed methods research process. A variety of data were collected to evaluate the effectiveness of the OCV approach. These data sources were both qualitative and quantitative.

A number of steps were taken to ensure rigour within the evaluation of the OCV programme in Implementation 1 and Implementation 2:

- Data was collected from three sources: the teachers, students and the researcher;
- Data collected was both qualitative and quantitative;
- Multiple data sets were collected within each case study

Table 3.4 summarises the data collected in each of the case studies. These were a combination of qualitative and quantitative data. Table 3.5 summarises the qualitative and quantitative data collected in each of the case studies.

Data collection varied slightly between Implementation 1 and Implementation 2. Due to time constraints, the researcher taught the programme during the Implementation 1 but not Implementation 2. In Implementation 1, teachers were interviewed following implementation as a group through a focus group, while they were interviewed individually following Implementation 2. Students in both Implementations completed the pre- and post- spatial ability test. However, students in Implementation 1 completed Assessment 1 while students in Implementation 2 completed Assessment 2. The content examined on these assessments was very similar, however the structure of the questions differed. This will be discussed in Section 3.6.3. All data sources collected in Implementation 1 and Implementation 2 respectively are summarised in Figure 3.6 and Figure 3.7.

A small group of students from Implementation 1 participated in an additional study following completion of the OCV programme. This was used to inform execution of Implementation 2. Students in Implementation 2 all underwent a modelling test and interview following completion of the programme. All of these data sources will be discussed further.

Table 3.5: Summary of data collected in each case study

Level	Study	Data Collected
2nd level	OCV Pilot study	Teacher Reflective Journal
	OCV Implementation 1	**Student:** Pre-Post spatial ability test Assessment 1 (written test) Part C: Reactivity assessment
		Teacher: Teacher reflection sheets Data from teacher focus group
		Researcher: Field notes from observations Field notes from researcher implementation
	Follow-up Case Study	**Student:** Additional study worksheet
		Researcher: Field Notes
	OCV Implementation 2	**Student:** Pre-Post spatial ability test Assessment 2 (written test) Results from modelling test Data from paired interview
		Teacher: Teacher reflection sheets Data from teacher interviews
		Researcher: Field notes from observations
3rd level	Representations Exploratory Study	**Student:** Structural representations test Organic questions from end of semester test
	Process modelling Exploratory Study	**Student:** Animation created in ChemSense

Table 3.6: Summary of qualitative and quantitative data collected in each case study

Level	Study	Quantitative Data	Qualitative Data
2nd level	OCV Pilot study	-	Teacher reflective journal
	OCV Implementation 1	Pre-Post spatial ability test Assessment 1 (written test) Part C: Reactivity assessment	Researcher field notes Teacher reflection sheets Data from teacher focus group
	Follow-up Case Study		Structures drawn by students Researcher field notes
	OCV Implementation 2	Pre-Post spatial ability test Assessment 2 (written test) Results from modelling test	Data from paired interview Researcher field notes Data from teacher interviews
3rd level	Representations Exploratory Study	Structural representations test Organic questions from end of semester test	
	Process modelling Exploratory Study		Animation created in ChemSense

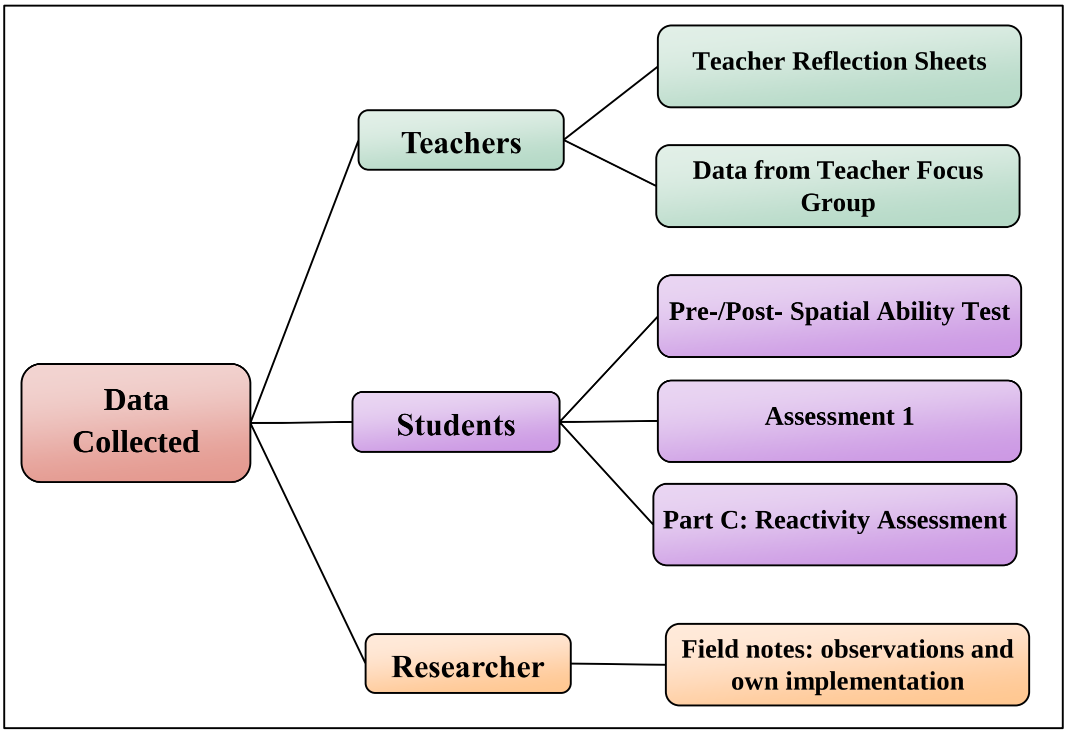


Figure 3.6: Data Collection for Implementation 1

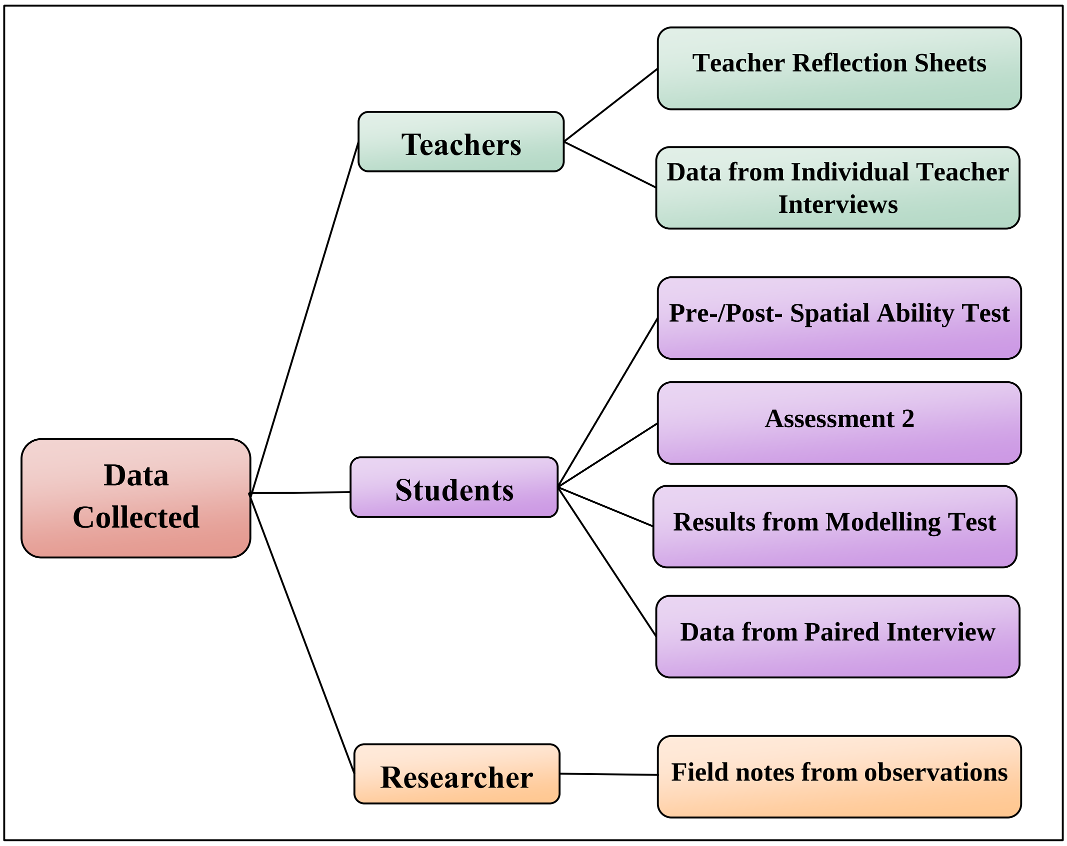


Figure 3.7: Data Collection for Implementation 2.

3.6.1 Teacher Data

(a) Pilot Teacher Reflective Journal

During the pilot study, the pilot teacher opted to keep a reflective journal discussing the progress of all conversations and activities throughout the 4-week pilot. This was analysed qualitatively to inform Implementation 1 and Implementation 2.

(b) Teacher Reflection Sheet (TRS)

Participating teachers were asked to complete a Teacher Reflection Sheet (Appendix C) upon completion of each lesson. The 7-item reflection contained closed, open and Likert-scale type questions. The questions were developed to gather information on teachers' implementation of the resources and students' engagement with the approach. Teachers were asked to record any changes made to each lesson/activity, if students were able to carry out the activities suggested, any difficulties students experienced, etc.

(c) Informal Discussions with Teachers

Field notes were taken during informal discussions with the participating teachers following classroom observations. These notes will be used as part of the evaluation of the programme.

(d) Teacher Focus Group

A semi-structured focus group was held following implementation of Implementation 1 of the OCV Programme with three of the participating teachers (B, C and H). The purpose of this focus group was to gain extra feedback from teachers regarding their students' engagement, difficulties and areas of achievement during participation in the programme. It was also an opportunity for teachers to expand on what had been written in the Teacher Reflection Sheets. This focus group was recorded, with the permission of the teachers, and was transcribed for qualitative analysis. These transcripts were used to inform redevelopment of materials and assessments for Implementation 2.

(e) Teacher Interviews

Teachers were interviewed individually following Implementation 2 of the OCV programme. The structure of these interviews was similar to the focus group. These interviews were also recorded and transcribed for qualitative analysis.

3.6.2 Researcher Collected Data: Field Notes

Classroom observations provided qualitative data regarding students' participation, motivation and interest in the programme. Observation allows the researcher to directly see the actions of the participants without having to rely on what they say, they do and can allow for relatively objective measurement of behaviour (Tasahkkori & Teddie, 1998). Observations played a significant role in understanding the effectiveness of the teachers' implementations of the resources and the engagement of students with the approach. Informal questioning of students and Resesarcher Observation Sheet (Appendix D) were used during observations. The Researcher bservation Sheet is a semi-structured instrument comprised of open, closed and ranking-style questions. It was created to compliment the TRS; the reasoning behind this was to determine if the teachers' and researcher's opinions of student participation, areas of difficulty experienced, etc. agreed.

Classroom observations took place at least twice during the Pilot phase, at least once every two weeks in each of the classes involved in each Implementation. The researcher took the role of participant-as-observer, discussed in Section 3.1.2, becoming involved in the lesson by helping and questioning during activities, while also listening to student discussions. While it was not possible to record students during these classes, extensive field notes were taken of discussions overheard by the researcher between students. These were used to assess student thinking and understanding during the activities in which they were observed.

The researcher taught the OCV programme to a Transition Year class group during Implementation 1. It was a valuable experience as it allowed the researcher to gain an insight into the timing of activities, the engagement of students and the areas of difficulty experienced.

3.6.3 Student Data

As already shown at the beginning of this section, the data collected from students varied slightly between Implementation 1 and Implementation 2. Each of the data sources will be described below.

(a) Spatial Visualisation Tests

Spatial ability has been linked with success in organic chemistry (Pribyl and Bodner, 1987; Small and Morton, 1983; Bodner and Guay, 1997). It was decided that a spatial test should be used to identify if a change occured in students' spatial ability by learning organic chemistry through the approach that has been developed. The Revised Purdue Spatial Visualisation Tests: Visualisations of Rotations test (PSVT: R) (Yoon, 2011) was used with permission from the author So Yoon Yoon of Purdue University. Students were tested pre- and post- pilot.

Feedback from the pilot teacher indicated that the full 30-item test was too long. This feedback will be discussed in Chapter 4. Bodner and Guay (1997) validated a 20-item version of this test as a predictor of spatial abilities, however, this was still considered too long. Thus, a shorter 10-item version was used for Implementation 1and Implementation 2 of the programme. Five symmetrical and 5 non-symmetrical items were randomly selected from the original 30-item RSVPT. As this test was being used to measure change and not as a measure of absolute spatial ability, this 10-item test was not validated.

(b) Implementation 1-Assessment 1

A 7-item written assessment was developed to assess the achievement of the learning outcomes of the programme. This was completed by the six classes involved in Implementation 1 upon completion of the programme. This assessment can be found in Appendix E. The questions of this assessment are summarised in Table 3.7 below.

The primary aim of this assessment was qualitative; to identify if and how students could translate between representations, if students were successful with the concept of isomers and if they could predict physical properties of simple and complex molecules. Questions 1-4 focus on students' understanding of and translation between representations, while Question 5-7 assess their ability to predict and compare physical properties.

Table 3.7: Description of questions in Assessment 1

Question	Description
1	Drawing 2D representation from 3D representation
2	Drawing isomers (2D representation of structure given)
3	Writing molecular formula from 3D and 2D representations
4	Identification of cis/trans isomers
5	Comparison of intermolecular forces in an alcohol and an alkane; prediction of physical state, from 2D representations
6	Ranking style question; comparing boiling point of organic compounds with different functional groups from 2D representations
7	Assigning partial charges to complex molecules. Comparison of boiling point of complex molecules. Complex molecules used to see if students can identify the ‘signal’ from the ‘noise’

Assessment 1 is designed to assess parts A and B of the OCV programme. A separate assessment of Part C of the OCV programme was designed because only one class group in Implementation 1 completed Part C of the OCV programme. Parts A-C of the OCV programme and the varied execution will be discussed in Chapter 4.

(c) Implementation 1-Part C: Reactivity Assessment

Part C: Reactivity Assessment consisted of five questions, assessing students' abilities to identify reactive centres in unknown molecules in the presence of various electrophiles and nucleophiles. This assessment can be found in Appendix F. Several of these questions were adapted from a 3rd year third level examination in organic chemistry. Again, these questions were analysed qualitatively for the purpose of this research but a marking scheme was created in order to provide a quantitative grade for the teacher of this group.

In all questions, students were required to identify reactive sites in molecules which were unknown to them. The structures of the molecules were also presented to students in both 2D and 3D representations. Table 3.8 contains a description of each question in Part C: Reactivity.

Table 3.8: Description of questions in Part C: Reactivity

Question	Description
1	Molecule with Ph symbolism- unknown molecule with unknown symbols
2	Nucleophile H^- to ensure students don't hold the misconception identified by Hassan et al (2004); that bond polarities depend on absolute electronegativity of atoms only, i.e.: Hydrogen is always positively charged.
3	Multiple reactive sites (2) -students asked to predict *most likely* reactive site
4	Reaction between 2 molecules- students were given a starting point by identifying the dipoles in the attacking molecule.
5	Multiple reactive sites (4)-students asked to predict *most likely* reactive site

Students' achievement and mistakes in Assessment 1 and Part C: Reactivity Assessment was compared to their results from the post-spatial ability test to determine if there was a correlation between spatial ability and achievement in the OCV programme. Despite the qualitative purpose of these assessments, participating teachers required a quantitative analysis of the assessments in order to provide a full end-of-year report for their students. Thus, following an initial qualitative analysis of the assessments, a marking scheme was devised.

(d) Assessment 1-Follow-up Study

Following qualitative analysis of the Assessment 1 from Class B in Implementation 1, the researcher decided to hold a follow-up study with three of the students from this class. This class was composed of a number of students who had English as a second language. These particular students performed poorly in Q2 of Assessment 1. The purpose of the follow-up study was to discern if these students did not understand the concept of isomers or if they simply did not understand the word 'isomer'. The results of this follow-up study will be discussed in Chapter 5.

(e) Implementation 2-Assessment 2

For Implementation 2, the structure of the written assessment was changed to include more multiple choice questions, while the content was still similar. This assessment can be found in Appendix G.

Table 3.9: Description of questions in Assessment 2 MCQ= multiple choice question

Question	Description
1	Same as Assessment 1
2	MCQ: IUPAC naming- molecule presented with expanded hydrogens to test students' abilities to extract the important information from a given structure
3	Same as Assessment 1
4	Select an isomer pair from four similar compounds. Students also asked to explain their selection
5	Structural communication grid with 8 questions attached- questions on isomers

The final question in Assessment 2 was a structural communication grid modelled on that used by Hassan et al (2003). Students were also asked to explain their selection for answers (g) and (h). Communication grids are highly recommended for insights into conceptual understanding (Reid, 2003). Structural communication grids present data in the form of a numbered grid, students are given questions and asked to select appropriate boxes in response to these questions. Use of these grids gives an insight into sub-concepts and linkages between ideas held by students, so that understanding can be assessed. The wrong answers selected by students can reveal misunderstandings and misconceptions held by students.

Students' responses to Assessment 2 were analysed qualitatively and compared with students' modelling test and interview data.

(f) Implementation 2-Modelling Test and Paired Interviews

Following Implementation 1 of the OCV programme, it was felt that the assessment methods did not match the teaching approach; students who had been modelling on a regular basis were still assessed using a standard pen-and-paper assessment. Thus, an additional assessment was required to evaluate students' modelling abilities.

The modelling test and interview protocol selected was similar to that used by Nicoll (2003), as already discussed in Section 1.1.1, and was designed to probe:

1. Students' ability to translate from (a) the molecular formula to a 2D representation of structure and (b) 2D representation of structure to a 3D model.
2. Students' mental models of the 3D structure of organic molecules following the use of molecular model kits during the OCV programme.

The protocol for the paired interview can be found in Appendix H. Students were first asked to draw the structure for ethanal from its molecular formula, testing students' ability to translate from the molecular formula to a 2D structure. Ethanal was chosen for a number of reasons; firstly, it is a relatively simple molecule compared to those that students engage with throughout the OCV programme. While Nicoll (2003) selected formaldehyde in their study for the same reason, ethanal was chosen because it contains both a tetrahedral and a planar carbon, which would allow the researcher to probe students' understanding and internalisation of the spatial arrangement of both types of carbon. As ethanal contains more than one element and also an oxygen double bonded to a carbon, students have to consider the connectivity between atoms within the molecule.

Nicoll's pilot study in 2003 demonstrated the importance of how the molecular formula is presented to students; the formula for formaldehyde was presented as CH_2O, which resulted in students believing that the structure was simply a water molecule (H_2O) with a carbon bonded off the oxygen. Thus, the formula was changed to COH_2. For this reason, the formula for ethanal was presented as CH_3CHO, rather than C_2H_4O.

The second question asked students to construct a 3D model from modelling clay and sticks. Students were presented with a kit which contained modelling clay of six different colours and sticks of two different colours. This gave students' the flexibility to construct their molecule as they wanted. Regardless of the molecule students constructed, students were asked to explain why they constructed the molecule in the way that they did, what each component represented and how the shape of the molecule arose. Additionally, students were asked to suggest areas of higher electron density within the molecule and if they thought that ethanal was water soluble.

Photographs of students' models were taken before the interviews concluded. Following the interviews, recordings were transcribed and a coding scheme was developed for analysis of both students' models and their answer to interview questions. This will be discussed in Chapter 6.

3.7 Data Analysis

The case study design of the project allowed for a mixed methods research process to be employed. As discussed in Section 3.6, a combination of qualitative and quantitative data was collected. The analysis of the qualitative and quantitative data will now be discussed.

3.7.1 Qualitative Data Analysis

A coding scheme was developed for each piece of qualitative data collected. This allowed for similar and dissimilar responses to be identified. An example of a coding scheme for the paired interviews and its application to a transcript can be found in Appendix I

3.7.2 Quantitative Data Analysis

Following qualitative analysis, all students' responses were coded for comparison and further quantitative analysis. Statistical analysis was performed on students' spatial tests and multi-dimensional scaling was applied to student data from Implementation 2. Table 3.10 summarises the quantitative tests used in this project and their purpose.

Table 3.10: Summary of quantitative analysis

Quantitative Test	Purpose
Paired-samples t-test	Compare students' pre ad post spatial ability tests
Multi-dimensional scaling (MDS	Identify similarities and dissimilarities between students' responses

(a) Paired-samples T-Test

In order to identify if students' spatial abilities changed through the use of molecular models, a paired-samples t-test was conducted to compare students' results in the pre and post spatial ability tests. A p value of less than or equal to 0.05 will indicate a significant difference between students' pre and post spatial ability tests. A p value above 0.05 will indicate no signifcant difference.

(b) Multi-Dimensional Scaling (MDS)

Multi-dimensional scaling (MDS) graphically represents similarities and dissimilarities between objects. The overall aim of MDS is to create a configuration of points in which the distance between the points correspond as close as possible to the proximities between the objects. Objects that are considered similar to each other are represented by points that are closer together on the configuration. In this case, the 'objects' are the students and the distances between these objects represent how similar/ dissimilar students' responses to the assessment items were.

MDS was applied to student data from Implementation 2; the written assessment, modelling test and interview questions. The 'ideal' response was also included in this configuration to give a visual of how successful students were in these assessments; the closer students were to the 'ideal' the 'more correct' their answers. An example of the coding applied to student data for MDS analysis can be found in Appendix J. The results of this analysis will be described in Chapter 5.

3.8 Summary

This research study was underpinned by Case Study research design, with inspiration drawn from the Action Research model in the framing of each implementation of this study of organic chemistry visualisation processes. In this regard, each implementation of the study contained cycle/s of 'plan, act, observe and reflect'. There were three interventions at post-primary level; a pilot study and two implementations, in which the OCV approach was trialled, evaluated and redeveloped. At third level, there were two interventions, the first of which was carried out at the outset of the research study, and which explored whether there were weaknesses in abilities to translate molecules among first year undergraduate students in Ireland. The second intervention at third level took-place at the end of the study and further examined the use of organic chemistry animations to enhance understanding of molecular structures among pre-service teachers. The data collected during each implementation has been detailed and methods of analysis have been discussed. The next chapter will detail the development of the teaching approach in the OCV programme.

Chapter 4

Development of the OCV Programme

Introduction

Chapter 3 described the development of the following research question:

> **Can students learn organic chemistry through an approach where the focus is on meaningful understanding of (a) molecular structure, and (b) the basis of chemical reactivity?**

Having identified the range of difficulties experienced by students related to representations of organic structures, structure-property relations and organic mechanisms, and the possible reasons behind these difficulties, the development of the teaching approach and teaching package for the OCV programme will now be discussed.

4.1 Development of the OCV Approach

The Representations Exploratory Study with third level students (details in Appendix A) indicated that students leaving second level education in Ireland can engage with three dimensional cues in representations of organic molecules but struggle to translate between them. This study helped to inform the development of the OCV approach.

The general learning that the OCV approach should incorporate was first identified. We wanted the approach to include time for a social constructivism which would be rooted in discussion and argument amongst students. Activities that are designed to give rise to variations amongst students will bring about this discussion between students. The approach will be interactive, with a focus on students' constructing models and drawing structures. Larger molecules which are relevant to students will be used to pique students' interest and encourage engagement.

Practical work will be an important element of encouraging understanding of structure-property relations. These will take a phenomena-oriented approach, in which students make observations during the practical session and apply their knowledge of structures to explain their observations. The reactivity of organic molecules will be addressed by asking students to predict reactive sites in larger molecules. The focus of predictions will not be on leading students to getting the ‘correct answer’ but on developing their scientific arguments and ability to communicate their ideas.

Once the general learning that we wanted to incorporate into the approach was outlined, the core values of the OCV programme were identified.

4.1.1 Core Values of the OCV Programme

The core values that we wanted to incorporate into the OCV programme were informed by the literature review, which identified the difficulties associated with studying organic chemistry and recommendations for facilitating learning. Following the identification of the general learning which we wanted to take place within the approach, core values of the programme were chosen. These informed the design of the approach and materials in the teaching package. The seven core values chosen are listed and discussed below

a) Learning through molecular models;
b) Inter-relating between 3D and 2D representations of organic molecules;
c) Discussion-led activities;
d) Engaging with relevant organic compounds;
e) *Predicting* and *comparing* physical properties and reactivity of organic compounds using electron density;
f) Phenomena-oriented experimental work;
g) Addressing misconceptions.

a) Learning through molecular models

Many students in fifth and sixth year in Ireland are still only at the concrete stage of cognitive development (McCormack, 2009). As a result, it is difficult for them to comprehend abstract concepts that require formal cognitive operations, such as visualising and understanding molecular structures. The use of molecular models can be an effective learning resource for facilitating the abstract operation of inter-relating between 3D and 2D representations of molecules (Tasker and Dalton, 2006). This facilitates students' understanding of the 3D shape and structure of organic molecules, the variety of bond angles, isomerism, their physical properties and their reactivity. Molecular models provide students with a concrete representation of these structures and allow for a more tangible communication than could be explained through 2Ddiagrams, which can be often incorrectly be perceived as flat 2D molecules. Molecular models have been shown to not only help students to create accurate mental models (Tasker and Dalton, 2006) but also promote long term retention of understanding (Copolo and Hounshell, 1995). However, it has been found that looking at the models is not enough; *'they have to be handled, rotated and manipulated*' for them to be a useful learning tool (Hassan et al, 2004).

b) Inter-relating between 3D and 2D representations of organic molecules

We know from the literature that students struggle to form 3D mental images from 2D representations (Copolo and Hounshell, 1995) and this hinders their understanding of organic chemistry. Activities were specifically designed to develop students' ability to move between the varieties of representations used in organic chemistry. An example of this inter-relation is illustrated in Figure 4.1 using the structure of paracetamol. Therefore, the activities will be designed to educate students in moving backwards and forwards between 3D and 2D representations, including symbolic representations.

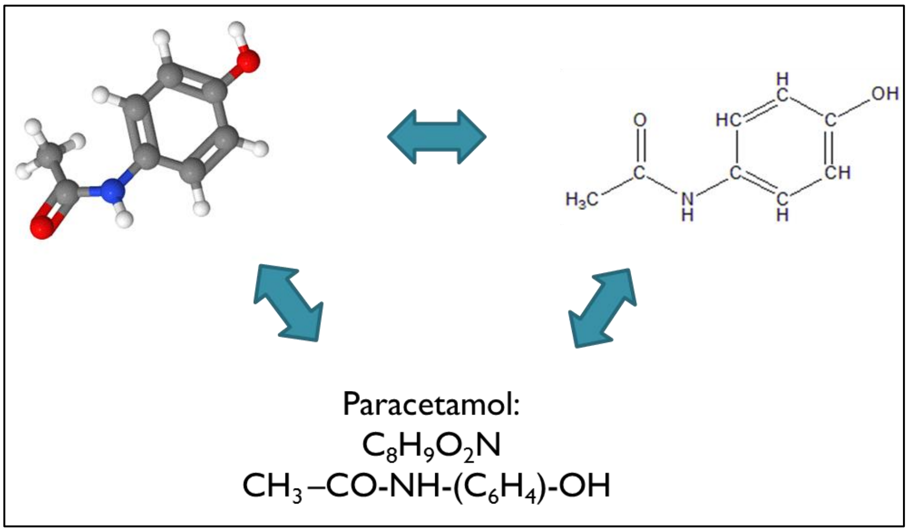


Figure 4.1: The inter-relation between representations that OCV aims to promote.

The traditional approach to learning organic chemistry is to begin with a 2D representation and relate that to its 3D structure later. If we examine a common LC textbook, Chemistry Live!, the first organic compounds that students are introduced to are alkanes. Students are actually shown a table with the name and molecular formula first, see Figure 4.2 (a). A table with the structural formula and 3D representation follows, see Figure 4.2 (b). This textbook introduces students to the alkanes by presenting them with representations that are the furthest from their true 3D structure. By following this textbook, students are being taught organic structures without being given a deep understanding of their true nature.

(a)

Name	Molecular Formula
Methane	CH_4
Ethane	C_2H_6
Propane	C_3H_8
Butane	C_4H_{10}
Pentane	C_5H_{12}
Hexane	C_6H_{14}
Heptane	C_7H_{16}
Octane	C_8H_{18}
Nonane	C_9H_{20}
Decane	$C_{10}H_{22}$

Table 21.1 The first ten members of the alkanes.

(b)

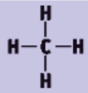
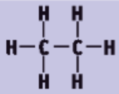
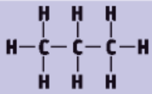
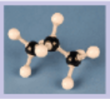
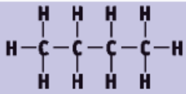
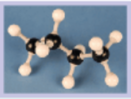
Name	Formula	Structural formula	Molecular model
Methane	CH_4		
Ethane	C_2H_6		
Propane	C_3H_8		
Butane	C_4H_{10}		

Fig. 21.3 The first four members of the alkanes.

Figure 4.2: Examples of first organic molecules presented to students in Leaving Certificate chemistry textbook Chemistry Live!

A foundational aspect of the OCV programme will be introducing students to organic molecules using 3D models first. Only when students have experience of constructing and manipulating models, will they devise methods of representing these molecules on paper. The traditional approach to introducing organic structures is more in line with the sequence outlined in Chemistry Live! Students are only required to know the structures of alkanes to C5 (DES, 1999), thus the current syllabus suggests that structures do not require a significant period of time. However, the OCV approach to introducing structures will be more in line with the Key Skills Framework (NCCA, 2009) and the ongoing revisions to the chemistry syllabus.

c) Discussion-led activities

All activities in the OCV programme were designed with a collaborative and discussion led approach in mind.

'*Children, we now know, need to talk, and to experience a rich diet of spoken language, in order to think and to learn. Reading, writing and number may be acknowledged curriculum 'basics' but talk is arguably the true foundation of learning'* (Alexander, 2005)

The way students process new information is affected by the setting in which they learn. The social constructivism theory of learning sees learning as more than the cognitive structuring of information based on interactions with physical events and phenomena, as described by the information processing model in Chapter 1. Learning is seen as symbolic and socially constructed and communicated.

The social constructivist model of learning outlined by Krajcik (1991) was described in Chapter 1. Treagust et al (2003) provided a number of examples of student discourse which demonstrate that students were not only learning through the use of physical models but were also using their models in their explanations to each other.

In order to challenge students' understanding, and aid them in creating new understandings, activities in the OCV programme will be designed to ensure that variation arises amongst students. This variation will encourage discussion and allow for new knowledge to be constructed.

d) Engaging with relevant organic compounds

Chapter 2 identified the link between narrow learning outcomes and limited learning. An important aspect of the OCV programme is that students will not be confined to learning a prescribed ‘set’ of molecules, as is typically specified in curricula. Context based approaches to teaching organic chemistry have been shown to increase student engagement and enhance learning (Bennet and Lubben, 2006; Schwartz, 2006; Reid, 2000). Molecules which students will be able to engage with contextually will be selected, for example vanillin, which is found in vanilla essence. These molecules are more complex in structure than those specified on the current LC Chemistry Syllabus (DES, 1999).

e) *Predicting* and *comparing* physical properties and reactivity of organic compounds using electron density

Taagepera and Noori (2000) found that students who could identify areas of electron density were better able to predict the physical properties of organic compounds. The activities in OCV will be designed to enable students to use variations in electron density in molecules to predict intermolecular forces in organic compounds and thus predict the physical properties. Another key element of this approach will be students not only predicting the physical properties of one compound, but also comparing the physical properties of a group of compounds. Again, these activities take a collaborative and discussion led approach, as in the social constructivist model, where students are encouraged to verbalise their thoughts and puzzle activities out together.

Once students are proficient in identifying areas of high and low electron density, they will then apply this understanding to suggest reactive sites in the presence of nucleophiles and electrophiles. An important aspect of this approach is the emphasis on students’ predictions and logic, rather than if they have arrived at the ‘correct’ answer.

f) Phenomena-oriented experimental work

As discussed in Chapter 1, the main principle of the *PIN-Concept* (Phenomena-Oriented Inquiry-Based Network Concept) for teaching organic chemistry was learning through inquiry and discovery (Barke et al, 2012). This will also be an integral part of the approach that will be developed for the OCV programme, particularly for the experimental work.

An example of an experiment developed for the OCV programme is an adaption of the demonstration outlined in Section 1.3.3, in which students investigate the solubility in water of a variety of alcohols. Students are given the name and molecular formula for each alcohol and are asked to, first, draw the structure of each alcohol, and second, suggest which of the alcohols, if any or all, are soluble in water. Before beginning the experiment, students also have to decide on the criteria for judging the solubility of the alcohols; as they are also liquids, how will they know if they are soluble or not? Students then test their predictions, recording observations. Following the experiment, students compare their predictions to their observations and suggest reasons for any variance. Students' explanations are rooted in the structures of the alcohols and students have to refer back to the structures and intermolecular forces for any predictions or explanations.

These core values will frame the development of the activities and materials for the OCV programme. Following identification of these core values, the learning progression that students will follow when learning through the OCV developed. This will be discussed in Section 4.1.2

4.1.2 Learning Progression of the OCV Programme

A learning progression is an evidence-based description of pathways that are likely to lead to improved mastery of core ideas in science (Cooper et al, 2012). The OCV learning progression is illustrated in Figure 4.3. Students are required to have studied bonding and intermolecular forces before beginning the OCV programme.

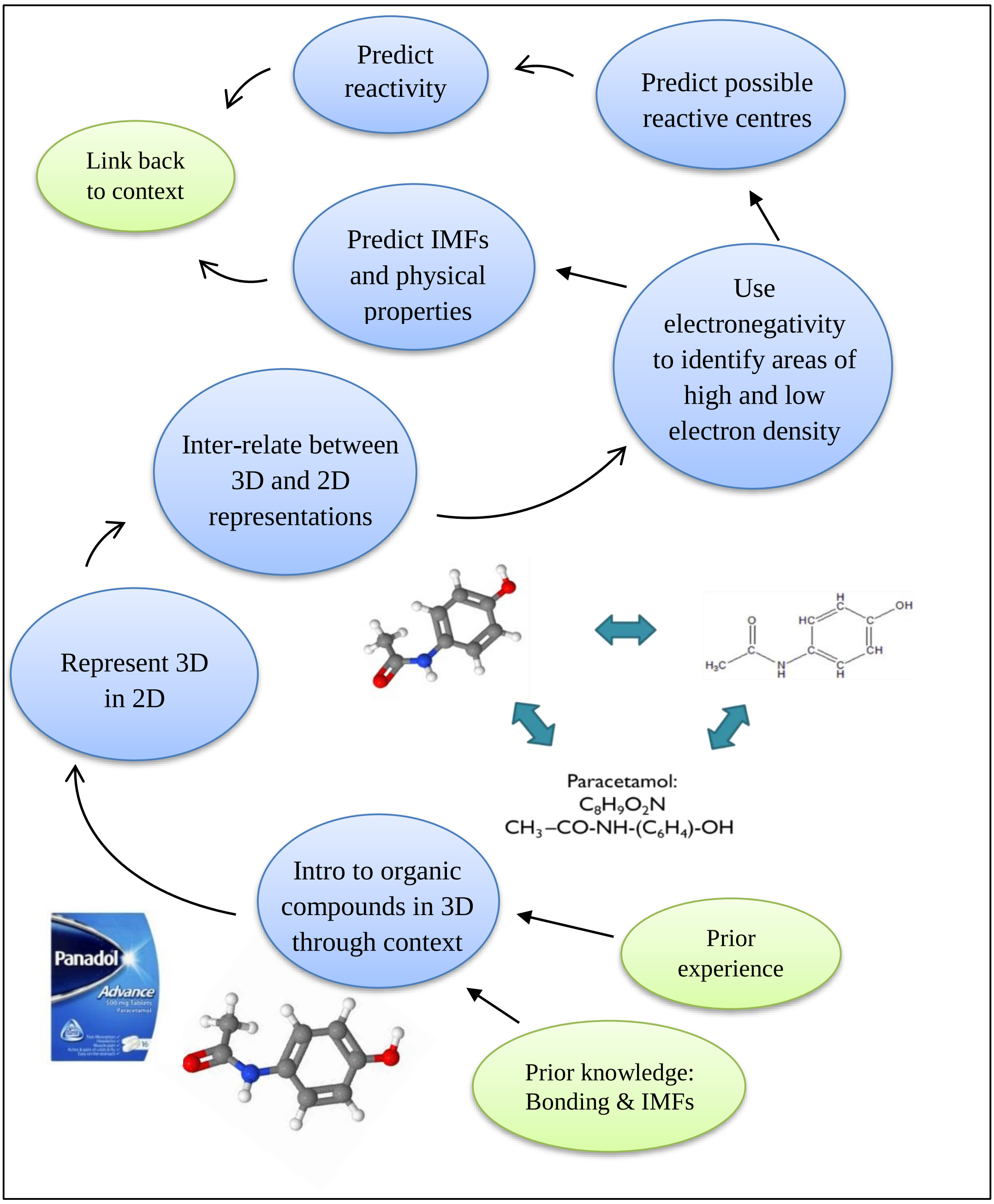


Figure 4.3: Learning Progression of the OCV programme

4.1.3 Structure of the OCV Programme

Having discussed the core values that will inform the design of the OCV programme and outlined the learning progression that the programme will follow, the structure of the OCV programme will now be detailed.

The programme is split into three main parts (see Table 4.1). Each part is split into chapters, with eight chapters in total. Each chapter contains a series of activities followed by 'Challenge Questions'. The structure and sequence of the activities were finalised following feedback from the pilot study, which will be discussed in Section 4.5.

Table 4.1: Summary of the OCV programme

Part	Concepts	Chapters
A	Modelling and visualisation of organic molecules	1-5
B	Predicting and comparing physical properties of organic compounds	6-7
C	Predicting reactivity of organic molecules	8

Table 4.2 summarises the learning outcomes that were identified for each chapter. It should be noted that the OCV programme was not designed to align with the current LC chemistry syllabus. It was designed with the Key Skills Framework developed by the NCCA (2009) in mind, as discussed in Section 2.1.5.

The total number of class periods suggested for the implementation of OCV is approximately 27, as shown in Table 4.2.

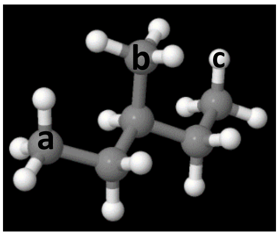
Table 4.2: Learning Outcomes of each chapter of the OCV programme

	Chapter	Learning Outcomes.	Approx. no of classes
Part A	1	**Students will be:** - aware that there is a large variety of organic molecules with many different uses - aware that all organic molecules contain at least hydrogen and carbon - aware that carbon has 4 bonds (tetravalent) - aware that hydrogen has 1 bond (monovalent) - familiar with the use of molecular models to represent molecules	**1**
	2	**Students will** - be more familiar with the use of molecular models to represent molecules - be able to construct models of hydrocarbons - understand the term hydrocarbon - be able represent 3D models of hydrocarbons as 2D drawings - be able to construct 3D representations from 2D drawings of hydrocarbons - use the molecular formula to represent hydrocarbons - apply the IUPAC rules for nomenclature to hydrocarbons	**3**
	3	**Students will be able to:** - construct models of molecules containing the following functional groups: -OH; >C=O; -COOH; -COOR; -Cl; -Br; $-NH_2$; =NH; - represent these molecules using 2D drawings and write their molecular formula - apply the IUPAC rules for naming compounds containing these functional groups	**2**
	4	**Students will:** - understand the concept of isomers - be able to construct 3D models of and draw 2D representations of all isomers for any hydrocarbon up to 8 carbons - be able to describe how double carbon- carbon bonds influence the spatial arrangement of atoms in molecules -understand the significance of cis/trans isomers in relation to animal pheromones - apply the IUPAC rules for nomenclature in relation to structural and geometric isomers	**3**
	5	**Students will be able to:** - identify the position of electrons in polar covalent bonds - identify areas of high and low electron density in molecules containing electronegative elements - represent partial charges in complex molecules using δ^+ and δ^-	**2**

Part B	6	**Students will be able to:** -predict and compare the boiling point of straight chain organic compounds (based on C6) and their isomers, using intermolecular forces and the shape of the molecule to rationalise their prediction - predict and compare the boiling point of organic compounds containing hydrocarbon, oxygen, nitrogen and halogen functional groups, using intermolecular forces and the shape of the molecule to rationalise their prediction	**4**
	7	**Students will be able to:** - predict and compare the solubility in water and hexane of organic compounds containing hydrocarbon, oxygen, nitrogen and halogen functional groups, using intermolecular forces and the shape of the molecule to rationalise their prediction	**7**
Part C	8	**Students will be able to**: - describe an electrophile and nucleophile - predict reactive centres in any organic molecule in the presence of electrophiles and nucleophiles	**5**

Part A of the programme focuses on the visualisation of organic molecules and enabling students to inter-relate between 3D and 2D representations of organic compounds. Students are first introduced to complex organic compounds using models and real-life examples of these compounds (such as paracetamol). Students then go on to construct simple hydrocarbons and are led to using appropriate 2D representations of these hydrocarbons. Activities are designed to facilitate students' movement between different types of representations. An example of this is shown in Figure 4.4.

Match the atoms labelled in the 3D picture with their corresponding carbons in the 2D drawing of the following molecules:



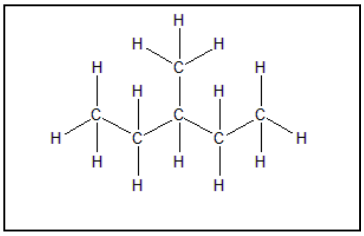


Figure 4.4: Activity designed to facilitate inter-relation between representations.

Students are introduced to the concepts of isomers, both structural and geometric, and polar organic compounds, through the use of models. Rules for IUPAC nomenclature are also introduced in this part of the programme; however, the emphasis is on constructing and drawing structures, with the IUPAC rules only being introduced when students are comfortable working with compounds in terms of 2D and 3D representations. The IUPAC rules were originally left out of the programme as it was felt they did not contribute to the overall aims of the project. However, they were included at the request of participating teachers following Implementation 1, who were still preparing their students for the LC chemistry exam, based on the current syllabus

In **Part B** of the programme, students discover how to compare and predict differences in the physical properties of organic compounds using intermolecular forces and the shape of the molecule. The physical properties focused on are boiling point and solubility in water, as students will be aware of these physical properties from their studies of science at Junior Certificate. Students are introduced to this section by giving the structures of three compounds. They are asked to draw their structures, identify the intermolecular forces present in the compound and depict the intermolecular forces between molecules of the compounds. The table into which they are asked to fill this information is shown in Figure 4.5. Following a discussion with the teacher, students are then asked to rank their molecules in order of increasing boiling point. Students can then check their answers with their teachers. Teachers are provided with a selection of three-compound groups and it is suggested in the OCV-TM that they repeat this activity until their students are confident in identifying intermolecular forces, depicting them and using them to predict relative boiling points. Once students are comfortable with this activity, the teacher can lead them through the rest of the chapter.

A core element of Part B is students being able to actually "see" how organic molecules behave. Students investigate these properties experimentally; first predicting what will happen, then conducting experiments, followed by using their previous knowledge to explain both their predictions and experimental observations. Students are introduced to the link between solubility in water and functional group using an experiment. Students are given a range of liquids whose molecules have the same number of carbons but different functional groups. The liquids are presented to students with their structure displayed and students are asked to predict which ones are going to be soluble in water. Students then test this, compare their observations to their predictions and then are led to examine the structures of each of the compounds to explain their observations. A section of the table in which students record this experiment is shown in Figure 4.6.

Another experiment which students carry out in this section is to identify the link between number of carbons and solubility in water of alcohols. This experiment is modelled on the demonstration from Barke et al (2012) discussed in Chapter 1.

Drawing of Compound			
Intermolecular Forces			
Representation of Intermolecular Forces			

Rank these compounds in order of *increasing boiling point*

(rank molecules 1-3 where 1=lowest boiling point, 3=highest boiling point)

Rank	**Molecule** (**draw structure**)
1= lowest boiling point	
2	
3= highest boiling point	

Figure 4.5: Introduction activity to Part B of OCV programme.

	A	B	C
Structure			
Prediction			
Will it be soluble in water? Why?			
Experimental Section			
Observation when added to water			
Conclusion: Is it soluble/insoluble/partially soluble in water?			
Can you explain why? (with reference to structure)			

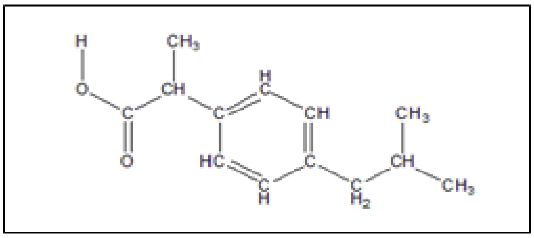
Figure 4.6: Table used for solubility experiment in Part B (Chapter 7) of OCV programme

Part C of the programme introduces students to the reactivity of organic compounds in specific conditions; the main focus is on the reactivity of organic compounds with electrophiles (such as H^+) and nucleophiles (such as OH^-, Cl^- and Br^-). With the ability to predict areas of high and low electron density in any molecule, students will firstly, be able to predict the possible reactive centres of any molecule and secondly, predict the most likely reactive centre when in the presence of electrophiles and nucleophiles. The focus of this chapter is not on students getting the 'correct' answer but in their ability to provide a comprehensive argument for their predictions. An example question is shown in Figure 4.7.

Activity 8.1

Ibuprofen is the active ingredient in Nurofen, a common anti-inflammatory used for pain relief, including migraine, headaches, back pain and muscle aches.

a) The structure of Ibuprofen is shown below. Identify the reactive centres of Ibuprofen in the presence of OH^- (circle them).



b) Redraw the structure below and on it; identify the reactive centre which you think OH^- is most likely to attack. Explain your answer.

Figure 4.7: Example question from Part C of OCV programme

4.1.4 Cognitive Demand of OCV Activities

A primary aim of the OCV programme is enabling students to predict and compare intermolecular forces (IMFs) and physical properties of organic compounds. When developing the OCV approach, several initial evaluation items were created. An example of these questions is shown in Figure 4.8.

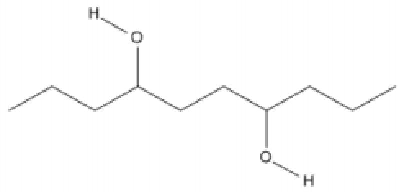
In Part A of this question, the structures of three molecules with different functional groups are given. All molecules have 10 carbons. Students are asked to first identify electron rich and electron poor centres within each molecule and then rank these molecules in order of increasing boiling point. The final question in this part asks students to explain their answer. It should be noted that the 'electron rich and electron poor' terminology was replaced with 'areas of high and low electron density' when developing the full OCV programme.

The structure of Aspirin is given in Part B. Similar to Part A, students are first asked to identify electron rich and electron poor areas in a molecule. Students are then asked to identify and label the reactive centres within the molecule if OH^- was added to it. Finally, students are asked to suggest which reactive centre would be the most likely to react with OH^-.

Part A

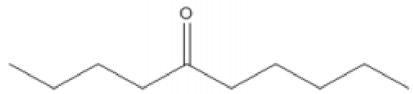
For the following molecules:

A.



B.

C.



i) Identify the electron rich and electron poor centres, i.e. assign δ^+ and δ^-, to the organic molecules above

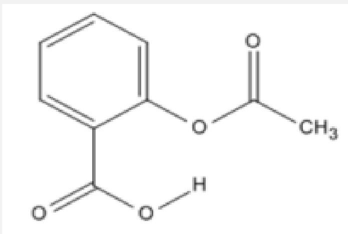
ii) Rank the organic molecules in order of increasing boiling point in the table below.

Lowest boiling point	
Highest boiling point	

iii) Explain your answer to part ii)

Part B

Acetylsalicylic acid, also known as Aspirin, is a common pain killer. Its structure is shown below:



i) Identify the electron rich and electron poor centres in Acetylsalicylic acid, i.e.: assign δ+ and δ- to the structure above

Redraw the structure of acetylsalicylic acid.

ii) If OH^- is added to the molecule, identify the reactive centres of the molecule, i.e.: where in the molecule is the OH^- likely to react with.

iii) Label the reactive centres 1, 2, 3, etc.

iv) Propose which react centre you believe is most likely to react with the OH, explain your reasoning.

Figure 4.8: Question Y of the OCV programme analysed using assessment framework by Walshe (2015)

Question Y was analysed by Walshe (2015) using the framework outlined in Section 2.2.1. The results of this analysis are shown in Figure 4.9. Each part of this question was scored significantly higher than the typical LC question which was analysed in Section 2.2.1. The average demand of the assessment criteria is approximately 3 (manipulation, analysis and evaluation of data) and the average demand of the knowledge dimension is approximately 2.5, between conceptual and procedural knowledge. The average demand of the cognitive process dimension is approximately 4.5, between analyse and evaluate.

This analysis demonstrates the higher order nature of the thinking involved in the OCV approach. Through the use of questions like Question Y, higher order thinking skills can be developed within students, in line with the Key Skills Framework discussed in Chapter 2. While this framework was not applied to all questions developed within the OCV programme, this particular question is illustrative of the quality of thinking which the OCV programme aims to promote within students.

	Question	A	K	C
A i)	Identify the electron rich and electron poor centres to the organic molecules	3	2	4
A ii)	Rank the order of increasing boiling point	3	3	4
	Explain your answer to ii)	4	2	6
	Highest demand	4	3	6
	Average demand	3.3	2.3	4.6
B(i)	Redraw	2	3	2
B (ii)	Label reactive centres if OH- is added	3	3	5
B (iii)	Propose which react centre is most likely to react with the OH^-explaining your reasoning	4	2	6
	Highest demand	4	3	6
	Average demand			

Figure 4.9: Results of analysis of Question Y of OCV programme by Walshe (2015)

4.2 OCV Materials

Teachers participating in the project were provided with a Teacher Manual (TM) and a Student Manual (SM) for each student in their class. Molymod molecular model kits were also provided for each student. Each of these materials will be discussed below.

The iterative approach taken in this project means that two versions of each of the manuals exist: the version for Implementation 1 that was developed following feedback from the pilot study and the finalised version which was used for Implementation 2 following evaluation of Implementation 1. The manual used in the pilot study will be discussed in this chapter, along with alterations made following feedback from the pilot study. The alterations made following evaluation of Implementation 1 will be discussed in Chapter 5. The final OCV programme (both TM and SM) are given in Appendix K and L on the included CD.

(a) OCV - Teacher Manual (TM)

The role of the teacher in the OCV programme is to lead students through the activities while encouraging discussion and comparison amongst students. The purpose of the TM is to aid teachers in achieving this. The TM contains the learning outcomes and rationale for the programme. At the beginning of each chapter, the learning outcomes are listed for the teacher, along with the corresponding page for each activity in the SM.

Details of each activity are outlined in the Teacher Manual, including a suggested sequence for guiding students through the activities, key discussion points to prompt students thinking, possible misconceptions that could arise and suggested answers. Key points of each activity are highlighted for teachers to encourage students to record in the 'My Chapter Notes' section at the end of each chapter. The final copy of the TM after Implementation 2 can be found in Appendix K on the included CD.

(b) OCV - Student Manual (SM)

The SM is basically a subset of the TM. It is designed so that students can move through the activities independently and at their own pace if required. This will allow teachers to facilitate the different levels of students that may be in their classroom. At the beginning of the SM, a box entitled ‘Understanding your Models’ is provided to illustrate to students what all the components of their model kit are (see Figure 4.10). Similar to the TM, learning outcomes are listed at the beginning of each chapter. At the end of each chapter, there is page entitled ‘My Chapter Notes’ for students to summarise the key learning of each chapter. It was suggested to teachers that they should allocate time for this activity. Final version of SM given in Appendix L on the included CD.

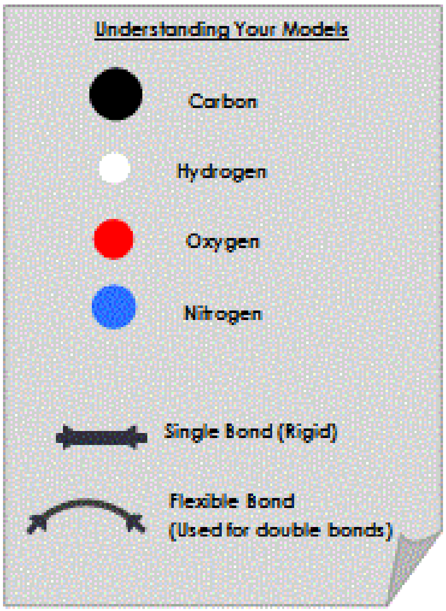


Figure 4.10: Understanding Your Models box provided to students in the OCV - Student Manual.

(c) Molymod Molecular Model Kits

Molymod molecular model kits were provided to each student who participated in the trial. These kits were composed of the following:

- 6 carbon ‘atoms’
- 14 hydrogen ‘atoms’
- 2 oxygen ‘atoms’
- 1 nitrogen ‘atom’
- 1 halogen ‘atom’
- 19 single bonds
- 4 flexible bonds

These kits contain significantly less atoms and bonds than traditional Molymod molecular model kits. The reason for this was primarily due to the cost of these full kits; the researcher wanted to ensure that each student could work individually with molecular models to gain the full benefit of modelling but also keep costs as low as possible. Full Molymod kits were bought and separated into the OCV kits. The activities in OCV programme were also designed with the availability of these kits in mind.

4.3 OCV Pilot Study

The pilot study took place in April 2013 and ran for approximately four weeks. A 5th year chemistry class from an all-girls secondary school participated in this study. This class reached the end of Chapter 7 of the original OCV programme.

The purpose of the pilot study was primarily qualitative; to gauge student and teacher engagement with the approach, the appropriateness of the sequence and structuring of the activities and the clarity of instructions for teachers, to determine a more accurate time-scale and to gain initial insight into the effect, if any, of this approach on spatial visualisation abilities and understanding of key organic chemistry concepts.

The Teacher Reflective Journal from the pilot teacher was analysed to identify students' engagement with the approach and areas of difficulty experienced by students and the teacher, to ensure teachers are provided with enough support and materials and to identify any changes that needed to be made to the manuals. Following the pilot study, a number of alterations were made to the TM, TRS and Spatial Visualisation Test. The feedback from the pilot teacher, the student difficulties that were identified and alterations that were made to the OCV materials will now be discussed

4.3.1 Feedback from Pilot Teacher

Feedback from the pilot teacher was gathered in the form of a reflective journal and informal discussions following execution of the pilot. The pilot teacher described a very positive engagement by students with the approach, both in terms of their modelling and willingness to engage in class discussion.

> *'This approach provoked discussion, interest and debate'.*

> *'For some reason, students were much more enthusiastic about the odours of these molecules when they were involved in molecule building than they otherwise would have been (going on previous years' experience). It seemed they had greater ownership of the phenomenon of how structure affects smell.'*

The pilot teacher also noted students' use of chemical concepts to argue their opinions:

> *'They argued that by looking at the molecular formulae, you could be sure the same molecules were involved'.*

There was a very collaborative feel to the pilot teacher's description of some class discussions, where students struggling to explain a phenomena were helped and guided by the teacher and their fellow class mates;

> *'Although there was an air of uncertainty, most recognised that these molecules would definitely have a different boiling point. Interestingly, this brought the idea of being able to convey a mental model to the surface. One student who knew what she was talking about and started off correctly answering the question, while bravely explaining her answer, got mixed up during her explanation as she was concentrating on getting the English right (she was a non-national but I'm not sure if this made any great difference). She also voiced that it was not easy to explain what was in her head. I asked her to use terms she was aware of which she duly did such as 'branching'. However, she got frustrated and did not finish her explanation. Another student took over for her and indicated that while the level of branching was the same, more carbon-hydrogen bonds were free for intermolecular bonding in D so this would have a higher boiling point.'*

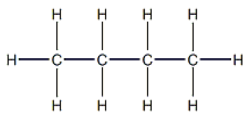
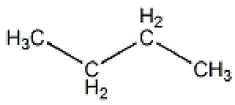
Students in the class were also noted by the pilot teacher to be making cross-curricular links with another subject;

> *'She said to the other two members of her group while modelling that there was 'no way one could fully understand biology without understanding this chemistry'. She argued, 'All biology classes contain this material if you think about it'.'*

Overall, feedback from the pilot teacher in terms of student engagement and discussion was extremely positive. The pilot teacher did identify the modelling approach as significantly time-consuming, along with drawing structures on the board. The teacher did however assert that the benefits of using the models outweighed the extra time required.

Some difficulties experienced by students were also identified. The key areas of difficulty which arose from the pilot were mostly related to structures:

- Using linear structures instead of more accurate 'zig-zag' structures, i.e.:

   instead of 

  The researcher used the linear method of drawing structures, as is found in the LC chemistry textbooks. However, during the pilot, the teacher noted that students drew their structures using the more accurate 'zig-zag' structure instead of the alternative shown to them by the teacher, demonstrating that students actually preferred to use this representation.
- Initially, the pilot teacher noted that students were mixing up the valency of carbon, oxygen and hydrogen atoms, when translating from 3D to 2D, with hydrogen being drawn as tetravalent and carbon being drawn as monovalent. It was suggested that this was possibly due to students not understanding the colour coding of the Molymod kits.
- Condensed structures representing H_3C- and -CH_2- were used initially in a number of questions without explanation of what this represents. Some students struggled with these representations and the teacher had to explain. It is for this reason that an activity to make this more explicit was developed and included in the programme for future trials.

4.3.2 Adaptions to OCV Materials following Pilot Study

The feedback obtained from the pilot study informed areas of improvement for the approach, activities and materials. No issue was identified with the sequencing of activities or chapters, so the overall structure of the approach was maintained. Perhaps most importantly, the representations used by students indicated that they preferred the use of zig-zag structures to linear, thus structures in the manuals were changed to this style of representation. Difficulties experienced by students identified a need for additional activities to make some forms of representations more explicit. The increased time requirement of the approach suggested the need for additional resources to aid teachers moving through the activities. These will be discussed.

(a) **Additional Activities**

The pilot teacher identified students' confusion between the valency of carbon and hydrogen during initial drawing activities. For this reason, an activity which involved students actually counting the number of atoms of each element within a range of molecules was added to OCV - Chapter 1. The molecules involved were butane, paracetamol and vanillin.

Figure 4.11 shows an activity designed to further facilitate this learning, in which students are given six structures and asked to identify any that are incorrect. Structures (a), (c), (e) and (f) have incorrect valency.

Can you identify which of the following drawings of organic molecules are incorrect? Circle which parts of the molecules are incorrect. (Construct them if necessary)

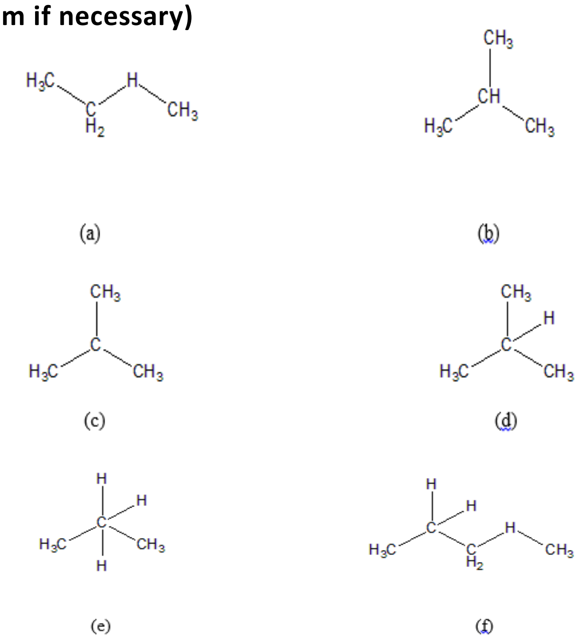


Figure 4.11: Activity designed to facilitate understanding of valency of carbon and hydrogen in OCV programme.

Another difficulty identified by the pilot teacher was the use of condensed formulae such as CH_3. The activity shown in Figure 4.12 was designed to help students form an understanding of these representations. Students are given structures with extended hydrogens and asked to redraw the structure with condensed hydrogens and given structures with condensed hydrogens and asked to redraw the structure with extended hydrogens. Students are also instructed to construct the structures using their Molymod kits.

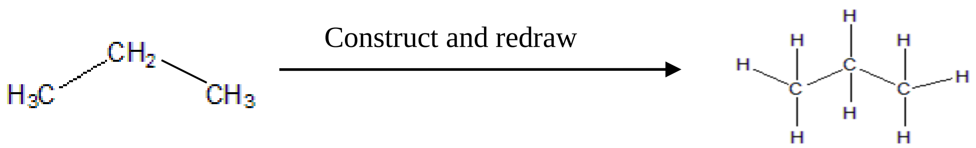


Figure 4.12: Activity designed to facilitate understanding of condensed structures.

'Challenge Questions' were also added to the end of each chapter to further encourage students who are capable of moving through the activities on their own.

(b) **Additional Resources**

PowerPoint slides were provided as an extra visual aid for the teacher to display learning outcomes, activities and answers to activities. These were included at the request of the pilot teacher, who identified time as a possible barrier to fully completing all activities. Additional animations/diagrams were included in these presentations as supplementary material for teachers. For example, additional animations and diagrams are provided to aid the explanation of tetrahedral and planar carbons.

Chapter 1 of this thesis identified the use of molecular modelling software with an animation tool as an effective tool to aid understanding of processes at the molecular level. The main reason for not including this in the OCV programme was the time required to teach students how to use the software. It was felt that this would be too much additional time on top of the time taken to implement the modelling approach. However, in order to examine its potential for including this type of environment in future OCV implementations, a case study with 2nd year undergraduate pre-service teachers was run. This will be discussed in Chapter 7 of this thesis.

(c) **Teacher Manual**

Following the pilot implementation, it was possible to gain a better insight into the time required for completing the activities developed. This allowed for a more comprehensive time-scale for the implementation of the full programme to be formulated, which was then included in the introduction of the TM. A small excerpt from the timescale provided is shown in Table 4.3

Table 4.3: Excerpt from suggested time-scale given in OCV - Teacher Manual.

Class #	Chapter	Pages in TM	Pages in SM	Activities	Concepts Covered
Part A approx. 10 classes					
1	1	15-18	4-6	1.1 – 1.3	Introduction to organic molecules
2	2	19-23	7-11	2.1 – 2.4	Constructing and drawing hydrocarbons

A table was also placed at the beginning of each activity, which provides a suggested time for the activity, the corresponding page in the SM for the activity and a brief rationale or description of the activity. Suggestions for guiding students through each activity are included in this table. Figure 4.13 displays an example of this table. The purpose of this was to make the TM and SM easier for teachers to navigate.

Activity 2.2

Suggested Time: 10 mins	**S.M page: 8**
The purpose of this activity is to get students thinking about how to represent these 3D molecules using 2D drawings. You need to lead them to using the normal 2D structure towards the end of the activity; it is important that you don't simply tell them.	

Figure 4.13: Example of information provided to teachers at the beginning of each activity in the OCV - Teacher Manual.

(d) **Teacher Reflection Sheets (TRS)**

Based on the pilot teacher's use of a reflective journal, the TRS were modified to give teachers clearer reflective guidelines. The following modifications were made to the TRS following the pilot study:

> 'Could students carry out the activities suggested?' was changed to: 'Rate students' ability to carry out the activities suggested'. Teachers were given a scale of 1-5 for this question, with 1 being not able and 5 being fully able.
>
> Similarly, 'Do you think students achieved the anticipated learning outcomes?' was changed to 'Rate students' achievement of the anticipated learning outcomes and state evidence for this'. Again, teachers were given a scale of 1-5 for this question, with 1 being not achieved and 5 being fully achieved.

Teachers were also provided with space to elaborate on these items. The above changes were made to make it easier for teachers to complete and to avoid 'Yes or No' answers, making the answers more meaningful.

4.3.3 Conclusions from Pilot Study

The overall feedback from the pilot teacher was very positive in terms of the students' engagement and willingness to participate in the modelling activities. The pilot study provided an insight into how teachers would use the OCV materials and changes that could be made to make the materials more 'teacher friendly' and easier to use.

4.4 Summary

This chapter described the development of the OCV approach and materials. The seven core values that the approach was designed around were detailed in Section 4.1. The use of physical models to promote the inter-relation between 3D and 2D representations is a foundational aspect of the OCV approach. Activities were designed with a social constructivist approach in mind, with discussion being a core element of the activities. Relevant molecules were used to pique students' interest and motivation. When students are comfortable translating between different representations of organic compounds, they will use areas of high and low electron density to predict and compare their physical properties. Physical properties were further investigated using a phenomena-oriented experimental work.

The OCV programme comprises three parts; Part A, Part B and Part C. The learning outcomes for each part of the OCV programme were outlined in Section 4.1.3. An example question from the OCV programme was demonstrated to be of higher order than typical organic chemistry questions found on the LC exam in Section 4.1.4.

Section 4.2 detailed the development of materials for the OCV programme. These included the TM, SM and Molymod kits.

Finally, Section 4.3 described the pilot study of the OCV programme. Feedback from this pilot was very positive in terms of the students engagement. The pilot study informed necessary adaptations to the OCV materials for a full implementation of the programme. Following these adaptations, the approach was finalised and teachers were recruited for a full implementation of the programme. This implementation will now be discussed in Chapter 5.

Chapter 5

Implementation 1

Introduction

Implementation 1 of the OCV programme took place between February and May of 2014. Six class groups were involved. As can be seen from Table 5.1, each participating teacher spent a different number of weeks implementing the OCV programme and only class 1D finished the full programme. The other class groups finished at different sections of the programme, this is detailed in the final column of Table 5.1. Teacher D continued the programme in September of 2014 to fully complete the programme.

Table 5.1: Breakdown of participants in Implementation 1

Class	Teacher	School Gender Mix	No. of Students (N*)	No. of Observations	No. of weeks teaching **	Section of the programme finished
1B	B	Girls	9	2	5	Part B.
1C	C	Co-ed	16	3	6	Part B
1D	D	Boys	11	2	3	Chapter 6
						Part C in Sept.
1E	E	Boys	11	1	3.5	Part A
1F	F	Girls	5	2	2	Section 3.2
1G	G	Co-ed	11	¥	8	Chapter 6
	6 Groups		**N = 63**	**N= 10**		

* N refers to the number of students in the class who completed the pre and post spatial ability tests and the post-implementation assessment.
** Number of weeks teaching is based on 5 classes a week, 3 single and 1 double
¥ This class was taught by the researcher and took place over 8 weeks with three classes per week

Due to the participating teachers' individual class plans, each class group began the programme at different times of the year. This staggered implementation had both positive and negative outcomes. The staggered implementation of the programme allowed for the molecular model kits to be shared amongst the class groups, for example: as class group B finished the programme and no longer needed the molecular model kits, class group E was only beginning the programme. This allowed for each student in the pilot programme to gain the benefits of using their own molecular model kit. On the other hand, class groups who started later in the year (after Easter holidays, 1st May) came under pressure after a couple of weeks into the programme due to end-of-year school activities and commitments. As a result, differing amounts of time were spent on the implementation of the programme by different class groups.

The researcher implemented the programme with Class 1G, a TY class group. Due to the class level, implementation of the programme varied slightly. Instead of the standard five classes a week, the TY class had three classes a week; one single class and one double class.

Evaluation of Implementation 1 of the OCV programme was triangulated using multiple data from three sources: the teachers, students and that collected by the researcher. These are summarised in Figure 5.1.

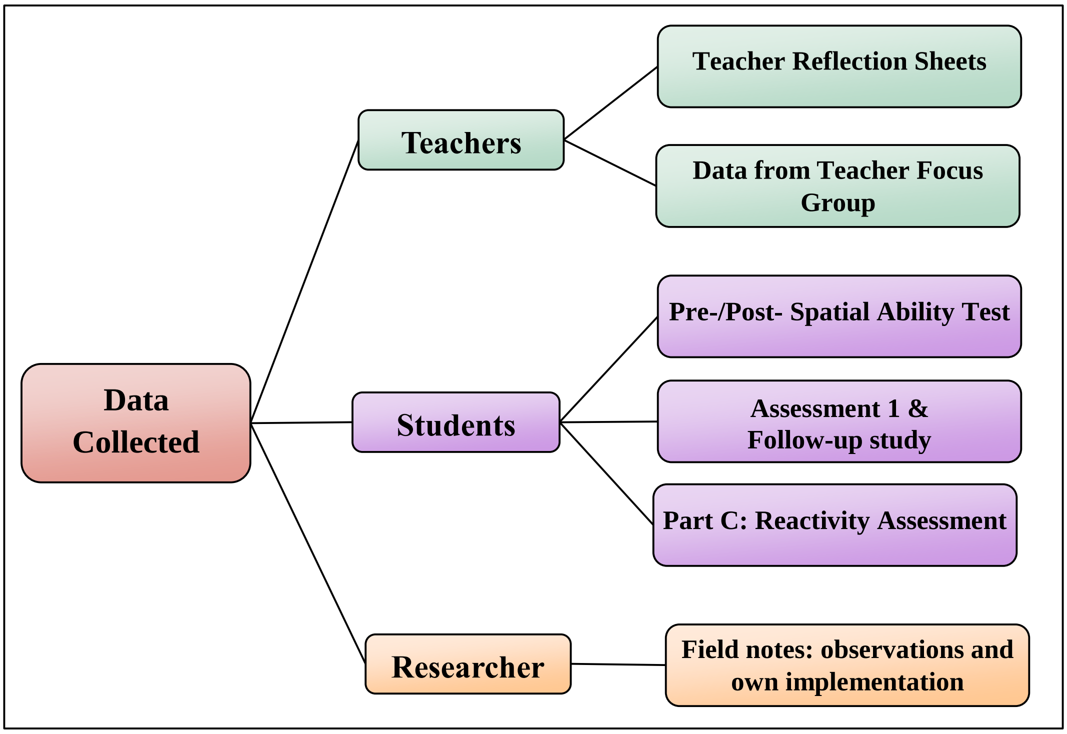


Figure 5.1: Summary of the sources and types of data collected in Implementation 1

To evaluate student learning and achievement of the learning outcomes of the OCV programme, data from students is considered first and then discussed using input from the teacher and researcher collected data.

5.1 Student Data

Data were collected from students in Implementation 1 in the form of, pre and post spatial ability tests, Assessment 1 and an additional follow-up study with three students from class group 1B following assessment, see Figure 5.1. Each of these will now be discussed and summarised.

5.1.1 Spatial Ability Tests

All class groups completed spatial ability tests at the beginning and end of the programme. The development of the 10-item test was discussed in Section 3.4.3. The purpose of this test was to measure a change in students' spatial ability rather than to measure their absolute spatial ability A paired-samples t-test was conducted to compare students' results in the pre and post spatial ability tests. There was a significant difference between students scores in the pre-test ($M= 5.79$, $S.D=2.069$) and post-test ($M=6.63$ $S.D=2.094$); $t(55)= -3.577$, $p= 0.001$. These results suggest that students' spatial ability has improved through the use of the molecular model kits and learning through the OCV approach.

There was, however, no correlation found between students' spatial ability score and their overall score on Assessment 1. This contrasts with previous research identifying the link between spatial ability and organic chemsitry (Pribyl and Bodner, 1987; Small and Morton, 1983; Bodner and Guay, 1997).

There was no statistically significant difference found between male and female scores on either the pre-spatial ability test, the post-spatial ability test or their scores on Assessment 1. These results suggest that those students who scored higher on the spatial ability test were not necessarily better at the questions in Assessment 1 and thus, this approach is useful for all students, regardless of their spatial ability.

5.1.2 Assessment 1

The students involved in Implementation 1 (N=62) completed Assessment 1. However, only 47 of the completed assessments were available for further analysis as, due to unforseen circumstances, it was not possible to obtaincopies of the Assessment 1 from Class C. Class D also completed a further assessment based on Part C: Reactivity of Organic Molecules of the OCV programme in the following Septemeber; these results will be discussed further in Section 5.4.

Students' responses to Assessment 1 will be discussed on a question-by-question basis first, followed by a discussion of the emergent themes from the responses. There were seven questions in total. Each question will be presented, along with a rationale for the question and summary of results.

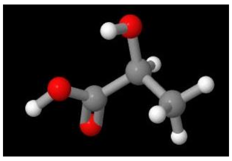
Assessment 1 - Question 1: Transfer from 3D to 2D representation

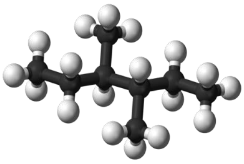
Question 1 assessed students' ability to translate a 3D representaion into a 2D representation. See Figure 5.2 for the rationale and summary of results for Question 1.

The majority of students were capable of completing this task. Students' ability to translate from the 3D picture into a 2D drawing indicates that students are able to differentiate between the atoms in the picture by colour and/or valency. It is interesting to note that students varied in their selection of complexity of their structures and the style selected; some drew the hydrogens extended, to explicitly show all the bonds, as in Figure 5.2, while some students condensed the hydrogens, as in Figure 5.3.

Question 1

Draw 2D structures of the following organic molecules represented by 3D pictures:

(a) 

(b) 

Rationale:

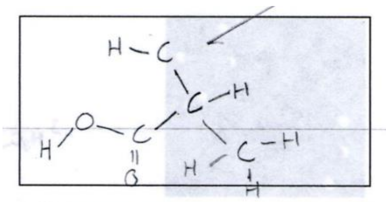
This question asks students to draw 2D structures from 3D representations of organic structures. The structure (a) contains 2 –OH groups and a carbonyl group, while structure (b) is a branched hydrocarbon. Students will need to remember the colour coding from using the Molymod kits to distinguish between different atoms.

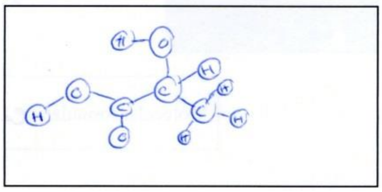
Summary of Results:

43 students successfully completed this task.

3 out of 4 students made mistakes with the first structure. All mistakes made by students concerned the valency of atoms. Their structures are shown below.

Incorrect Structures:

F2 

G9 

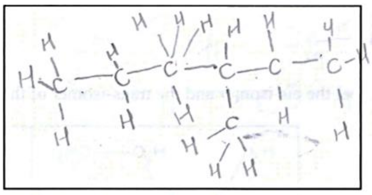
G18 

Figure 5.2: Assessment 1 - Question 1, rationale and summary of results

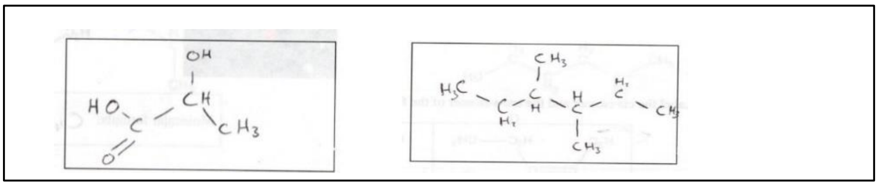


Figure 5.3: Example of structures drawn with condensed hydrogens

Some students also varied in the style of drawing their structures. Some opted for linear style with approximately 90 degrees between atoms, while some drew their structures in a zig-zag style. Students' selection was possibly influenced by the orientation and shape of the 3D representation presented to students. This will be examined further in Section 5.2.

<u>Assessment 1 - Question 2</u>: Identify isomers

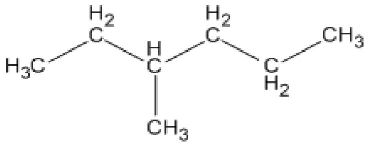
Question 2 assessed students' ability to draw isomers of a given structure. Figure 5.4 displays the question, rationale and summary of results. Examples of errors are also presented.

Table 5.2 details the number of students who were successful in identifying two isomers, students who were unsuccessful and the errors which arose in each class group.

The most common mistake made by students who could not identify any isomer was to redraw the original molecule with a different orientation; two examples are shown in Figure 5.4. Three students appeared to struggle to maintain the correct number of carbons when attempting to draw the structures of isomers. These students drew structures containing 6, 8 and 9 carbons. Two of these students could draw one correct isomer but drew a second structure with an incorrect number of carbons. These structures could be interpreted as a counting error rather than a misunderstanding of isomers. The third student, B2 in Figure 5.4, drew one structure with 8 carbons and one structure with 9 carbons. Again, this could be interpreted as a counting error, however, without asking the student it is not possible to know this.

Question 2

Draw 2 isomers of the following molecule:



Rationale:

Question 2 presented students with a structure and asked them to draw two isomers. There are nine possible isomers of the given structure. This will test students' understanding of isomers while further assessing their ability to represent in 2D.

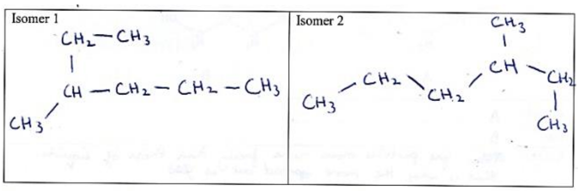
Summary of Results:

28 out of 47 students could draw two correct isomers. Eight students could draw one isomer and eleven students were unsuccessful at drawing any isomers.
Student errors fell into four categories:

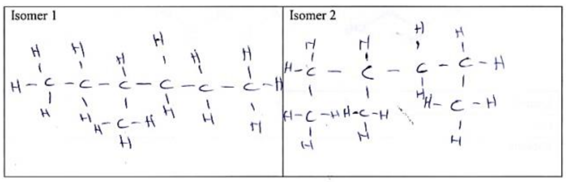
- The original structure was redrawn (see G7 and E9 below);
- The number of carbons was not maintained (see B2 below);
- Structures were drawn with a double bond (see E4 below);
- No attempt.

Examples of Errors

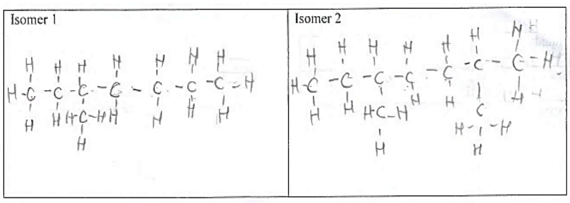
G7



E9



B2



E4

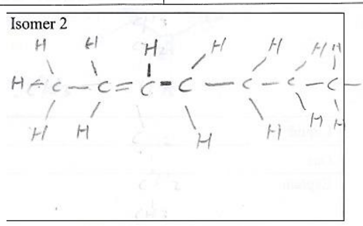


Figure 5.4: Assessment 1 - Question 2, rationale and summary of results

Table 5.2: Breakdown of student succes and errors in Assessment 1 – Question 2

Class	Isomers Identified			Errors			
	2	1	0	Same as original	# of C not maintained	Isomoers drawn with double bond	No attempt
B n=9	6	2	1	1	1		1
D n=11	10	0	1				1
E n=11	5	2	4	1		3	2
F n=5	2	1	2	2	1		
G n=11	5	3	3	3	1	1	1
Total= 47	**28**	**8**	**11**	**7**	**3**	**4**	**4**

One student in particular was originally marked as failing to identify any correct isomers as they did not maintain the correct number of carbons. Two structures were drawn with six carbons, see Figure 5.5. However, the two structures drawn were in fact isomers of themselves. Thus, it can be interpreted that this student had an understanding of the concept of isomers but simply made a counting error.

F9

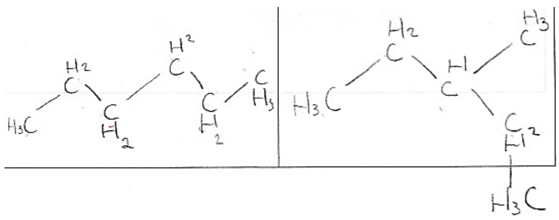


Figure 5.5: Assessment 1 – Question 2. Examples of structures drawn by students with incorrect number of carbons

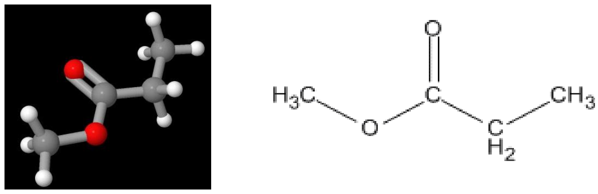
Students in Class E appeared to struggle with isomers, as they drew molecules containing double bonds. It is possible that students confused this question with geometric isomers. Thus, perhaps the question should have been worded to ask for two *structural* isomers. Nonetheless, it indicates confusion around the concept of isomers, as the ratio of carbons and hydrogen is not maintained by inserting a double bond into the structure.

<u>Assessment 1 - Question 3</u>: Structural formula to molecular formula

This question asks students to identify the components in a structure and translate into a molecular formula. See Figure 5.6 for Question 3, rationale and summary of results.

<u>Question 3</u>

Write the molecular formula for the molecule represented in both 3D and 2D below.



Molecular formula:

Rationale:

Question 3 asked students to construct the molecualr formula for a molecule that is presented to them in both 3D and 2D. The molecule was given in both forms to facilitate students who are more comfortable working in one form or the other.

Summary of Results:

43 students successfully completed this task.

2 students did not make an attempt at this question. 2 students identified the number of components incorrectly.

Figure 5.6: Assessment 1 **-** Question 3, rationale and summary of results

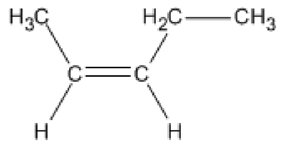
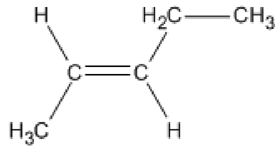
The 2 students who gave formulae with an incorrect number of components could either be considered totally incorrect or be considered correct but for a counting error. One of these students could identify the correct number of hydrogens and oxygens but had an extra carbon in their formula. The other student had the correct number of carbons and hydrogens but an incorrect number of oxygens.

<u>Assessment 1 - Question 4</u>: Identify cis and trans isomers

Question 4 was a naming exercise in which students were asked to identify the cis and trans isomers of a pair of alkene isomers. Figure 5.7 details Question 7, the rationale for the question and the summary of results.

<u>Question 4</u>

Label the cis-isomer and the trans-isomer of the following isomer pair:

Rationale:

This question asks students to identify cis and trans isomers of pent-2-ene. The structures are oriented in such a way as to give a hint to students that the double bond is important in this question.

Summary of Results:

Only classes B and D attempted this question as this section was not covered by classes E, F or G. All but four students were correct.

Three students who were unsuccessful in this question were from class B. One unsuccessfully attempted to write the molecular formula of the structures, one unsuccessfully attempted to write the structures in condensed form and the other student attempted to depict the electron distribution within the molecule, i.e. assign partial charges.

1 student did not attempt this question.

Figure 5.7: Assessment 1 - Question 4, rationale and summary of results

The unsuccessful attempts by the three students from class B indicate a clear lack of understanding of the terminology of cis and trans isomerism. The students who re-wrote the structures in the form of molecular formula and condensed structure could have been influenced by the previous question as they were unsure of what the question was actually asking.

It is interesting to note that the student who attempted to write the molecular formula for each compound redrew the structures given into a form that they were obviously more comfortable in, see Figure 5.8. This translation was successful; however, the student was still unable to write the correct molecular formula. Interestingly, the student could count the correct number of hydrogens but not the correct number of carbons. This student made the same error in Question 3, so it is possible that there is a misidentification of components rather than a counting slip.

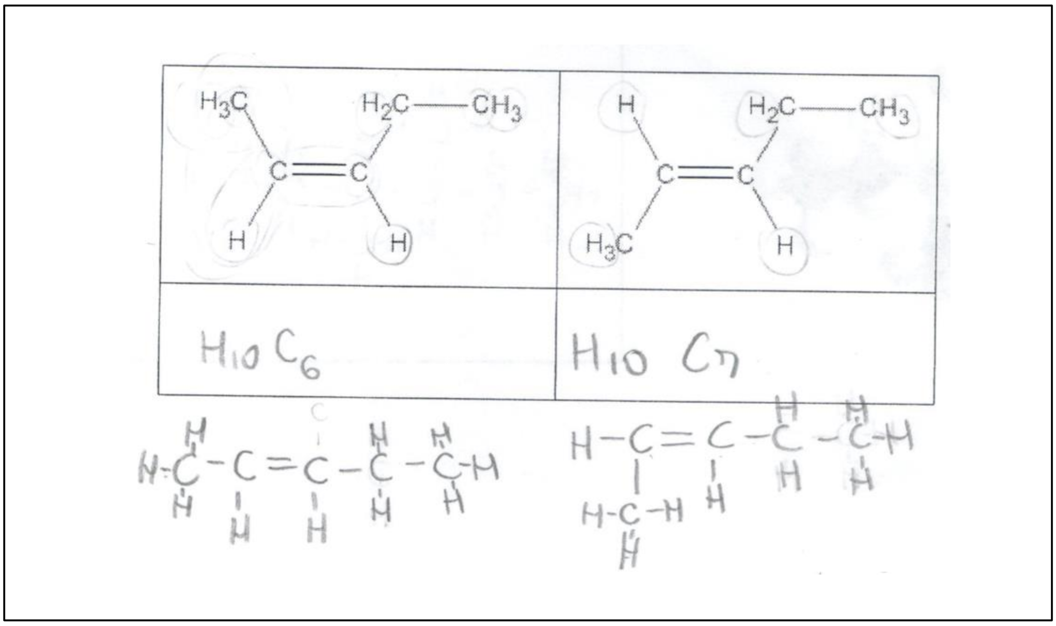


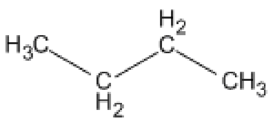
Figure 5.8: Assessment 1 – Question 4, drawing from Student B7

<u>Assessment 1 - Question 5</u>: Predict physical state using knowledge of intermolecular forces

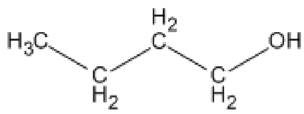
Question 5 asked students to compare the structure of two compounds and predict the physical state of each. Figure 5.9 details Question 5, a rationale for the question and a summary of student success.

<u>Question 5</u>

One of the organic compounds below is a gas at room temperature and the other is a liquid at room temperature. Using your knowledge of inter-molecular forces, suggest which compound is a gas and which is a liquid. Explain your answer.



A



B

Rationale:

Students were presented with the structures of two relatively simple compounds, butane and butanol, and told that one exists as a gas while the other exists as a liquid. Students were required to identify the –OH group in compound B as contributing to a higher boiling point and offer a full explanation of how this will result in different intermolecular forces and thus, different states.

Summary of Results:

Class B, D, F and G attempted this question. This section was not covered by class E.

29 out 36 students correctly identified the liquid and gas, however only 4 could fully explain their prediction. The majority (14) provided incomplete explanations. 7 students incorrectly identified A as the liquid.

Figure 5.9: Assessment 1 - Question 5, rationale and summary of results

Table 5.3 gives a breakdown of students' answers to Assessment 1 – Question 5. As can be seen in this table, 29 students correctly identified B as the liquid and A as the gas. For a student's explanation to be considered a full explanation, students were required to identify and describe the intermolecular forces between molecules. For example:

'B is a liquid at room temperature as both Van der Waals forces and hydrogen bonds can form between molecules of B. Only Van der Waals forces can form between molecules of A. Since B has stronger intermolecular forces than A, it is a liquid at room temperature.'

Students' answers were considered incomplete if students identified the intermolecular forces but did not discuss them between molecules.

'B would have a higher boiling point because it contains a hydrogen bond which is stronger than Van der Waals, which A has.'

These types of explanations are not considered incorrect but it is not clear if students understand the concept of intermolecular forces occurring between molecules rather than within molecules.

Table 5.3: Breakdown of students' answers to Assessment 1- Question 5 of Assessment 1

Class	Correct answer N= 29					Incorrect Answer N= 7		
	Full explanation	Incomplete explanation	Incorrect explanation			Incorrect explanation		
			-OH group part of chain	Other	No Attempt	-OH group part of chain	Other	No Attempt
B n=9	1	4			2	1	1	
D n=11	2	4	4			1		
F n=5		2		2	1			
G n=11	1	4		2			2	2
Total= 36	4	14	4	4	3	2	3	2

A misconception which appeared mostly in the Class D responses is the idea of the -OH group being part of the main chain of the molecule and thus, giving the molecule a higher boiling point. All of these students also identified molecule B as undergoing hydrogen bonding, indicating there is a misunderstanding of what comprises the main chain of an organic molecule. Explanations that are classified as 'other' included students referring to the number of bonds within each molecule and identifying molecule B as a gas because it contains oxygen.

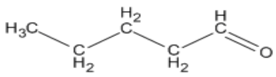
Questions 6 and 7 in Assessment 1 also assess students' understanding of intermolecular forces and physical properties. Students' answers in Questions 5, 6 and 7 will be compared to determine their understanding of the nature of intermolecular forces and physical properties. This will be discussed later in section 5.2.1.

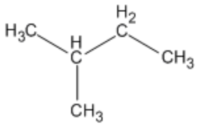
<u>Assessment 1 - Question 6</u>: Predicting and comparing physical properties of similar compounds

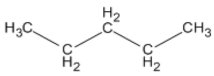
Question 6 asks students to compare the structures of four compounds and predict the order of their boiling point (BP). Figure 5.10 shows the structures given to students and provides a rationale and summary of student success for Question 6.

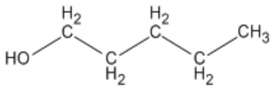
<u>Question 6</u>

Rank the following molecules in order of *decreasing* boiling point. (i.e.: highest to lowest). Explain your answer.

A


B


C


D


Rationale:

This question requires students to first read the structures and identify any similarities/differences. It was hoped that students would recognise that B and C are hydrocarbons while A and D contain oxygen. It would be a starting point for students to first rank these relative to each other before ranking the full set of molecules in terms of boiling point (BP).

Summary of Results:

Class B, D and G attempted this question (N= 31)
17 students successfully ranked these compounds in the correct order of decreasing boiling point but only two of these students provided a full explanation of the intermolecular forces. 11 students were able to rank some of the molecules relative to each other, while three students were unsuccessful in ranking the compounds.

Figure 5.10: Assessment 1 - Question 6, rationale and summary of results

Table 5.4 gives the breakdown of students' rankings and the explanations provided for Question 6. Of the 17 students who were successful in ranking these compounds:

-only two provided a full discussion of intermolecular forces between molecules;

-13 of these were able to identify the intermolecular forces in each but did not discuss them fully.

As in Question 5, these are not considered incorrect responses but we cannot be sure of the students' full understanding of the link between intermolecular forces and boiling point.

Table 5.4: Students rankings and explanations for Assessment 1 - Question 6
<u>Note:</u> exp = explanation

Class	All ranked successfully N= 17				D highest and B lowest N= 2			C>B or D>A N= 5			Incorrect ranking but A with D, C with B N= 4			None N= 3	
	Correct exp		Incorrect exp			Incorrect exp			Incorrect exp		Correct exp				
	Full explanation	Incomplete explanation	-OH part of chain	No Explanation	Correct explanation	-OH part of chain	No Explanation	Correct explanation	Branching cause higher BP	No explanation	Full explanation	Incomplete explanation	No Explanation	Branching causes higher BP	No explanation
B n=9		3				1			2	1			1		1
D n=11	2	5	1									1		1	1
G n=11		5		1			1		1	1	2				
Total = 31	2	13	1	1	0	1	1	0	3	2	2	1	1	1	2

Incorrect explanations were similar to those given in Question 5. Students continued to identify the –OH group as part of the carbon chain while also identifying hydrogen bonding. Another misconception which arose in this question, in relation to B, is the idea that branching causes a higher boiling point rather than a lower boiling point.

Eleven students were successful in ranking some of the molecules relative to each other. These responses fell into three main rankings:

- D has the highest BP and B has the lowest BP;

-The BP of D is greater than the BP of A (D>A) or the BP of C is greater than the BP of B (C>B)

-Grouping D and A together and C and B together but none ordered correctly.

Two students were able to recognise that D would have the highest BP and B would have the lowest. It is possible that these answers were guesses; one student did not give an explanation for their prediction and the other identified the –OH group as being part of the chain in D, using the incorrect argument that a longer chain gave D the highest BP. This student was unsuccessful in Question 5 and also used this rationale in their explanation.

Five students could rank D relative to A (D>A) or C relative to B (C>B), however, students could not provide correct explanations. Three students could correctly rank D>A but incorrectly ranked B>C using the argument that branching causes a higher boiling point. Two students did not attempt to explain their rankings. Two students correctly ranked C>B but did not provide an explanation.

Four students' rankings, although unsuccessful, demonstrated their recognition of similarities between the hydrocarbons (B and C) and the oxygen containing compounds (A and D). Two of these students provided a reasonable explanation as to their rankings; indicating in their explanations that the hydrocarbons have lower boiling points than the oxygen containing compounds.

Questions 5 and 6 have revealed some gaps in students' ability to explain their understandings while also unveiling some core misconceptions. These will be discussed further in the section. Despite students' incomplete explanations, students' ranking in this question demonstrates their ability to examine, group and compare structures.

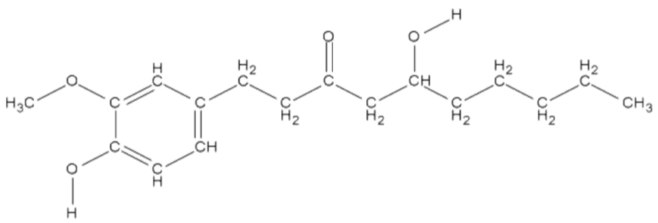
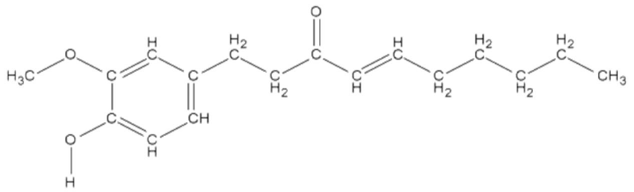
Assessment 1 - Question 7: Identification of electron density and prediction of relative physical properties

The structures of two relatively complex molecules are given to students. They are first asked to identify areas of high and low electron density and then predict physical properties. Figure 5.11 presents Assesment 1 - Question 7, the rationale for the question and a summary of students' success.

Question 7

Gingerol (structure A below) is the active ingredient in ginger.

When ginger is dried or cooked, Shogaol (structure B below) is produced. Shogaol also has a pungent ginger smell.

A Gingerol	
B Shogoal	

(a) Identify areas of high and low electron density in each compound on their structures above (i.e. assign partial charges)

(b) The boiling point of gingerol (A) is approx. 453^{o}C. Would you expect shogaol (B) to have a higher or lower boiling point than gingerol?

Explain your answer (consider intermolecular forces and the shapes of the molecules)

(c) Which of these compounds do you think will be **more** soluble in water?

Rationale:

Part (a) asks students to identify areas of high and low electron density in the structures of gingerol and shogaol. Large structures were selected to see if students could 'pick out' the important parts of the structure, such as the oxygen. This question was phrased two different ways, i.e. areas of electron density and partial charges were used to reduce students' failing at this question due to a misunderstanding of terminology.

In part (b) students were given the boiling point of gingerol and asked to predict if shogaol would have a higher or lower boiling point, with an explanation. Students will need to examine both structures and identify any differences between the molecules. The difference students were expected to recognise was the additional –OH group on the gingerol structure.

Part (c) asks students to predict which of these would be more soluble in water, with an explanation. Again, this is a relative question, and students need to decide which structure is going to have more interaction with water molecules.

Summary of Results:

Classes B, D and G attempted this question (N= 31), however only Class B attempted part (c) as Classes D and G did cover solubility.

(a) 17 students were able to successfully identify all partial charges, with a further five students identifying approximately half of the partial charges. Five other students attempted to apply partial charges to C-C bonds and C-H bonds. Four students did not attempt this question

(b) 20 students correctly identified shogoal as having a lower BP, however, explanations were still lacking full discussions of the link between IMFs and BP. 12 students identified the presence of extra hydrogen bonding in gingerol, while a further seven identified the presence of the extra –OH group in gingerol as significant.

11 students suggested shogoal would have a higher BP than gingerol. Six of these students identified the –OH group as an extra branch on gingerol which would cause it have a lower BP

(c) Six students attempted this question, five of which correctly identified gingerol as being more soluble.

Figure 5.11: Assessment 1 - Question 7, rationale and summary of results

Table 5.5 summarises the results of Assessment 1 - Question 7. Approximately half of the students were able to assign partial charges to the structures of gingerol and shogoal; nine students were unsuccessful, with four not attempting the question at all and 5 students attempting to apply partial charges to C-C and C-H bonds. These nine students clearly did not have an understanding of the terms areas of electron density or "partial charges".

Table 5.5: Breakdown of students' responses to Assessment 1 - Question 7

Class	(a) Assigning partial charges				(b) Shogoal BP						(c) Most soluble				
					Lower			Higher			A			B	
	All	Approx. Half	Applied to C-C and C-H bonds	None	Full discussion of link b/w extra hydrogen bond and BP	Extra hydrogen bond but no link to	Extra –OH group no explanation	–OH as extra branch.	Number of atoms	No attempt	Full explanation	Extra -OH	More negative charges from more oxygen	No explanation	No attempt
B n=9	4	3		2		5	1			3	1	1	3	1	3
D n=11	9		1	1	1	5	1	3		1					
G n=11	4	2	4	1		2	5	3	1						
Total = 31	17	5	5	4	1	12	7	6	1	4	1	1	3	1	3

Twenty students correctly identified shogoal as having a lower BP than gingerol; 19 of these could identify the extra –OH group in gingerol compared to shogoal as contributing to its higher boiling point but could not fully describe it. Despite students' incomplete explanations, this is a positive outcome as it demonstrates students' ability to compare larger molecules and identify specific components in their structures. Likewise, students' ability to identify partial charges demonstrates students can read larger structures.

Six students identified shogoal as having a higher BP than gingerol due to the extra –OH in gingerol being seen as a branch. While these students understand the concept of how branching affects BP, they are not clear on what constitutes a branch and what constitutes a functional group.

Only six students attempted Part (c) of Question 7, with five students identifying Gingerol as being the more soluble of the two compounds. Four of these students identified the extra –OH group or the negative charges on the oxygen as contributing to this but, again, did not fully complete their explanations. Only three students made a link between the partial charges on the oxygen in the molecules as contributing to the solubility of the molecules.

Results from Questions 1-4 indicate that the majority of students are capable of translating between different types of representations and working in 2D with structures. Students are also capable of comparing different structures of organic molecules and predicting relative physical properties. Students' explanations in Questions 5-7 indicate some gaps in their ability to fully communicate their understandings. Caution has to be taken when inferring students' understanding from their explanations. Incomplete explanations do not necessarily mean that students do not have a full understanding of the concepts but it is difficult to tell if they do. However, students' explanations did demonstrate the existence of some misconceptions related to structure and intermolecular forces. Students' responses to Assessment 1 will be compared to identify the consistency of students' use of representations, explanations and misconceptions,

While the aims of the OCV programme have been achieved with the majority of students who participated in the programme, the assessment of these students has primarily been in 2D ie a traditional pen-and-paper test with a pen-and-paper spatial ability test. These students were working with models for a significant length of time and their skills in working in 3D have not been assessed fully. Thus, a second implementation is required to assess students' ability to work in 3D following completion of the OCV programme.

5.1.3 Follow-up study with members of Class B

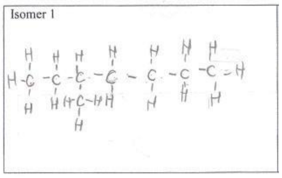
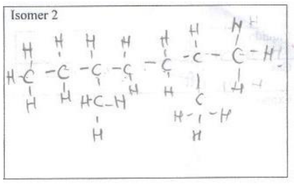
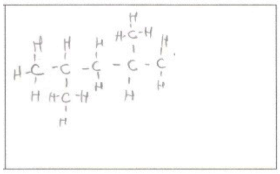
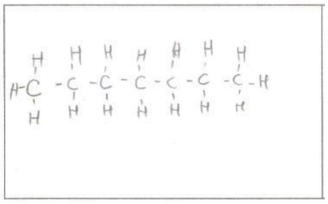
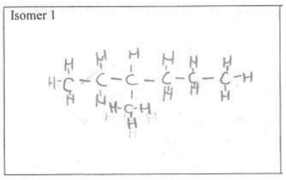
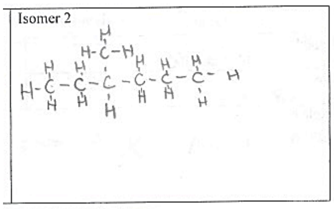
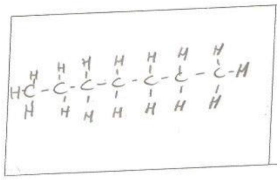
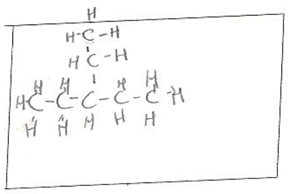
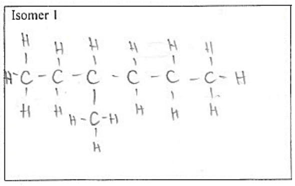
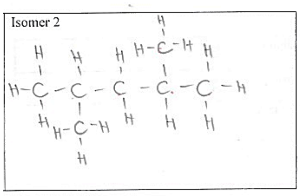
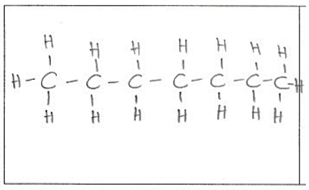
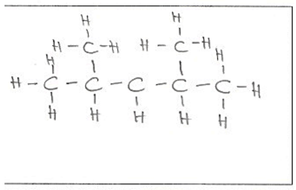
Following a discussion with Teacher B, it arose that English was not the first language of the majority of students in Class B. Taber (2015) discussed the limitations of questions where we cannot be sure whether students have understood the intended meaning of items, thus we may be picking up issues of limited literacy rather than indicators of poor conceptual knowledge. Three particular students in this class were unsuccessful in Questions 2, 3 and 4 of Assessment 1. These students had average spatial ability scores (5-7) which did improve between the pre- and post- spatial ability testing. These students were selected to participate in an additional study. The purpose of this study was twofold, to identify if these students:

1) Answered incorrectly due to a lack of understanding of the language, for example, the word 'isomer', and
2) Could answer correctly with the assistance of molecular models.

The three students were taken together for this study, however were sat facing away from each other so as not to influence each other's model and drawing. Each student was given three pre-made molecular models of 3-methylhexane, the original molecule from Question 2 of Assessment 1 (as in Figure 5.4). They were instructed to keep one molecule the same and to change the other two models in some way so that they have three different molecules. The word isomer was not used. Students were then asked to draw the new molecules.

During the follow-up study with these students, all three students were able to construct and draw two different isomers of the molecule. Table 5.6 displays the structures drawn by each student in Assessment 1 and those drawn in the follow-up study. The researcher observed students rotating and manipulating all three of their models to ensure that they did indeed have three different molecules before they drew their 2D representations, indicating students could recognise different arrangements of atoms in 3D to give different molecules.

Table 5.6: Students' drawings of isomers in Assessment 1 and the follow-up study.

Student	Isomers drawn in Assessment 1	Isomers drawn in Additional study
B2	 	 
B7	 	 
B9	 	 

There are two possibilities that can explain the students' improvement. First, the use of molecular models may have aided students in successfully identifying and drawing two molecules which are different to the original. These students spent a significant amount of time using the molecular models and transferring from their 3D structures to 2D representations. Thus, it was possibly easier for the students to successfully construct 2 different molecules, manipulate their models to confirm this and then draw them, as this is what these students have done in class.

The word 'isomer' was also omitted from this study. It is possible that students were unsuccessful in this question on Assessment 1 because they did not understand the term 'isomer'. Indeed, Taber's assertion that some language issues can be mistaken for a lack of conceptual knowledge may hold true in this case.

This follow-up study has important implications for Implementation 2. The 3D approach has not been assessed fully and Assessment 1 has reduced the approach to a 2D assessment of a programme which was focused on 3D structures and modelling. This has important implications for Implementation 2 as there is a need to redevelop the evaluation of student learning. Caution is also required to ensure that questions developed for evaluation of the approach actually assess what is intended to be assessed.

5.2 Consistency in Student Learning

Having discussed each question from Assessment 1 individually and identified areas where students achieved the learning outcomes of the OCV programme and areas where students could improve, themes which have arisen from student responses will now be discussed. Two particular themes emerged from student responses: the nature of students' drawings and the nature of discussions of intermolecular forces (IMFs). Students' drawings in Question 1 and 2 of Assessment 1 will be examained to determine if the style chosen by students was consistent. Students' explanations to Questions 5, 6 and 7 will be exmained to determine consistency in their predictions and application of IMFs.

5.2.1 The Nature of Intermolecular Forces

Analysis of the questions in Assessment 1 individually identified some key areas of learning for students in terms of predicting physical properties of organic molecules However, students' explanations revealed some gaps.

A common trend which arose in students' explanations in Questions 5, 6 and 7 was their lack of completeness. As discussed in Section 5.1.2, 28 of 36 the students successfully predicted which molecule would be a gas and which would be a liquid. While four students provided a full explanation, 14 students provided incomplete explanations to explain their predictions.

When presented with four molecules to compare in Question 6, the number of successful students fell to 15 of 31 students, with two students successfully providing a full explanation and 13 providing incomplete explanations. These students provided incomplete explanations for Question 5 also. The two students who provided full explanations for Question 6 also did so for Question 5. The other two fully successful students in Question 5 did not complete Question 6 and 7 of Assessment 1.

It is interesting to note that students were actually more successul in comparing the physical properties of two larger molecules in Question 7 than they were in comparing four smaller molecules in Question 6. Twenty of the 31 students correctly identified shogoal as having a lower boiling point than gingerol. This indicates that students were generally successful at applying their understanding to larger, more complex molecules. However, only one of these provided a full explanation and 12 provided incomplete explanations.

Students who provided incomplete explanations were not considered incorrect; all students identified the forces between molecules of each compound presented to them. However, these students did not discuss how they influenced the physical properties of the compounds being compared.

Students who offered incorrect explanations highlighted the existence of some misconceptions regarding the size and shape of molecules, the components of molecules and the intermolecular forces. Consistency in students' incorrect explanations regarding intermolecular forces will now be discussed under the following headings: (i) the effect of shape and size. and (ii) the effect of functional group .

(i) Effect of shape and size

The effect of chain length and branching on intermolecular forces is addressed in the OCV programme. Question 6 in Assessment 1 (Figure 5.10) required students to recognise the difference in structure between molecules B and C, both of which were hydrocarbons. Many students (17) successfully ranked all molecules in this question, indicating that these students had a good understanding of this concept, however, 13 of these provided incomplete explanations. These explanations identified the difference in structure between molecules B and C but did not go on to explain how the branching in B reduces the boiling point.

One student who correctly ranked the molecules in Question 6 incorrectly discussed the -OH group as being part of the main chain of molecule D, which along with hydrogen bonding contributed to it having the highest boiling point. This is a misconception that has arisen in all three questions 5, 6 and 7.

This particular student maintained this misconception throughout Question 5 and 6 and also incorrectly identified the extra –OH group of gingerol's structure as a branch which means it will have a lower boiling point than shogoal, when in fact it does not. Four other students who were successful in their predictions of Question 5 and 6 offered this misconception in their explanations. Despite the incorrect explanations, these students were successful in their predictions in Questions 5 and 6. However, they were unsuccessful in Question 7, as all four students also identified the –OH group as an extra branch on gingerol which would lower its boiling point.

Another misconception related to the shape of molecules which arose from students' explanation in Question 6 is the concept of branching causing a higher boiling point. While four students offered this misconception as part of their explanation, this was not carried on into Question 7 and all four students identified the –OH group in gingerol as the structural difference which would give it a higher boiling point than shogoal.

The existence of these misconceptions indicate some gaps in students' learning. Students who identified the –OH group as part of the main chain in compounds also recognised the ability for the compunds to undergo hydrogen bonding, indicating a misunderstanding of the difference between the main chain and its branches. The identification of the –OH group as a branch also indicates this misunderstanding. While the number of students identifying these misconceptions is small, the misconceptions were held throughout Questions 5, 6 and 7. These misconceptions will be discussed further with teachers during the teacher Focus Group.

(iii) Effect of functional group

Being able to recognise the existence of functional groups within molecules of compounds is the first step to identifying IMFs and thus predicting physical properties. The identification of the –OH group as part of the chain in Questions 5 and 6 and as a branch rather than an additional functional group in the structure of gingerol in Question 7 indicates a gap in students being able to recogise functional groups within molecules.

Interestingly, no student identified the =O in molecule A in Question 6 as resulting in stronger IMFs than the –OH group in molecule D.

5.2.2 Consistency in Student Drawings

Drawings of four 2D structures were required in Assessment 1: two structures in Question 1 and two in Question 2. Students' drawings are important to examine further as they can suggest elements of students' mental models. Students' drawings in these questions will be examined regardless of their success in completing the question.

As already mentioned in Section 5.1.2, students' styles of drawings varied. There were two main variations when students were drawing their structures; the style chosen and the extension of hydrogens. The two styles chosen by students were structures drawn in a linear style with approximately 90 degrees between angles or structures drawn in zig-zag style to reflect the 'true' shape of a carbon chain.

Students also either extended the hydrogens on their structures to explicitly show the bonding or chose to condense the hydrogens and only show the bond between carbons and/or oxygen.

Table 5.7 shows the percentages of structures drawn by students which showed either condensed or extended hydrogens. Approximately half of the students assessed drew structures which consistently either extended the hydrogens or condensed them; 14 students extended the hydrogens in all structures while 11 condensed them in all structures. A further 12 students drew half of their structures with condensed hydrogens and half with extended hydrogens.

It is suspected that the presentation of the molecules in Questions 1 and 2 influenced these students' preference for extended or condensed hydrogens. The molecules in Question 1 are 3D and clearly depict all bonds within the molecules, while the structure presented in Question 2 actually contains condensed hydrogens. All 12 of the students who drew 50% structures with extended hydrogens and 50% structures with condensed hydrogens, condensed the hydrogens in Question 1 but condensed those in Question 2, indicating their drawings were influenced by the presentation of each molecule.

Table 5.7: Percentage of structures drawn with extended or condensed hydrogens by students in each class.

Class	% of structures extended				% of structures condensed			
	100	75	50	25	100	75	50	25
B n=9	5	1	3				3	1
D n=11			1	2	8	2	1	
E n=11	5	2	4				4	2
F n=5	4				1			
G n=11			4	5	2	5	4	
Total= 47	14	3	12	7	11	7	12	3

Note: There are 4 structures in total, therefore, 75% = 3, 50% = 2, 25% =1

It is interesting then that the 14 students who drew 100% of their structures extended had to make the translation from condensed to extended hydrogens for their drawings in Question 2. In fact, five of these students were unsuccessful in identifying isomers, making the error of redrawing the original molecule twice with different orientations. Of these students, three were the students selected from Class B to take part in the follow-up study

Likewise, the 11 students who drew 100% of their structures condensed had to make the translation from extended to condensed hydrogens for their drawings in Question 1. All of these students were successful in making this translation. This could suggest that the translation from extended to condensed structure is easier than the translation from condensed to extended structure.

The other variation to students' structures was the style of drawing selected. Table 5.8 displays the percentages of structures drawn by students which were either zigzag or linear. It is possible that there is a teacher-effect influencing students' selection of style; however, this was not examined.

Table 5.8: Percentage of structures drawn using zigzag or linear style by students in each class.

Class	% of structures zigzag				% of structures linear			
	100	75	50	25	100	75	50	25
B n=9	1		1		7		1	
D n=11	4	6	1				1	6
E n=11				6	5	6		
F n=5	4	1						1
G n=11	6	4		1		1		4
Total= 47	15	11	2	7	12	7	2	11

Just over half of students drew structures which were consistently either zigzag or linear, with 15 students drawing 100% of their structures using a zigzag style and 12 students drawing 100% of their structures using a linear style.

A further seven students drew 75% of their structures using a linear style. All seven students drew molecule (a) in Question 1 using a zigzag style. Similar to students' use of extended or condensed hydrogens, it is suspected that the presentation of the molecule in this question influenced students' drawing style. Students' selection was possibly influenced by the orientation and shape of the 3D representation presented to students. A direct translation from the 3D representation of molecule (a) into a 2D structure would result in a zig-zag style representation. Figure 5.12 is an example of a structure which appears to be a direct translation (angles and orientation maintained). The dashed lines demonstrate each component of the molecule in the 3D representation lining up with the students' representation.

Similarly, the 11 students who drew 75% of their structures using the zigzag style used a linear style for molecule (b) in Question 1. Again, the orientation of this molecule which is very close to linear, could have influenced these students' selection.

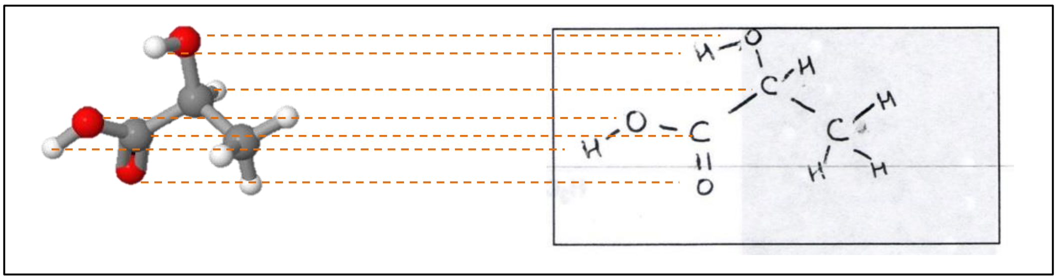


Figure 5.12: A 2D representation which appears to be a direct translation from the 3D representation. The dashed lines demonstrate each component of the molecule in the 3D representation lining up with the students' representation
Note: The 3D picture in this figure is the exact structure from Assessment 1 with the black background removed for the purpose of this comparison.

It is possible that the orientation of the pictures influenced students' drawings; however, without asking the students it is not possible to say if students simply copied the shape from the 3D representation or that was the shape chosen by the students themselves.

The preferences of students for representations for each structure are summarised in Table 5.9. The extended styles were preferred for structures in Question 1, while the condensed structures were prefered for structures in Question 2.

Table 5.9: Representational styles used for each structure in Question 1 and Question 2 of Assessment 1
Note: Ext = extended   Cond = condensed

Class	Question 1								Question 2							
	a				b				a				B			
	Ext + linear	Ext + zigzag	Cond + linear	Cond + zigzag	Ext + linear	Ext + zigzag	Cond + linear	Cond + zigzag	Ext + linear	Ext + zigzag	Cond + linear	Cond + zigzag	Ext + linear	Ext + zigzag	Cond + linear	Cond + zigzag
B n=9	7	2			8			1	5		2	2	5		2	2
D n=11		3	1	7		1	6	4				11			1	10
E n=11	6	5			11				6		4	1	6		5	
F n=5		4		1	1	3		1		4		1		4		1
G n=11		9		2	3		1	7			2	9			2	9
Total= 47	13	23	1	10	23	4	7	13	11	4	8	24	11	4	10	22

Just over half of students appeared to have a preferred style of drawing, whether this was a zigzag/linear style or condensed/extended hydrogens. It has been shown that students' who did not use a consistent style of drawing could have been influenced by the orientation of the molecules in Question 1 and the condensed presentation of the hydrogens in Question 2. Regardless, examination of students' structures indicate that the majority of students are capable of drawing structures in 2D.

In summary, analysis of students' drawings indicated students' ability to bring different styles (linear or zigzag) and levels of complexity (extended or condensed hydrogens) to their structures. It is possible that some students' structures were influenced by the manner in which molecules were presented to students. However, just over half of students stuck with their preffered style and level of detail, indicating they were comfortable enough working between the different types of 3D and 2D representations.

Student explanations were incomplete and lacking detail that would indicate a full understanding of the link between IMFs and physical properties. The majority of students were successfully able to identify the IMFs present in each question, however, they failed to demonstrate a clear and deep understanding. Students who could predict and compare the physical properties of smaller molecules in Questions 5 and 6, were also able to compare the physical properties of the larger and relatively more complex structures in Question 7.

Misconceptions which arose from a small group of students were focused around confusion between components of a structure; differentiation between a branch, the main chain and the functional group in molecules of organic compunds. This is an important discovery which informs the need for differentiation between these components of organic structures which is emphasised in Implementation 2.

5.3 Teacher and Researcher Data

Data was collected from teachers in Implementation 1 in the form of Teacher Reflection Sheets (TRS) and a Teacher Focus Group (TG). Researcher observations were used to gather further feedback and support feedback obtained from teachers.

Observation is a key component in the case study approach (Cohen, 2007). This allows the researcher to gain a clearer understanding of students' participation, engagement and motivation during the programme, while also identifying students' achievements and difficulties. The exact number of observations of each class can be found in Table 5.1.

An Observation Sheet was developed to correspond with the (TRS) to identify if the researchers' observations matched the recordings of the teachers. This can be found in Appendix D. Field notes were also used to record discussions between students that were overheard during observations.

TRS were useful to gain feedback from teachers after each lesson or series of lessons. TRS were collected from teachers B, C, D, E and F. The purpose of these reflection sheets was to give teachers a structured medium in which to record their immediate feedback and reflection on the lesson. The template for these reflection sheets can be found in Appendix C. Teachers were asked to:

-Detail any changes made to the lesson;

-Identify where students achieved the learning outcomes or experienced difficulties with achieving them;

-Identify any additional instruction that they or the students required and;

-Describe any changes they might make if they were to repeat the lesson.

The focus group with teachers from Implementation 1 took place in August 2014. Due to personal commitments and holidays, only Teachers B, C and F took part. The purpose of this focus group was to gain extra feedback from teachers regarding their students' engagement, difficulties and areas of achievement during participation in the programme. It was also an opportunity for teachers to expand on what had been written in the TRS.

The focus group was of a semi-structured format. The researcher began by highlighting the rationale and aims for the project; these had already been discussed with teachers individually prior to their implementation but it was decided to begin the focus group in this manner. Each of the teachers was then invited to describe their own experiences of the programme and the teaching approach. Further discussion was facilitated regarding the improvement of assessment, challenges faced when implementing the programme, students' engagement with the molecular model kits and the experimental activities in the programme.

This collection of data has been qualitatively analysed and emergent themes identified. They will now be discussed under the following headings; how the approach was perceived (5.3.1); appropriateness of content and adaptations (5.3.2); student learning (5.3.3); recommendations for future implementations (5.3.4) and improvement in future assessment (5.3.5). In the following extracts codes are used for teachers, for example, Teacher C will be referred to as TC.

5.3.1 How the approach was perceived

Teachers' feedback on the approach were extremely positive. All identified the approach as helping to make the topic more interesting and relevant for students:

> *'what I really liked was the physical properties stuff… from a text-book point of view, like, it's so dull it's not even funny. And bringing the models into it….. made it more interesting for them. Something that would have become almost a kind of a rote learning exercise for the sake of an exam had some relevance.'*
>
> (TB, FG)

> *'It brings something from the pages of the textbook that is otherwise, something very difficult to do…. it just made something that's at such a small scale, it made it tangible'*
>
> (TF, FG)

> *'…for example, paracetamol, they could relate to this chemical, they could relate to this, you know, because they have used it….. That was something that was very useful in my eyes….. In*

relation to the pheromones; they did, they could really identify with that as well.' (TC, FG)

The approach was described as closer to that of how 'real' chemists work;

'Chemists experiment with molecules and this allows students to make their own little experiments with the models. I think that was a good dimension of it too, that it was already slightly experimental, even though it wasn't liquid chemistry.' (TF, FG)

Teachers identified the format and incorporation of discussion as particularly useful for students:

'the step-by-step nature of what you had prescribed there worked very well and even fairly weak students came along and got the idea of it.' (TB, FG)

'*It is a great model in relation to group work; they were actively working with each other and that 100% did benefit them…that was one thing I really did get from it. With a shy class, 5th Year Chemistry who don't all know each other…it does help with the interactions.'* (TC, FG)

'it promoted an atmosphere of curiosity in the class and promoted discussion….I think it takes the fear out of it when they're working together and talking about things. That process allows them to say well I don't get this' (TF, FG)

Teacher C explicitly highlighted the engagement of their students in the programme:

'Some days you'd have a double class and I'd think we'd need a triple to keep going, they love it. Who ever wanted to do triple Chemistry? They were actually upset to leave the class'

(TC, FG)

The positive engagement reported by the participating teachers was also observed by the researcher. All class groups were observed to be actively modelling, constructing and manipulating their models and discussing during the activities observed. Students were noted examining each other's models and drawings, comparing and assisting each other and asking questions of themselves and the teacher. During the physical properties activities, students were verbally problem solving and discussing problems as a whole class. Class B was observed to have a lower engagement than others; however for the majority of these students, English was their secondary language. This could explain the lack of engagement. Teacher B did note that during and following completion of the programme, students became more willing to volunteer answers and discuss their thoughts with the class.

The teachers were also observed to be successful in guiding the activities and leading students through the activities. Discussion was fostered in each classroom and students were encouraged to verbalise their understandings while also using their models.

One teacher did identify some frustrations experienced by their students in relation to having to take apart their models after spending time constructing them. The teacher aided this situation by taking photographs of the models constructed by students and displaying them on the projector and printing some photographs to be placed on the walls. While we do not want students to feel that the construction of molecules is not worthwhile because they are going to be taken apart, the fact that students are taking ownership of their molecules demonstrates their enjoyment and engagement with the model kits.

> *'It came to a point* (for students) *where, ok, I'm after building a lovely model, now I have to transfer to paper and convert it to a different form again, that they got a little bit frustrated then. They preferred the actual model building to working in 2D.'*
>
> (TC, FG)

An aspect of using the models that came up in discussion was the 'novelty' of using the model kits continuously throughout the programme. Teacher C expressed his concerns that it felt like a 'treat' for students to be modelling and that perhaps, students weren't actually taking in the definitions and concepts as they normally would.

Teacher B noted that they felt, because there was no specified homework in the programme, that they had given their students a few 'easy months' and suggested that a homework section be indicated. Teacher F also agreed:

> *'You kind of focus on the interaction with the students and their discussions….and then the bell has gone and you've forgotten about homework. It's by no means a criticism.'* (TF, FG)

This raised the issue of students taking the model kits home with them to complete modelling activities for homework:

> *'I know that's probably not really feasible, well I wouldn't be happy with them taking them home…so it would kind of need to be something alternative'* (TB, FG)

The time requirement for the modelling approach and the experimental activities was identified as an issue by all participating teachers. However, teachers did agree that the extra time put into modelling is worth it:

> *'From my point of view…. time constraints really did catch me I think. It's very difficult to have time to do all of the lab work'* (TC, FG)
>
> *'I took a bit of a risk but I would say it paid off in the long run'* (TB, FG)

Teacher E identified a lack of time to complete modelling activities on numerous occasions throughout the Teacher Reflections Sheets; these were identified throughout all chapters:

> *'Too little time allocated to each part-teaching moments rushed due to time difficulty. Bring in isomers for Activity 2.1. Didn't finish 2.4, had no time to make models of finish drawings.'* (TE, TRS)

5.3.2 Appropriateness of content and adaptations made by teachers

Teachers were encouraged to alter the order of activities as they saw fit to tailor the material to their individual classes. The OCV activities were designed with flexibility in mind to ensure any chemistry teacher could use the OCV programme with any class group.

The experimental work was identified as a particularly engaging and useful component of the programme. Teacher C discussed his/her students' need to be able to quantify the strength difference between the intermolecular forces, (which was demonstrated using the experiments in Chapter 6 and Chapter 7), as students were able to record the boiling point and compare the solubility in water of the organic liquids and explain this using their knowledge of intermolecular forces.

Teacher B also identified the importance of the experimental work in relation to the students' understanding of the physical properties concepts. They did, however, note the irrelevance to the ever-present LC exam.

> *'I was just delighted to have an experiment to do for this concept…again it was another section that meant we were a bit behind time-wise….but I have to say, I'm glad we did…By the end of it, I think the majority did come along with it…As the tasks increased in difficulty, I was surprised with how many came along with it.'* (TB, FG)

For the most part, teachers did not change the sequence of activities. Teachers E and F did not make any changes to the activities. All teachers spent at least one class revising intermolecular forces before starting Part B of the programme. Teacher B followed the activities as they were laid out and did not make any changes to the implementation.

Teacher C made the most alterations to their implementation; s/he decided to introduce organic families and nomenclature after completion of Chapter 2 to *'aid clarity when students are describing what they have constructed'.* While Teacher B did not actually introduce nomenclature during his/her implementation of the programme, s/he did suggest that it be added in the same area of the programme for further implementation. Teacher C also took several double classes away from the programme to complete some of the LC mandatory practical experiments. When discussing pheromones and cis/trans isomerism, Teacher C also used a case study of thalidomide to show extra context. As students in Class C were completing Chapter 6, Teacher C provided laptops for students to check boiling points to verify their predictions. All of these changes described by Teacher C are excellent examples of a teacher bringing their own resources and knowledge to a programme. This shows a significant benefit of the OCV programme, in that it is flexible enough to allow a teacher to put their own spin on the material, while preserving the essence of the approach.

Changes made by Teacher D centred on not completing all parts of activities due to time constraints:

> *'Completed (a) and (b) of Challenge 2.1 and 2.2. Did not do other parts as did not have time'*
>
> *'Didn't have time to make models in 6.5-so just answered the questions'*
> (TD, TRS)

It should be noted that Class D completed the largest proportion of the programme given the time spent; they reached the end of Chapter 6 in three weeks. It is up to the teacher to identify if their students are capable of completing the activity without the use of models and if they feel students will experience the same learning without them. This was discussed during the FG in terms of students' learning

The main area identified by teachers as needing additional clarification for students was intermolecular bonding; all teachers spent at least an extra class revising this topic before completing Chapter 6. Teachers D and F did not record any other areas of additional clarification.

Teacher B found some students required extra guidance in Chapter 7:

> *'Some students struggled to see the effect of polar groups and branching and the differences between the compounds seemed very slight.'* (TB, TRS)

Teacher C discussed two further areas in which Class C required additional instruction: in clarifying the method of drawing 2D from 3D, which was reinforced with the subsequent activities in Chapter 2 as discussed above, and in differentiating between molecular and structural formulae.

Teacher E had to guide students through completion of the chapter notes initially.

> '*When doing chapter notes; I had to extract most of the important points. They could not.'* (TE, TRS)

Teacher E did not participate in the focus group. However, when this was queried in the focus group, no other teacher identified it as an issue.

5.3.3 Student Learning

Teachers were required to record areas of achievement and areas of difficulty experienced by students via the TRS as they completed the programme. It should be noted that most teachers' completed these with very brief comments. The results compiled here are areas that teachers noted where students had a particular achievement or difficulty.

An area of particular achievement identified by Teacher C was throughout Chapter 6; *'predictions accurate'.* Teacher C identified only minor difficulties experienced by students. *'Constructing 3D from 2D'* was identified as a difficulty during activities 2.5-2.8, however, following completion of Chapter 2. Teacher C identified '*constructing molecules quickly'* as an achievement. Thus, this difficulty was overcome with practice.

Teacher D identified one key area of achievement namely in Chapter 4, students were able to define an isomer themselves without help from the teacher. Students in Class D did have difficulty identifying hydrogen bonding. This is not necessarily a product of the programme as students had studied bonding in advance of starting the programme.

One question that was put to the teachers in regard to the use of the models and working in 2D was, 'At any stage was there a sense that the 'good' students don't need to use the models but the 'weaker' students still do'. All teachers replied 'no' to this question:

> '*The models were seen as part of the module and the learning.'*
> (TC, FG)

> *'I think it's an abstract concept…and it's abstract enough to keep the good ones on their toes and interested in models without losing any weaker students.'* (TF, FG)

Teacher B identified particular achievement by students in Chapter 5 and Chapter 6:

'This was probably the most successful chapter of the module in terms of learning outcomes. Students had a really good grasp of intermolecular forces and branching by the end. This is a topic they would usually struggle with if models are not used.'

(TB, TRS)

A difficulty which was identified initially by several teachers was the valency of carbon. This was also identified by the pilot teacher during the pilot study. Teacher E identified students' difficulties with the number of bonds for carbon and hydrogen in both Chapters 1 and 2:

'The students still did not fully get that there has to be 4 bonds around every C.' (TE, TRS)

This was also a difficulty identified by Teacher F initially; however, it was identified as an achievement following the completion of Chapter 2:

'Tetravalent and affects # of carbon has on molecule
(TF, TRS)

This issue did not persist past Chapter 2, so it can be inferred that it is a concept that students require time to internalise.

5.3.4 Recommendations for Future Implementation

An issue identified by all participating teachers was the lack of LC material in the programme. This will be considered for adaptions for Implementation 2.

'Looking back at chapter notes, I realise that no naming has been taught yet. I would have introduced naming before now.'

(TE, TRS)

Teacher B put forward two recommendations: the first, as mentioned above, was to include some nomenclature after Chapter 2 or 3. The second recommendation was in relation to Chapter 7; the previous section discussed students' difficulties identifying the effect of polar groups or branching in some of the molecules. Thus, Teacher B suggested:

> ‘C*hoose compounds with more obvious differences between their polarities, van der Waals, etc. The differences between some seemed quite tenuous.’* (TB, TRS)

The intention of these activities was to challenge students with closely related compounds. It may be necessary to include some easier questions to aid students’ development of comparison and predictions in future versions.

Teacher C made several recommendations that were more in relation to incorporating group work and developing the activities further. The first suggestion was in relation to the first activity of the programme, where students are given models of molecules of four compounds; vanillin, paracetamol, butane and polyethene, and were asked to compare them:

> *‘Allocate one per group. Get the students to compare and contrast each other’s. They may be given a case study on the compound and describe it uses to the others also.’*
>
> (TC, TRS)

Another suggestion was to help students engage with the oxygen containing functional groups during Chapter 3:

> *‘Set up a table of possible families that the molecules constructed could be placed on. Students should justify why they place their molecule in a specific family group.’*
>
> (TC, TRS)

The final recommendation was to develop a case study to reinforce the relationship between physical properties and intermolecular forces:

> *‘Maybe design a case study on similar molecules i.e.: H_2S and H_2O to show importance of intermolecular forces.’* (TC, FG)

Recommendations from Teacher D focused on sharing out the modelling requirements so as to reduce the time taken for students to construct molecules. There are advantages and disadvantages to this approach; more material could be covered if there is less time taken constructing molecules. However, this could reduce the benefits students gain from spending that time modelling. Realistically, this is at the discretion of the teacher; if time is available for the students to model as much as possible they should allow them to. However, if the class is under time pressure, this could be a compromise to ensure students get the benefits of constructing some, if not all, of the molecules in the activities.

5.3.5 Improvement in Future Assessment

Following evaluation of Assessment 1, it had already been decided that there was a need for change in the assessment. The FG suggested giving the teachers an assessment scenario; eg if they were to give their students an assignment, in which they had to open today's paper, find an organic molecule that is mentioned and find/suggest a structure, did they think that their students would be able to do that?

> *'From the point of view of intimidation, if I had asked the students on day one, 'what is paracetamol?' they wouldn't have known where to start. But now they have the building blocks for, if they see a picture online, they can say, right, that's an –OH group.'* (TC, FG)

Teacher F described their students already making links during class to a topic that had been studied in Biology:

> '*I think if they can do that with the Biology, then certainly…they are already doing it a little bit, just not in a formal way.' (*TF, FG)

Question 2 of the Assessment 1 was discussed in terms of mistakes students made and how it could possibly be changed for future assessment. Several suggestions were made by teachers;

- Give students models when completing this question;
- If the term 'isomer' is causing confusion, change the structure of the question, for example: show students two isomers first, explain that they are isomers and then ask for another isomer, thereby telling students what an isomer is first. This will then assess if they can recognise differences in structure but the same components;
- Have pre-made molecules in zip-loc bags that are labelled and ask students to identify the isomers; pass the bag around.

Question 5, 6 and 7 of the Assessment 1 were also discussed; primarily the occurrence of confusion between inter- and intra- molecular bonding. Two key suggestions came out of this discussion:

- Instead of presenting just one molecule of each compound, present a 'beaker' or several molecules of each compound when asking a question relating to physical properties and intermolecular forces;
- Depending on the nature of the question, it could be useful to actually give students a definition of inter- and intra- molecular bonding. The question could then assess their understanding of and ability to apply these concepts to the compounds given.

5.3.6 Summary of Feedback

Overall, teachers had a very positive experience with the teaching approach and reported a high level of student engagement, identifying the discussions and collaborative nature of the approach, the use of relevant molecules and experimental activities as highly beneficial to students. This was confirmed during observations by the researcher. The flexibility of the programme was clear from the changes and additions that teachers were able to bring to the programme. The focus group was extremely valuable as it gave teachers the opportunity to suggest improvements in the assessment, which is an area the researcher identified as requiring development.

An obstacle that has been identified by several teachers is the time requirement for constructing the molecular models. However, teachers also noted that the positive learning that students gain from using the models outweighs the time investment of the modelling approach.

Student difficulties recorded by teachers were marginal and for the most part were addressed in the subsequent activities, some of these topics identified as difficulties went on to be identified as achievements by the teachers. There was minimal additional clarification required from students and where it was required, teachers could easily deal with it.

5.4 Assessment of Part C: Reactivity of Organic Molecules

Class D completed Part C of the OCV programme the following September after Implementation 1 took place. Assessment of Part C consisted of five questions, assessing students' abilities to identify reactive centres in unfamiliar molecules in the presence of various electrophiles and nucleophiles. Nine students completed this assessment. These will now be discussed in a similar manner to Assessment 1 in Section 5.1.

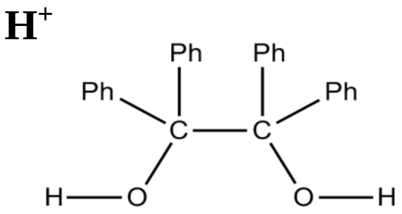
<u>Part C Assessment - Question 1</u>

Part C Assessment Question 1 is shown in Figure 5.13, accompanied by the rationale for this question and a summary of students' success.

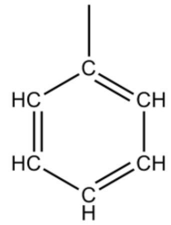
<u>Question 1</u>

Suggest the sites on the molecule below that a H^+ ion is likely to attack.

Circle the possible sites on the structure below.



<u>Note:</u> Ph=



Rationale:

Students are presented with a diol containing four phenyl groups represented by Ph within the molecule. This representation was not used in the OCV programme; however, this molecule was used to investigate if students could apply their knowledge to a molecule containing unfamiliar symbols.

Summary of Results

All students identified both oxygens as possible sites which the H^+ ion could attack.

Figure 5.13: Part C Assessment – Question 1

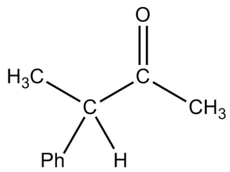
All nine students were successful in identifying the two oxygens as possible sites for attack by the H^+ ion. All of these first identified areas of high and low electron density by assigning partial charges. Four of the nine students only assigned positive dipoles to the hydrogens attached to the oxygen and not to the carbon that the oxygen is attached to. It is unclear here whether students did not fully understand the idea of dipoles or if these were left out as it did not affect students' correct identification of the sites.

<u>Part C Assessment - Question 2</u>

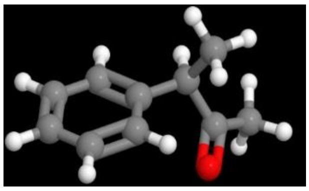
Part C Assessment - Question 2 is shown in Figure 5.14, accompanied by the rationale for this question and a summary of students' success.

<u>Question 2</u>

Identify the possible reactive centres of this molecule in the presence of H^-. Circle the possible reactive centres on the 2D drawing of the molecule's structure.



$\mathbf{H^-}$



Explain your answer:

Rationale:

The molecule in Question 2 is presented both in 3D and 2D representations. The nucleophile H^- is used to ensure students don't hold the misconception identified by Hassan et al (2004) that bond polarities depend on absolute electronegativities of atoms only, i.e. hydrogen is always positively charged.

Summary of Results

Seven out of nine students correctly identified the carbon double bonded to the oxygen as the possible reactive site for the H^- to attack this molecule.

Figure 5.14: Part C Assessment – Question 2

The two students who were incorrect, identified the hydrogen that is 'beside' the phenyl group in the structure as the reactive site. Neither of these students offered an explanation for their selection. These students also did not draw on their structures so there was no indication as to how these students came to their identification.

The explanations from the seven students who could identify the reactive site focused on the differences in electronegativity that results in the partial charges and the attraction between negative and positive charges, for example;

> '*The H^- is likely to attack the carbon double bonded to the oxygen. The oxygen has a larger electronegativity value than carbon. This gives it partial negative charge (δ-) and the carbon a partial positive charge (δ+). Thus, the negative H^- will attack the positive carbon'* (Student D4, Q2)

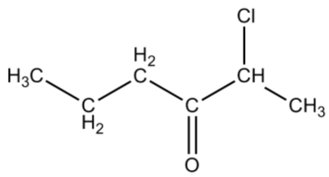
This type of explanation shows a good level of understanding of the occurrence of dipoles and the interaction between charged species.

<u>Part C Assessment - Question 3</u>

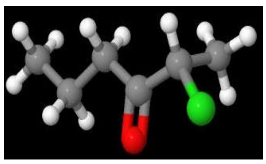
Part C Assessment - Question 3 is shown is Figure 5.15, accompanied by the rationale for this question and a summary of students' success.

<u>Question 3</u>

Predict the possible reactive centres of this molecule in the presence of H^-. Circle the possible reactive centres on the 2 dimensional drawing of the molecule's structure.



H^-



Which of these reactive centres do you think is most likely for the H^- to attack? Explain your answer:

Rationale:

Question 3 asks students to not only predict possible reactive sites but also suggest the most likely reactive site. Students will be required to fully examine the structure and provide a comprehensive explanation of their selection.

Summary of Results

All students identified the two possible reactive sites. Seven out of nine students identified the carbon attached to the oxygen as the most likely reactive centre.

Figure 5.15: Part C Assessment – Question 3

Seven out of nine students identified the carbon attached to the oxygen as the most likely reactive site. Five of these discussed the relative strength of the positive dipoles due to differences in electronegativity values; for example,

> *'I think that H^- would most likely attack the carbon that is double bonded to the oxygen atom. There is a higher electronegativity difference between oxygen and carbon (0.9) than carbon and chlorine (0.6). This means that the carbon double bonded to the oxygen is more likely to be attacked.'*
>
> (Student D6, Q3)

The other two students attempted to use the shape of the molecule as an explanation to their selection:

> '*The C-O double bond is most likely for the H^- to attack. Because it is easier to access.'*
>
> (Student D1, Q3)

One student failed to make an attempt at this question, while one student identified the chlorine as the most likely reactive centre:

> *'The C bonded to chlorine because it is more loosely bound and easier to access.'* (Student D12, Q3)

Part C Assessment - Question 4

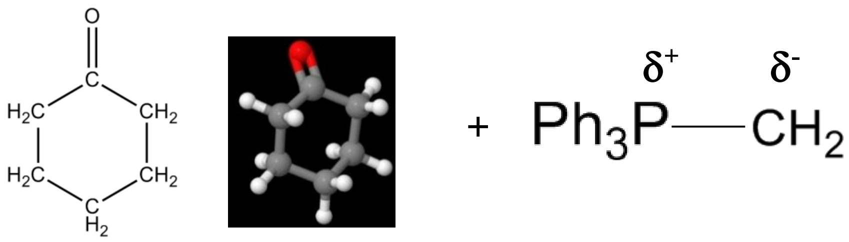
Part C Assessment - Question 4 is shown is Figure 5.16, accompanied by the rationale for this question and a summary of students' success.

Question 4

Carbon is more electronegative than phosphorus. As a result, when they are bonded together a polar covalent bond is formed, with the phosphorus taking a slight positive charge and the carbon taking a slight negative charge. An example of this occurs in the following molecule:

$$Ph_3\overset{\delta^+}{P}\text{—}\overset{\delta^-}{C}H_2$$

What are the two possible ways that this phosphorus containing molecule can attack the cyclic molecule below? Explain your answer



Rationale:

Question 4 is slightly more complex, with students being presented with a reaction between two molecules. As the OCV focused solely on the attack of electrophiles and nucleophiles on molecules, students were given a starting point by identifying the dipoles in the phosphorous containing molecule.

Summary of Results

Seven of nine students suggested the two correct interactions between the two molecules. Two students did not attempt this question, one of which did not attempt the previous question.

Figure 5.16: Part C Assessment – Question 4

It should be noted that the notation used in this question by the researcher is incorrect. The partial charge symbols (δ^+ and δ^-) were used when the symbols + and – should have been used.

All seven students who correctly suggested two interactions between the molecules were fully able to explain each attraction, some of whom provided diagrams as well as written explanations, see Figure 5.17 and 5.18.

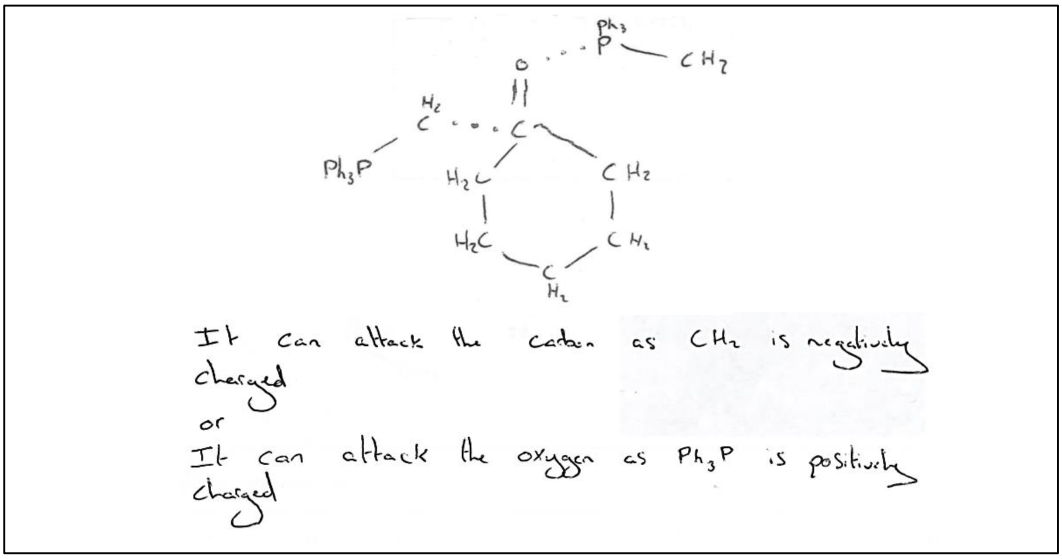


Figure 5.17: Answer provided to Queston 4 **(**Student D6)

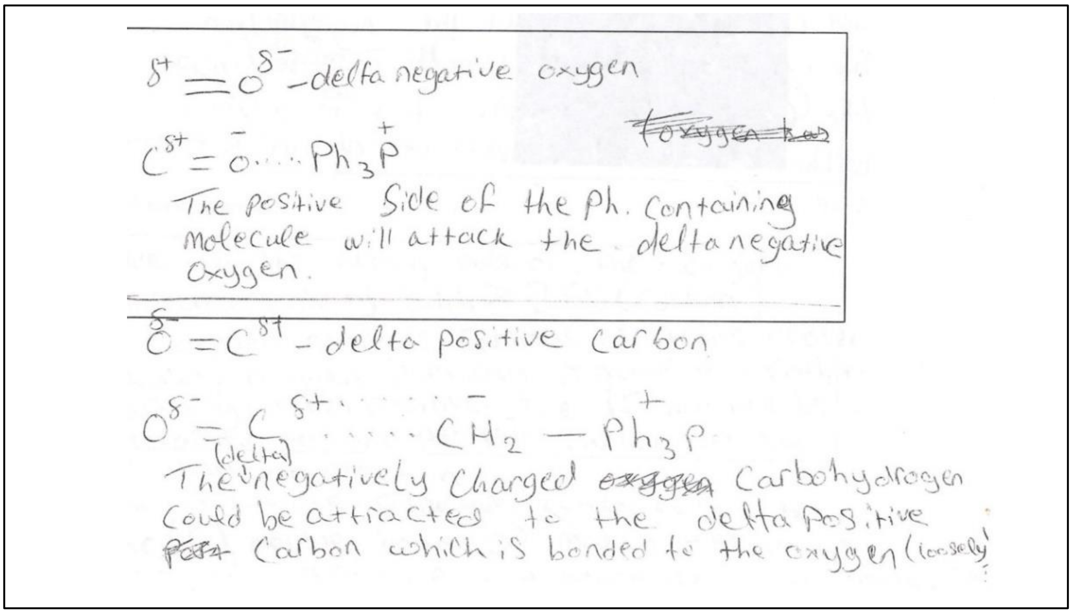


Figure 5.18: Answer provided to Question 4 (Student D11)

Despite this type of question being unfamiliar to students, they were able to use their knowledge of partial charges and interactions to suggest possible interactions. This is a very encouraging result and demonstrates that students at this level are capable of not just predicting reactive centres in the presence of nucleophiles and electrophiles but of predicting the reactivity of organic compounds.

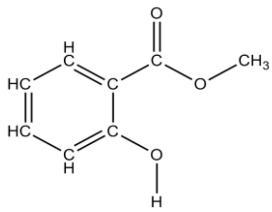
Part C Assessment - Question 5

Part C Assessment - Question 5 is shown is Figure 5.19, accompanied by the rationale for this question and a summary of students' success.

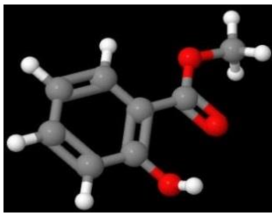
Question 5

Methyl salicylate, also called Oil of Wintergreen, is a clear organic liquid obtained from Wintergreen plants. It is used as a flavouring in chewing gum and mints.

Identify the possible sites on the Oil of Wintergreen molecule that an OH^- ion might attack. Circle the possible sites on the 2 dimensional drawing of the molecule's structure.



OH^-



Suggest which of these reactive centres do you think is most likely for the OH^- to attack? Explain your answer:

Rationale:

Students are asked to identify the reactive sites in methyl salicylate. The structure of methyl salicylate is presented in both 2D and 3D form. The molecule in this question is a relatively large molecule that contains four possible reactive sites. Students will have to examine the structure fully to identify all sites. Students are then asked to suggest which will be more likely and why.

Summary of Results

Eight of the nine students identified all four possible reactive sites, with five of these offering a comprehensive discussion of which was the most likely reactive centre.

Figure 5.19: Part C Assessment – Question 5

Of the nine students, eight identified all four possible reactive sites. This is very encouraging as it indicates that these students can select the appropriate information required from a relatively complex structure.

One student only identified two reactive sites; the hydrogen and CH_3 attached to the oxygens, see Figure 5.20. and did not offer an explanation. This student was succesful in Questions 1-3 but did not attempt Question 4.

Of the eight successful students, five identified the hydrogen of the –OH group as the most likely reactive centre as it is the most loosely bound and its location is least hindered.

> '*I think the OH⁻ would most likely attack the H bonded to the O. The electronegativity difference between C and O is less than the difference between O and H. The C single bonded to the O and which is part of the benzene ring would be too difficult for the OH⁻ group to attack. The carbon double bonded to O would be more difficult to access than the hydrogen. Thus, The OH⁻ group would most likely attack the hydrogen which is single bonded to the O as it is easiest to access and most loosely bound.'* (Student D4, Q5)

Another student went so far as to rank the reactive sites in order of likelihood of being attacked. While this student only identified three of the four possible reactive sites, their explanations indicate a deep understanding of the concept.

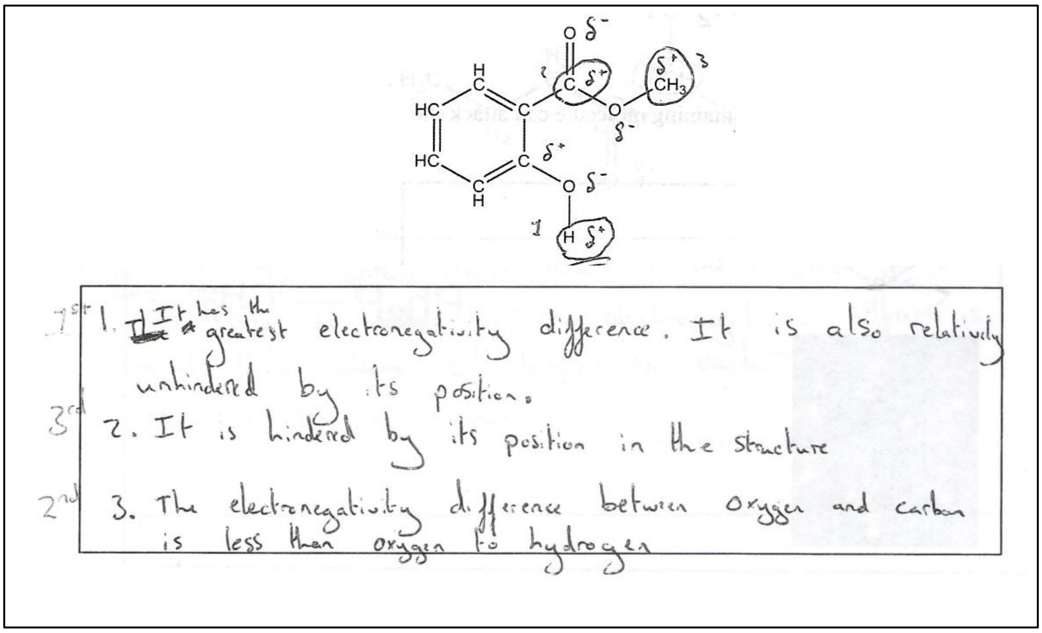


Figure 5.20: Answer provided to Question 5 (Student D6)

The other three students correctly identified the hydrogen of the –OH group as the most likely reactive site but provided incomplete explanations. Two of these students simply identified the hydrogen attached to the oxygen as 'the most loosely bound' reactive site. The other student identified it as the reactive site that is the easiest to access. These explanations are not incorrect, students simply decided not to include a comparison in their explanation.

Despite the small sample size, the results of Part C Assessment are very encouraging; the majority of students were not only able to identify reactive sites but also put forward reasonable explanations as to why they are reactive sites. These students have demonstrated the ability to complete the first steps to being able to predict reasonable reaction mechanisms without the need to rote learn steps from reaction schemes. Students in this class were capable of explaining their reasoning over a series of steps, regardless of the size of the molecule, the number of reactive sites or the familiarity of the symbols used.

5.5 Implications for Implementation 2

Evaluation of data collected during Implementation 1 will now be used to inform redevelopments for Implementation 2. The time requirement for the modelling approach has been discussed in length with participating teachers and suggestions were made to teachers prior to Implementation 2 as to how to minimise the excessive time requirement while also ensuring students spend enough time with the modelling approach. These included sharing modelling tasks within groups and amongst the whole class.

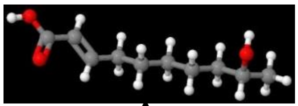
One of the key issues raised by the teachers participating in Implementation 1 was the lack of homework activities and the omission of the IUPAC naming system. Also identified as lacking in Implementation 1 was the assessment of students' ability to work in 3D, thus a new evaluation tool for Implementation 2 is required.

As discussed in Section 5.1.3 and also identified by the participating teachers, the evaluation of student learning needs to be more focused on students' ability to work in both 3D and 2D. Thus, there is a need to redevelop the evaluation of student learning. The evaluation of students learning in Implementation 2 will take several new forms; along with the spatial ability tests and a written assessment, students will also be given a modelling test and be interviewed in relation to their model to assess their understanding. This modelling test and interview will be modelled on that used by Nicoll (2003). This will be further discussed in Chapter 6.

Several of the teachers indicated during the focus group that students viewed the modelling activities as a novelty and were rarely given homework. Additional challenge activities, along with a set of case studies were created to combat this. An example of one of these case studies is shown in Figure 5.21. The full set of case studies have been included in the TM and SM on the CD

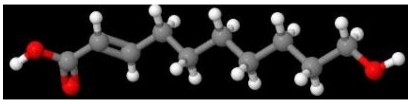
The purpose of these case studies was to provide teachers with additional activities which could be used for homework and also increase the amount of context-based organic compounds engaged with by students. These were kept as a separate set rather than insert them into the sequence of activities so that teachers could use them whenever they felt they needed an extra activity.

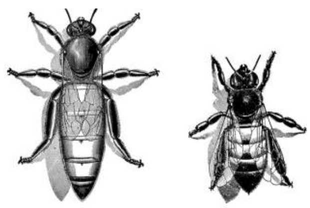
Bees use chemical signalling to tell the difference between workers and queens. They effectively see through chemistry. The structures of the molecules produced by the queen honeybee and a worker honeybee are shown below.



Produced by queen honeybee

Produced by worker honeybee





What are the main components of these molecules?

How do these molecules differ?

Draw the molecule produced by the queen honeybee in the box below

Figure 5.21: Example of a case study created for Implementation 2 of the OCV programme

The omission of the IUPAC naming system was identified as an issue for teachers, who were still preparing their students for the LC chemistry exam the following year. Naming activities will be introduced into the various sections of the programme as students are introduced to the different types of structures and organic compounds. The names of the organic molecules will only be introduced after students have practised constructing and drawing the various types of organic molecules. The molecules which students have to name will not be limited to a specific number of carbons.

Analysis of students’ explanations in Assessment 1 indicates some students struggled with differentiating between the main chain, branches and functional groups within molecules of organic compounds. These will have to be emphasised and students given practice in identifying these in order to succeed in applying IUPAC rules. Thus, these will be considered when developing activities for the IUPAC naming system in Implementation 2.

Observations during the Implementation 1 and feedback gathered afterwards gave the researcher a much clearer insight into the types of questions and answers which students will ask and offer during the OCV programme. This allowed for the development of much more detailed suggested sequences and discussion points for the TM. These will be presented in the TM in the form of a flow chart, an example of which is shown in Figure 5.22.

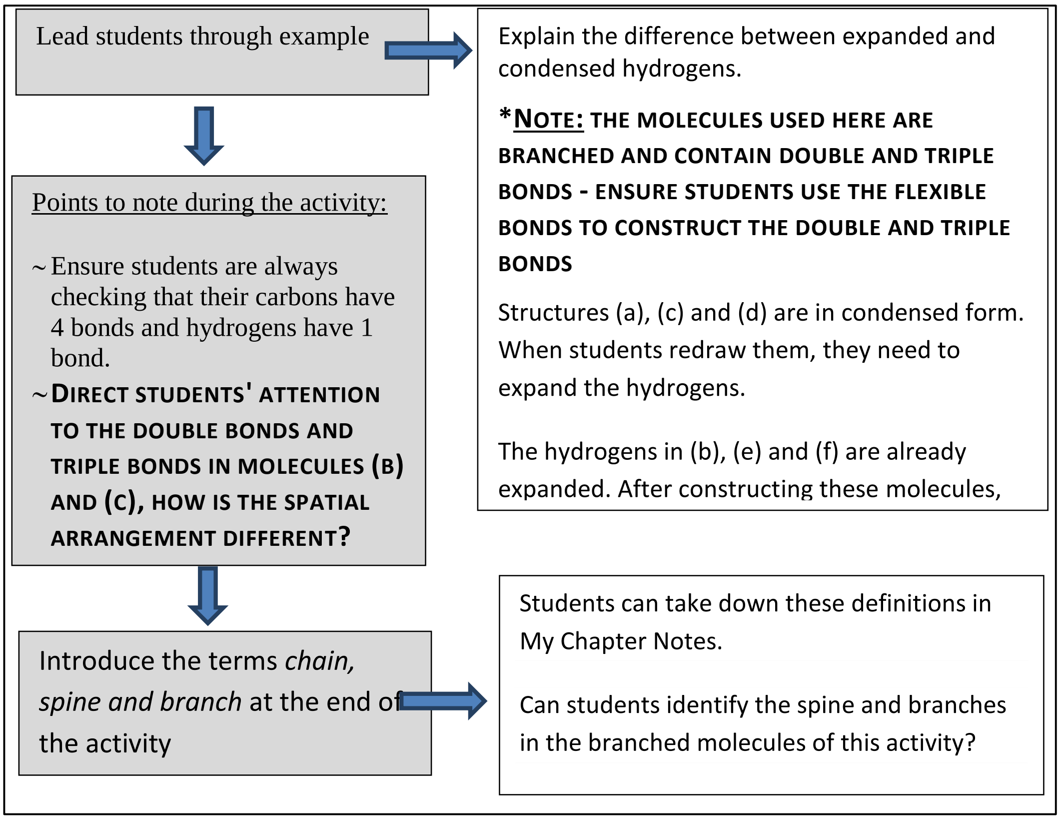
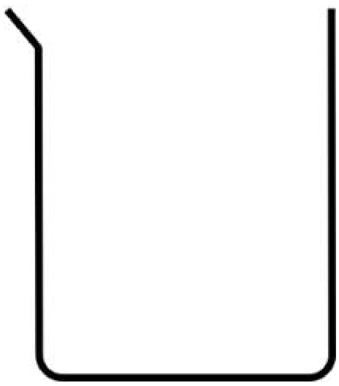
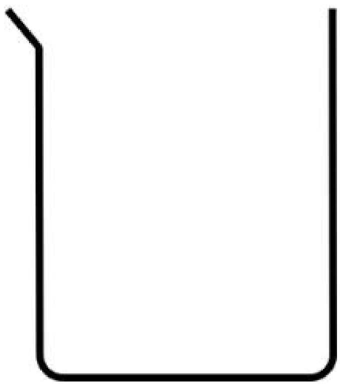


Figure 5.22: Example of flowchart added to activities in TM

This form of flowchart is introduced into the beginning of each activity in the TM to aid teachers’ implementation of the activities and give them a clear idea of how to guide students through each activity.

During the teacher focus group, the presentation of questions was discussed in terms of reducing the confusion between inter- and intra-molecular bonding when assessing understanding of physical properties. It was suggested that when discussing the link between intermolecular forces and physical properties, multiple molecules be presented rather than just one. Based on this discussion, multiple activities were changed in both manuals to include this type of presentation. For example, students are asked to draw a beaker showing four molecules of each compound and depict the intermolecular forces "within the beaker" This is shown in Table 5.10.

Table 5.10: New activity for intermolecular bonding in Chapter 6

Structure of Compound		
Intermolecular Forces		
Draw a beaker of this compound, showing: ~**4 molecules** of the compound ~the intermolecular forces between them		

5.6 Summary

Evaluation if Implementation 1 indicated the majority of students were capable of completing the translations asked of them in Assessment 1. While a large proportion of students could predict and compare the physical properties between a variety of compounds, students' explanations were found to be lacking the detail necessary to demonstrate a deep understanding of the link between IMFs and physical properties. Feedback from teachers indicated a positive engagement by students and this was further observed by the researcher.

Despite the small number of students who completed the assessment of Part C: Reactivity of Organic Molecules, the results are extremely encouraging and demonstrate the potential for including this type of teaching approach at second level. This type of task would previously have been considered too complex for second level students studying organic chemistry. However, the students' answers indicate that students at this level are capable of not just predicting reactive centres in the presence of nucleophiles and electrophiles but also of predicting the reactivity of organic molecules. This is extremely encouraging and suggests the need to consider including this type of learning in the new chemistry syllabus for LC.

While the evaluation tool used to assess students in Implementation 1 identified some key areas of achievement and misunderstandings, it did not assess students' ability to work in 3D. Thus, a second implementation is required to assess this element of the OCV approach. A new tool will be developed for this purpose. The cyclic approach of this project has informed further redevelopments for the materials in Implementation 2 that will enhance the OCV approach and support student learning.

Chapter 6

Implementation 2

Introduction

Implementation 1 identified a lack of consistency between the OCV teaching approach and the assessment of students' learning. Students who had been taught organic chemistry through a 3D approach using physical models were tested using a 2D form of assessment. Thus, there was a need for Implementation 2 to assess students' ability to work between 3D and 2D representations. A new form of assessment was developed for this purpose.

The teachers from Implementation 1 were invited to participate in Implementation 2. Of these, 3 teachers decided to participate again (Teachers B, C and F) and one additional teacher was recruited (Teacher H). Teacher E from Implementation 1 did not return to Implementation 2 as s/he believed the approach to be too time consuming. It is unclear as to why Teacher D did not return. Teacher H was new to the OCV programme and ran the OCV programme as an after school programme once a week throughout the year with a 5th year chemistry class group.

Implementation 2 took place between February and May of 2015. Details of each class participating in Implementation 2 are in Table 6.1 below.

Table 6.1: Breakdown of participants in Implementation 2

Class	Teacher	School Gender Mix	No. of Students (N*)	No. of Observations	No. of weeks teaching**	Section of the programme reached.
2B	B	Girls	6	4	6	Chapter 6
2C	C	Co-ed	16	5	8	Chapter 6
2F	F	Girls	11	3	5	Part A
2H	H	Girls	8	5	¥	Part A
		4 Groups	**N = 41**	**n = 12**		

* N refers to the number of students who completed both Assessment 2 and the modelling test

** Number of weeks teaching is based on 5 classes a week, 3 single and 1 double

¥ after school programme, once per week

Evaluation data collected in Implementation 2 varied from Implementation 1 and is summarised in Figure 6.1. The TG was replaced with individual teacher interviews. Students' change in spatial ability was measured using the same spatial ability test. A similar written assessment (Assessment 2) was used in combination with a modelling test that was developed to assess students' ability to work in 3D and translate between 2D and 3D representations. Students were also interviewed following completion of the modelling test. Questions in this interview focused on students' ability to describe their model, the shape, the bonding, the components and the physical properties of the molecule which they constructed.

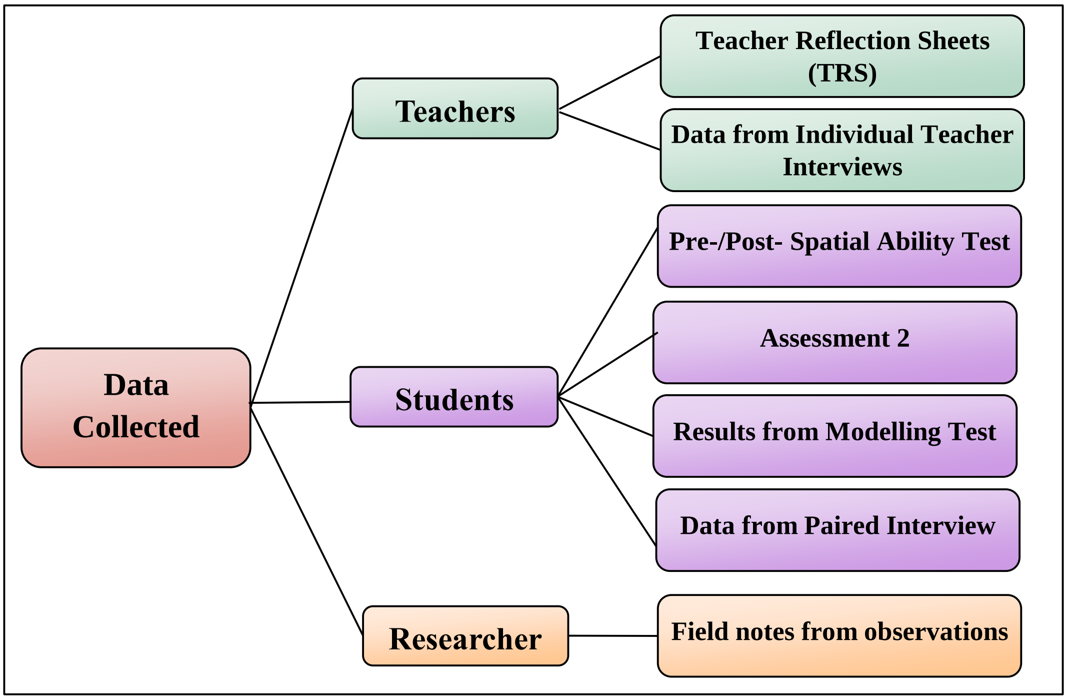


Figure 6.1: Evaluation data collection for Implementation 2.

Observations played a much bigger role in evaluation of Implementation 2. All classes were observed at least three times. This allowed for an evaluation of students' learning from a different perspective, identifying students' learning during the OCV programme as well as at the end of the programme. Observation of students' discussions allowed a probing of student understanding at a deeper level.

This chapter will first present a narrative on each of the four class groups on a case study basis to highlight key areas where student learning was visible. Student data will then be analysed and compared to identify areas of student achievement in Implementation 2.

6.1 Observations of student learning

An observation sheet was developed for use by the researcher during observations of class groups, this can be found in Appendix D. This observation sheet was designed to correspond with the TRS, which required the researcher to rank students' achievement of learning outcomes and identify areas of difficulty. However, during the observations it was felt that the structure was too rigid and did not allow for the variation between classes to be captured. Thus a narrative style of recording observations was adopted. Table 6.2 summarises the classes involved in Implementation 2.

Table 6.2: Breakdown of class groups in Implementation 2

Class I.D.	School Gender Mix	No. of Students (N*)	Type of School
2B	Girls	6	Inner-city school, 50% non-nationals
2C	Co-ed	16	Multi-dimensional community school
2F	Girls	11	Voluntary secondary school
2H	Girls	8	Fee paying school
4 Groups		**N = 41**	

Each class group will be discussed individually in terms of their observations, feedback from teachers and conversations overheard. The students are noted as S1, S2 etc. to ensure anonymity within each class group.

Class 2B

Class 2B was part of an inner-city all-girls school in Dublin with a diverse population. Approximately 50% of the students enrolled in this school are non-national students. The students in Class 2B were primarily students whose first language was not English.

Class 2B was observed four times during their implementation. This class was probably the quietest that was observed during Implementation 2. During the first observation students were very quiet and barely spoke to each other, let alone the teacher. Despite encouragement from the teacher to discuss with each other and between groups, students worked very quietly in pairs during activities, choosing to whisper when discussing with their partners. They did however, engage fully with the modelling activities, constructing and manipulating their individual models. Two students were overheard discussing how to know if their models were correct:

S1: *Oh, I don't think I have this ok. Mine doesn't look like yours.*

S2: *Does it have to? Check that the black ones all have 4.*

S1: 4…*Is that how I know it's ok?*

S2: *Yes, the black is the carbon. It has 4 things.*

S1: *What about the white? Oh wait, they only have one…so they are ok.*

This is obviously a conversation between a weaker and a stronger student but demonstrates the scope of the modelling process for collaborative learning. The use of the word 'things' instead of 'bonds' could indicate that this student has not yet made the connection between the physical representation and the idea of bonds. However, it could also be a result of the language barrier.

As the observations continued during the implementation, students could be observed to be engaging in more discussion with their partners and actually comparing each other's' models and drawings. Their confidence in suggesting answers appeared to grow as the class proceeded through the programme. Students were also observed helping each other during class discussions. One particular conversation that was overheard during a discussion with the teacher on constructing isomers demonstrates this, as one students' partner helps her to see;

TB: *So have we all constructed something different to my molecule? Student 3?*

S3*: I think so* (she rotates her molecule and compares it with the teacher's)

TB: *Are you sure?*

S3: *Yes. They look different. Yours is in a line, mine is not.*

S4: *But yours is squashed. If you move this one like this, and this one like this, it looks the same.* (This student rotates some of the bonds in the other students' molecule to stretch the carbon chain).

S3: *How do I make mine like yours? Yours is not the same.*

The two students continued to discuss their molecules without any prompts from the teacher and the second student helped the first to change their model so that they had a different molecule.

The students who became more engaged in the class discussions had a higher level of English than those who did not but the overall atmosphere of class seemed to change and these students helped to bring along the less confident students during class.

Teacher B noted the growing confidence of their students during the implementation, in particular with the use of the models:

> *'they seemed to get very hands-on, like after the first, probably about the third or fourth session they were very comfortable with coming up and just grabbing the kits…they were quickly putting together the models and deconstructing the models quite quickly to rearrange them into something else'* (TB, IV)

One of the other observations of this class took place during an experimental session in which students were carrying out Activity 7.2, to compare the solubility of alcohols. The teacher skipped Chapter 6 to ensure the class could do this activity as the teacher felt it was a useful activity from Implementation 1. During this session, students were highly engaged and were fully comfortable carrying out the activity. The teacher constructed models of the structure of each alcohol before the session and placed them beside the containers of each alcohol. Students carried out the experiment in pairs, however, when the class moved to a discussion around their observations and looked at the structures of the models, all six students came together around the model and were passing them around. One student noted that all had the same –OH group so they should all have done the same thing when added to water. The teacher led the students to identifying the differences in their structures, which is the number of carbons, as being the factor which influences their different behaviours. Students came to the conclusion that the longer the chain of carbons, the less soluble it is in water. Students seemed very comfortable coming to this conclusion with the teacher. This was the most engaged these students were observed during the implementation.

This activity took place towards the end of this class's implementation. The improvement in students' confidence was clearly visible and students were clearly learning through the use of the models. The following conversation arose during the correction of the previous nights' homework, when one student became frustrated at getting all questions incorrect:

> TB*: Would you think it would be helpful to have your own kit to take home to help with the homework?*
>
> S5*: Yes. Well I can imagine the molecules anyway but it's easier when you can build the model and have it front of you.*
>
> S6*: Yes it would help. I find it hard to learn from the book. The models help me see the molecules.*

This conversation demonstrates this students' preference for learning using the model kits.

Approximately half-way through their implementation of the programme, Teacher B decided to run a modelling test with Class B. This coincided with the Easter holidays and served as an Easter test. This test was completely created by Teacher B. Two questions from the test are detailed below:

1. Make two isomers of C_5H_{12}. Name each and draw both molecules below. What family of compounds do they belong to?
2. Make a model of butan-2-ol. Draw it below and show where the areas of high and low electron density are.

The researcher was invited to observe the modelling test but, as already discussed, became a facilitator of the test. Students were required to check their models with the teacher or researcher before disassembling their model to build the next one. The researcher's participation enabled this process to run much quicker.

Of the seven questions, only one gave students a molecular formula from which to work. The remaining six asked students to construct models from IUPAC names of molecules. For a class with a high proportion of foreign nationals, this test could have been designed to reduce the language deficit.

All students were successful at constructing two isomers of the given molecular formula. Despite the potential language barrier, the majority of students were successful in completing constructions.

Common errors which arose during this modelling test were:

- Ether (R-O-R') functional group instead of carboxylic acid (R-COOH);
- Confusion between naming the side chain and main chain of a molecule, for example: butyl-2-methane instead methyl-2-butane;
- The term *isomer* was not understood. When given the definition of an isomer, this was no longer an issue;
- Butan-2-one constructed instead of butan-2-ol.

This was a very engaging form of assessment and the researcher observed all students putting a significant effort into their constructions. This also shows the engagement of the teacher during this implementation who chose to create his/her own assessment.

Class 2C

Class 2C was part of a co-educational and multi denominational Community School in North County Dublin. Students in this class were of mixed ability and three of the students had English as a second language.

With 16 students, Class 2C was the largest class of Implementation 2 comprising three girls and thirteen boys. This was an extremely engaged class and there was always a buzz of discussion within the class. Interestingly, despite being almost completely composed of boys, this class did not stand out from the other classes in terms of engagement and discussion. The girls in the class were dispersed amongst the class and did not group together as may have been expected.

The first observation of this class was actually the first class of the OCV programme. Unlike Class 2B, students were engaged from the very beginning, and were curious about the models of molecules that were presented to them in the first activity. Students passed the models around and engaged in discussion with their teacher. The paracetamol molecules in particular gave rise to discussion amongst some particular students, who asked how many molecules of paracetamol would be in a paracetamol tablet. Further discussion arose around the vanillin molecule, where one student asked how this molecule gave rise to the smell of vanilla. The teacher facilitated a discussion which compared the structures of vanillin and paracetamol to identify differences and similarities which would give rise to different functions and smells. This conversation was very powerful as it introduced students to a guiding principle of the OCV programme; different structures give rise to different properties and different uses.

Following this discussion, students were eager to begin constructing models with the Molymod kit and immediately began comparing with each other, discussing with their teacher and the class as a whole. The subsequent observations that took place through the programme demonstrated a continuous engagement with the modelling and drawing activities.

Teacher C (TC) really brought his/her own elements to the approach. This teacher noted their class's frustration during Implementation 1 when the end of class came and students had to dismantle their models. TC combatted this by asking students to take pictures of their molecules before the end of class and upload the models to the class moodle site as part of their homework. The teacher then referred to these at the beginning of the next class as a recap before continuing with the programme.

One element of this class which stood out in comparison with other class groups is the potential for 'going off track' of the activities when working with the Molymod kits. While no student was observed disengaging from the approach, a pair of students were observed constructing alternative models than were requested. Students were asked to construct an isomer of a molecule constructed by the teacher. This particular pair built a ringed structure containing halogens. Rather than disrupt the class, TC turned this into a meaningful learning moment and showed the structure to the class. TC posed the question: 'Is this an isomer of my molecule?' Students immediately said no because the halogen was attached to the ring. The teacher proceeded to remove the halogen and replace it with a hydrogen and asked the question again. Students were not as immediately sure of this question and this led to students counting the number of hydrogen and carbon atoms in the ring structure to compare with the teacher's molecule. Students decided that no, it wasn't an isomer, as putting the carbons in a ring structure resulted in a different number of hydrogen atoms.

This sequence of events indicates the potential for distraction that the use of the Molymod kits hold for students when studying organic chemistry. However, this teacher has demonstrated an excellent method for turning a distraction into an opportunity for learning.

Class 2F

Class 2F was in a 'socially diverse', all girls voluntary secondary school in Dublin city. The students in this class were extremely confident and engaged the researcher in conversation immediately during the first observation. Students were curious about the researcher and asked questions regarding the researchers' institution and reason for being in the class.

The confidence and discursive nature of these students' were consistently observed during the implementation with this class and Teacher F was very capable of directing these students' confidence and discussions towards their models and molecules. Students not only checked their models and drawings with their partners, they also consulted other groups around them.

Several conversations were overheard in the class which demonstrate the success of the collaborative approach in the programme. The first conversation took place when a pair of students were trying to build isomers:

> S7*: I'm done*
> S8*: Me too. Are they different? I think they are.*
> S7*: Yeah, mine is longer than yours*
> S8*: And mine has that bit sticking up.*
> S7*: But can you move that bit to make it part of the long chain?*
> S8*: Oh, now they are the same.*
> S7*: How do we make them different?*

These students are discussing their structures between themselves and problem solving together. These particular students went on to construct a pair of isomers and then were observed helping their neighbouring group to compare structures and identify isomers.

During the naming of alkynes, the teacher led a discussion for naming the structure of pent-2-yne. Students were observed helping and explaining to each other how to obtain the correct name. While the IUPAC naming system was not a central component of the approach, the collaborative nature of the learning that takes place is very important:

> T*: What will we call this?*
> S9*: Pentyne*
> S10*: Pent-3-yne*
> S11*: No, it's Pent-2-yne*
> T*: So which one is it?*
> S10*: Well it's the third carbon so it has to be pent-3-yne*
> S11*: No because if you count from the other end, it's on the 2nd carbon not the third. Look (holds up model for student to see). If you look at it this way it's on the third carbon but you can turn it and then it's on the second.*

This activity encouraged a discussion between students in which S11 had to justify their answer and explain their reasoning to their peers.

<u>Class 2H</u>

Class 2H was part of a fee-paying all-girls school in Dublin city. Teacher H decided to run the OCV programme as a supplementary after-school programme but it was not optional; it was expected that all students from the chemistry class would attend. The nature of the programme did not appear to affect the level of engagement of the students; all students were observed to be as engaged as the other Implementations 2 classes.

The nature of the class did, however, affect the nature of the implementation. As the teacher was not under any time pressure, implementation was much slower. While this resulted in class 2H only reaching the end of Part A of the programme, it allowed for students to discuss their molecules in greater depth and ask more questions. As a result, more discussions and questions arose from this class group.

One particular observation during the introduction to alkenes saw many meaningful conversations take place. The teacher began by asking students to construct ethene and mentioned that this is the smallest alkene that exists. One student asked why this is the case when the smallest alkane that exists is methane. This led to a class discussion around what is the functional group of an alkene and the possibility of carbon forming a double bond with hydrogen instead of another carbon. The same student who asked the original question suggested the creation of a double bond between carbon and hydrogen but when she consulted her models, found it was not possible to do so.

Following the identification of the double carbon-carbon bond as the distinguishing feature of an alkene and students' construction of an alkene, the teacher gathered the students in a circle with their models to further discuss them. Another student posed the question: Does the double carbon-carbon bond have to be part of the main chain of the molecule or can it be a branch? The teacher asked this student to build an example and put it to the rest of the class to name it. The molecule was passed around and students gave suggestions. Students eventually decided that you had to rotate the molecule to make the carbon-carbon double bond part of the main chain of carbons.

Another student asked: 'What if a molecule had a very short main chain containing a carbon-carbon double bond but a very long branch?' Again, the teacher asked the student to construct this and the student did so by combining some of the other students' molecules with her own. By doing this, another conversation around the possibility of containing two double carbon-carbon bonds arose.

The questions which arose in this short space of time indicate the level of thinking of these students. The availability of the models allowed students to problem-solve their own questions, both individually and collaboratively.

Another conversation of interest which arose during an observation was around the idea of electronegativity and partial charges. When applying partial charges to a nitrogen atom bonded to three other atoms and to an oxygen atom bonded to two other atoms, one student asked if the notation of $\boldsymbol{\delta}^{---}$ (a delta sign with 3 minus symbol) should be used because it is pulling three electrons towards it, whereas oxygen is only pulling two towards it. This question led to a discussion around the relative strengths of electronegativity. While this class did not reach Part C, the reactivity of organic compounds, these conversations would have been a meaningful introduction to the concept of identifying more and less likely sites of reactivity.

Treating each class as an individual case study has demonstrated some key outcomes of the OCV programme. Despite the different circumstances of each school and the varying types of student and situations, all classes engaged fully with the approach. The gender of the class, the socio-economic class of the school, and the ability of the students, did not affect the students' participation and contributions to the programme. Students were consistently observed to be on track with activities, and even students who deviated from track actually gave rise to an interesting learning opportunity! The teachers were observed to be extremely successful in facilitating the discussion-led and collaborative nature of the approach, facilitating some very meaningful conversations and investigations. The data collected from students following Implementation 2 will now be discussed.

6.2 Student Assessment

As previously mentioned, four main sources of data were collected from students following Implementation 2. As the classes involved in this implementation did not complete Part B of the OCV programme, assessment focused much more on students' use, understanding of and ability to translate between different types of representations.

6.2.1 Spatial Tests

Unfortunately, due to unforeseen circumstances, only 26 of the 45 students in Implementation 2 completed pre- and post- spatial ability tests. A paired-samples t-test was conducted to compare students' results in the pre- and post- spatial tests. As in Implementation 1, there was found to be a significant difference in the pre-spatial test scores ($M=5.59$, $SD=2.043$) and the post-spatial test scores ($M=6.7$, $SD=2.016$); $t(26)= -4.057$, $p=0.000$. These results indicate an increase in spatial test scores following working with the molecular models during the OCV programme.

(Note: M = mean, SD = standard deviation, t = t-value, p = significance)

6.2.2 Assessment 2

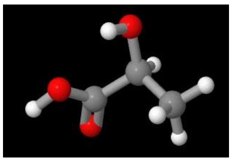
Assessment 2 was very similar to Assessment 1. While content was similar, more multiple choice questions were included. Questions 1 and 3 were in fact the same as those in Assessment 1. The answer scripts for 38 students were obtained for analysis. Assessment 2 will now be discussed in a similar manner to Assessment 1.

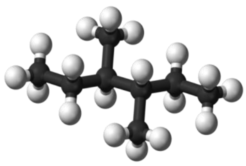
<u>Assessment 2 - Question 1</u>: Transfer from 3D to 2D representation

Assessment 2-Question 1 is the same as that in Assessment 1. Figure 6.2 details the rationale for including in this in Assessment 2 also and summary of results from this implementation.

<u>Question 1</u>

Draw 2D structures of the following organic molecules represented by 3D pictures:

(a) 

(b) 

Rationale:

This question was useful in determining students' ability to translate between 3D and 2D representations following Implementation 1. Thus, it was included in Assessment 2.

Summary of Results:

All 38 students were successful in completing this task

Figure 6.2: Assessment 2-Question 1, rationale and summary of results

All 38 students could successfully draw 2D representations of the given molecules. As in Implementation 1, students' drawings were categorised according to their style (linear or zig-zag) and complexity (extended or condensed hydrogen). In contrast to Implementation 1, there was much less variety in the complexity of students' structures; only three students drew structures with condensed hydrogens. A summary of the styles and complexity of students' structures is shown in Table 6.3.

As in Implementation 1, the presentation of the molecules influenced students style of drawing; the preferred style for molecule (a) in Question 1 was zig-zag style with extended hydrogens and the preferred style for molecule (b) in Question 1 was linear with extended hydrogens. Students' style of drawing will be compared with their drawings and models in the modelling test in Section 6.2.5.

Table 6.3: Representational styles used for each structure in Assessment 2-Question 1

Type of Structure	Question 1							
	Molecule (a)				Molecule (b)			
	Ext + linear	Ext + zigzag	Cond + linear	Cond + zigzag	Ext + linear	Ext + zigzag	Cond + linear	Cond + zigzag
Total= 38	14	21	2	1	21	14	2	1

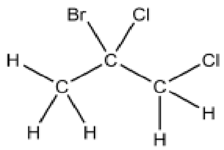
Ext = extended, cond = condensed

<u>Assessment 2-Question 2:</u> Naming an organic compound

Assessment 2-Question 2 was focused on the IUPAC naming system. Figure 6.3 shows Question 2 and details the rationale and summary of results.

<u>Question 2</u>

What is the name of the following compound?



(a) 2,3-dichloro-2-bromopropane

(b) 1,2-dichloro-2-bromopropane

(c) 2-bromo-2,3-dichloropropane

(d) 2-bromo-1,2-dichloropropane

Rationale:

The IUPAC naming system was included at the request of the teachers from Implementation 1, thus it was necessary to assess this.

The compound selected was 2-bromo-1,2-dichloropropane. The molecule was presented with expanded hydrogens to test students' abilities to extract the important information from a given structure. The purpose of this question was to decipher if students could 'read' a structural formula. Multiple choice was selected as the format of this question to move the emphasis of the question away from the IUPAC naming rules and more towards students' identifying the components of the molecule. Answers (b) and (d) were accepted as correct, as the only difference between these names is the placement of substituents in alphabetical order and this was not emphasised in the OCV programme.

Summary of Results:

16 students were successful in identifying either (b) or (d).

Figure 6.3: Assessment 2-Question 2, rationale and summary of results

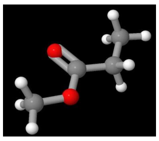
Less than half of students (16) identified either (b) or (d) as the correct name. Most students (25) selected either (a) or (c). It does not matter how many selected (a) or how many selected (c) as both of these answers indicate these students are reading the structure from left to right. While not a direct aim of the OCV programme it is interesting that despite the emphasis that was placed on the IUPAC naming system and the multiple activities added, the majority of students did not recognise the need to read the structure from right to left.

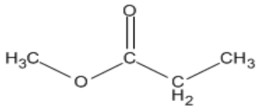
Assessment 2-Question 3: Structural formula to molecular formula

Assessment 3-Question 3 is the same as that in Assessment 1. Figure 6.4 details the rationale for including in this in Assessment 2 also and summary of results from this implementation.

Question 3

Write the molecular formula for the molecule represented in both 3D and 2D below.





Molecular formula:

Rationale:

This question was useful in determining students' ability to translate from a structural formula to molecular formula following Implementation 1. Thus, it was included in Assessment 2.

Summary of Results:

32 out of 38 students successfully wrote the molecule's formula. Two students did not make an attempt at this question. Four students identified the number of components incorrectly.

Figure 6.4: Assessment 2-Question 3, rationale and summary of results

The four students who made an unsuccessful attempt at this question were from different class groups. Three of these students gave the molecule's formula as $C_3H_8O_2$ while one student gave $C_4H_2O_2$. As in Implementation 1, these could be considered counting errors.

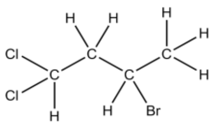
Two of these students were unsuccessful in Question 2. These students could be making errors in reading structures.

<u>Assessment 2-Question 4</u>: Identifying an isomer pair from four structures

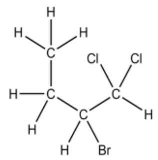
Assessment 2-Question 4 presents students with four structures and asks them to identify an isomer pair. Figure 6.5 shows the structures given, the rationale for the question and the summary of results.

<u>Question 4</u>

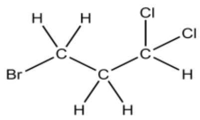
Four compounds, W, X, Y and Z are represented below:



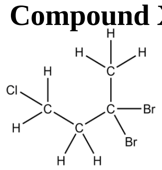
Compound W



Compound X



Compound Y



Compound Z

Which of the following is a pair of isomers?

W and Y
X and Y
W and X
Y and Z

Explain how you know these are isomers.

Rationale:

Students are required to evaluate the structures of the four compounds presented to them and identify a pair of isomers. The additional study in Implementation 1 suggested that some students may have struggled with the term ‘isomer’ and this may have reduced their chances for success in identifying isomers. While the term ‘isomer’ is still used in this question, it was hoped that using the term ‘pair of isomers’ would hint to students that they are required to look for two similar molecules.

Summary of Results:

35 out of 38 students successfully identified (c) W and X as the isomer pair.

One student identified (a) W and Y, while two students identified (d) Y and Z as the isomer pair.

Figure 6.5: Assessment 2-Question 4, rationale and summary of results

Most of the students (35 out of 38) successfully identified the isomer pair, which is slightly better than in Implementation 1; 28 out of 47 students could successfully draw two isomers of a given molecule in Question 2 of Assessment 1. This could indicate that identifying isomers is an easier task than actually drawing isomers. However, the structure in Assessment 1 was composed of seven carbons, while the structures in this question are composed of only four carbons. This difference in complexity could also explain these results.

Of the 35 successful students, 31 could also provide a full explanation as to why they are isomers, for example:

> *'Both have the same number of carbon, hydrogen, Br and Cl. But they are different structures'.*
>
> *'They both have the same molecular formula but different structural formula'.*

Of the successful students, four provided incomplete explanations, identifying the similar components in the molecules but not discussing their arrangement:

> *'They both have 4 carbons in their chain. As well as having equal numbers of hydrogen, bromine and Cl.'*

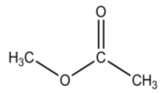
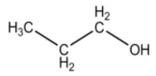
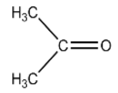
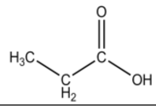
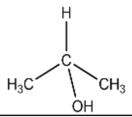
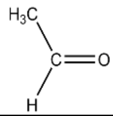
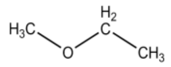
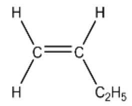
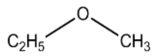
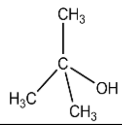
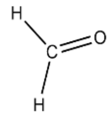
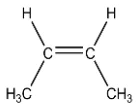
One student incorrectly identified (a) W and Y as isomers but clearly cited the definition of an isomer. Compound W contains two chlorine and one bromine atom while Compound Y contains two bromine and one chlorine atom. The two other unsuccessful students identified (d) Y and Z but did not provide an explanation.

<u>Assessment 2-Question 5</u>: Structural communication grid- identifying structures, isomers and physical properties

This question is a structural communication grid with 8 parts. Figure 6.6 shows the questions asked, the rationale for choosing a structural communication grid and a summary of students' success. Structural communication grids present data in the form of a numbered grid, students are given questions and asked to select appropriate boxes in response to these questions.

<u>Question 5</u>

Look at the boxes below and answer the questions that follow:

A 	B 	C 	D 
E 	F 	G 	H 
I 	J 	K 	L 

Select the boxes which show the structure of:

		Answer
(a)	An isomer of the compound shown in box G	
(b)	An aldehyde	
(c)	A compound which is identical to I	
(d)	An alkene with a cis- arrangement	
(e)	An isomer of the compound shown in box B	
(f)	An ester	
(g)	A molecule which will be insoluble in water	
(h)	A molecule with a higher boiling point than the compound shown in box B	

Rationale:

Students were asked to explain their selection for answers (g) and (h). Communication grids are highly recommended for insights into conceptual understanding (Reid 2003).

These questions are designed to assess students' abilities to read and compare structures.

Summary of Results:

20 students were successful in all three parts of the question.

Nine students could identify isomers in (a) and (e), while four were only successful in part (c).

Figure 6.6: Assessment 2-Question 5, rationale and summary of results

This question has eight parts. Rather than discuss each part individually, they will be grouped in terms of similar questions. Parts (a) and (e) ask students to identify an isomer while part (c) asks students to identify an alternative representation of the same molecule. These questions will be discussed together as they involve students' reading structures and identifying similarities and differences. The number of student successes in each question are detailed in Table 6.4.

Table 6.4: Students successful in questions involving isomers and reading structures

	Student Responses		
Answers selected	(a), (e) and (c) correct	(a) and (e) only (isomers)	(c) only
Number of students	20	9	4

Twenty students were successful in all three of these parts of the question, indicating an ability to compare the variety of structures and identify similar and different structures.

A further nine students could identfiy isomers as in part (a) and (e) but were unsuccessful in identifying a representation of the same molecule in part (c). Eight of these students identified the molecule in box E as identical to the molecule in box I, however this is an isomer. The other student identified the molecule in box J as identical, but this molecule does not even have the same number of carbons and hydrogens. These eight students were also successful in identifying the isomer pair in Question 4, indicating an ability to recognise molecules with the same components and different structure but they struggled to identify the same structure represented in a different orientation.

Four students were unable to identify isomers in either (a) or (e) but were able to identify a correct structure for part (c). A further six students were unsuccessful in all three parts of the question. Three of these were insuccessful in Question 4.

Comparison of these parts of Question 5 and students success in Question 4 indicates students are more successful at comparing structures and identifying differences rather than identifying the same structure presented differently.

Parts (b), (d) and (f) ask students to identify an aldehyde, an alkene with a cis-arrangement and an ester respectively. As with the IUPAC naming system, this was not a direct aim of the OCV programme but it was requested to be included in the programme, thus assessment was required. Twelve students were successful in all three parts.

The final parts of this question, (g) and (h) asked students to identify a molecule which would be insoluble in water and identify a molecule with a higher boiling point than that in box B, which is an alcohol. No class group in Implementation 2 actually reached Chapter 7 of the OCV programme, in which solubility of organic compounds is addressed. Only classes B and C, comprising 22 students, reached Chapter 6, dealing with boiling points.

There was one possible answer to part (h); the molecule in box D, propanoic acid, has a higher boiling point than that in box B, propanol. Half of the students (11 of 22) successfully identified molecule D, however all of them gave incomplete explanations for their answer. As in Implementation 1, incomplete answers identified the intermolecular forces in each compound, but did not describe their link to boiling point.

Five students did not attempt this question. Incorrect answers to this question identified molecules in boxes H, J and L as having a higher boiling point because they had more carbons. This explanation indicates that these students failed to recognise the importance of the functional group in influencing boiling point.

The focus of Assessment 2 was more on students' understanding of structures and abilities to read and compare structures. The results from Assessment 2 which require these skills are similar to those obtained in Assessment 1. Students were successful in translating from 3D representations to 2D representations and from a structural formula to a molecular formula. The majority of students were also capable of identfying isomers. Interestingly, students were better able to identify isomers than they were identifying structures of the same molecule which were oriented differently. Students' results from Assessment 2 will be compared with their results in the modelling test and follow up discussion in Section 6.2.5.

6.2.3 Free-Form Modelling Test

Following evaluation of Assessment 1 and discussion with teachers involved in Implementation 1, a need for development of a method to evaluate students' ability to work in 3D was identified. It was felt that while Assessment 1 was necessary to assess students' working in 2D and identifying their understanding of IMFs, the use of this as the primary assessment did not match the teaching approach. Students who had been modelling on a regular basis were still assessed using a standard pen-and-paper assessment. Thus, an additional assessment was required to evaluate students' 3D ability.

Nicoll (2003) used a free-form modelling test and structured interviews to assess students' ability to translate from symbolic to molecular representations in both 2D and 3D. This approach was successful in identifying gaps in students' translation between representations and in their understandings. While Nicoll's study used the compound formaldehyde, the compound ethanal (CH_3CHO) was chosen for this study. There were several reasons for this selection:

- Ethanal contains both a tetrahedral and planar carbon;
- Ethanal contains both single and double bonds;
- Formaldehyde was considered too small;
- Ethanal contains atoms of three elements.

The modelling test was conducted in pairs; students were asked to face away from each other so that neither influenced the others' drawing or model. Students were given the molecular formula for ethanal (CH_3CHO) and asked to first draw the structure of ethanal (translate from symbolic to structural formula) and then construct an accurate 3D model of the structure they had drawn (translating from 2D representation to 3D representation). Students were given a kit containing modelling clay of six different colours and sticks of two different colours. The purpose of giving students these materials rather than the Molymod kits which they were accustomed to using was to assess the elements of the Molymod kits and the 3D nature of organic molecule that students had internalised from using them. Students will not have any prompts in terms of the number of bonds and the geometry (shape) of the bonding.

Regardless of the model constructed by students, they were asked to explain why they constructed the model in the way that they did, what each component represented and how the shape of the molecule arose. Additionally, students were also asked to suggest areas of high and low electron density within the molecule and if they believed ethanal would be water soluble.

The free-form modelling test and follow up discussions, which were conducted with students in pairs, was performed by 45 students. The reason for this was an effort to take pressure off students and make them more at ease, thus make them more likely to discuss their opinions and understandings freely. Two independent researchers from the researcher's institution were recruited to help conduct these in a timely manner. The discussion protocol which the researchers followed can be found in Appendix H.

The results of this test will be discussed in terms of the structures drawn, followed by the models constructed by students. Table 6.5 summarises the categories used to code students' drawings and models, and the number of students whose drawings and models fell into each category. Student structures and student models are now discussed in the next sections.

Table 6.5: Modelling test rubric, showing categories and results
Categories used to code students' structures and models and the number of students who drew structures and built models according to categories outlined.

	Category	**# of students**
Student structure	Correctness	
	Correct	35
	Ethanol (incorrect functional group)	3
	Error in bonding of atoms (valency errors)	5
	3 carbon structure (incorrect reading of molecular formula)	2
	Nature of 2D structure	
	Linear with approx. 120^o angle in CHO group	13
	Linear with approx. 90^o angle in CHO group	24
	Linear with approx. 180^o angle in CHO group	5
Student models	Relationship b/w* drawing and model	
	Matches	42
	Does not match	3
	Differentiation b/w* atoms of elements	
	Colour	45
	Relative size: H smallest, C and O same	45
	Geometry of tetrahedral carbon (angles)	
	Reasonable attempt at tetrahedral	14
	Adequate attempt at tetrahedral	12
	Poor attempt at tetrahedral	6
	Flat linear (approx. 90^o angles)	13
	Geometry of planar carbon (angles)	
	Approx. 120^o angle O=C-H	24
	Approx. 90^o angle O=C-H	15
	Approx. 180^o angle O=C-H	4

*b/w = between

6.2.3.1 Student Structures

The structures drawn by students were analysed focusing on two main attributes of the structure; if it was correct (in terms of correct atoms and valency of atoms) and the nature of the drawings (in terms of style and shape).

Of the 45 students who took part in the modelling test, 35 students were able to correctly draw the structure of ethanal. The incorrect structures drawn by the remaining 10 fell into three categories;

- A structure with three carbons
- Errors made in bonding of atoms (valency errors)
- Ethanol (incorrect functional group)

Figure 6.7 shows examples of incorrect structures drawn by students. As can be seen in Table 6.6, two students drew a structure with too many carbons. These students had difficulty reading the molecular formula and identifying the number of components detailed in it.

Table 6.6: Number of students who drew correct/incorrect structures

Structure	**# of students**
Correct	35
Ethanol (incorrect functional group	3
Error in bonding of atoms	5
3 carbon structure	2

Five students made errors in the bonding of atoms. As can be seen in Figure 6.7, these mistakes included an oxygen atom missing a bond, a hydrogen atom with two bonds and a carbon atom with five. While these students could read the molecular formula and were sure of the number of components, their understanding of the bonding of each atom hindered them drawing a correct structure.

Three students drew a structure for ethanol instead of ethanal. These students have drawn a chemically correct structure but have not made the link between the number of each component detailed in the molecular formula and the number of components in the structure.

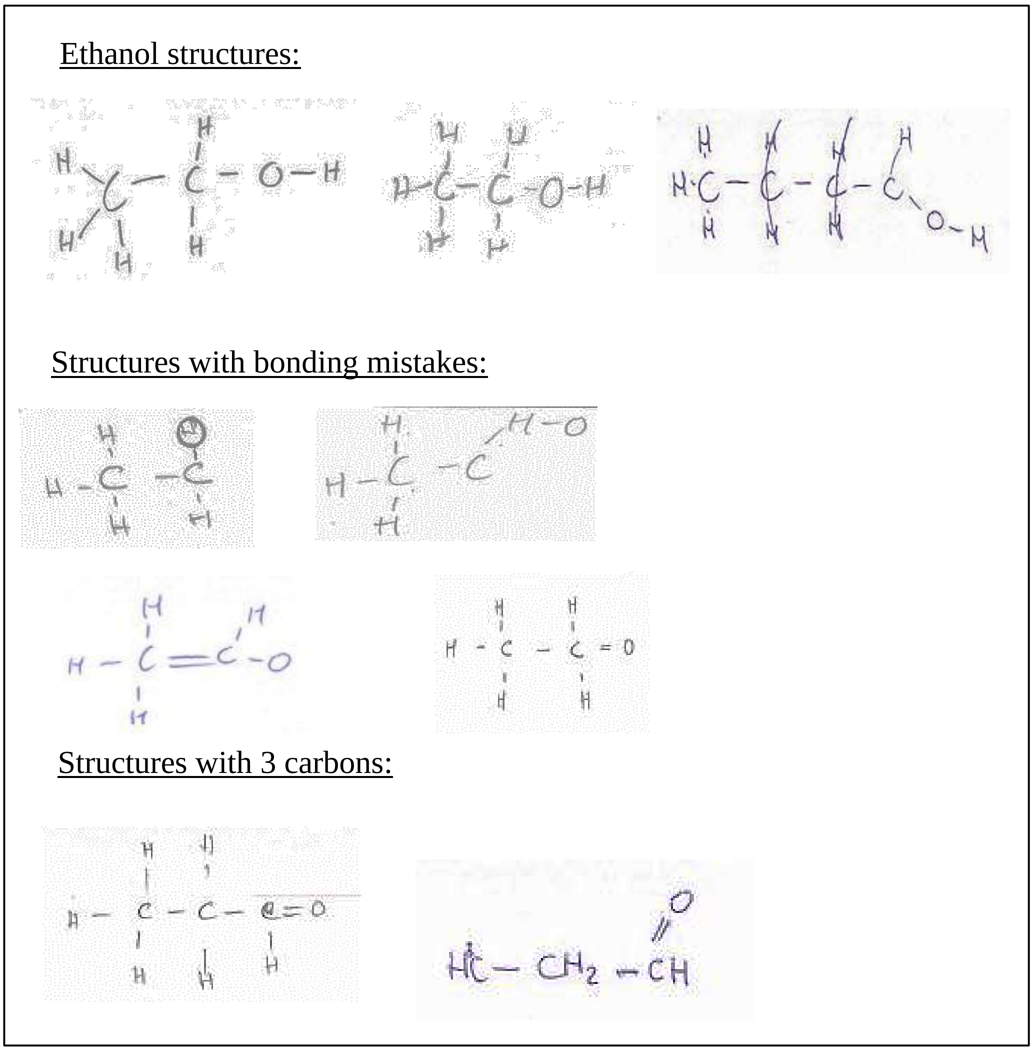


Figure 6.7: Incorrect structures drawn by students in the first part of the modelling test

The nature of drawings examined in Assessments 1 and 2 were categorised in terms of style (linear or zigzag) and complexity (extended or condensed hydrogens). However, in this assessment, no student chose to draw their structure with condensed hydrogens and the majority of structures drawn were linear with approximately 90 degrees between bonds of the tetrahedral carbon. The element of students' drawings that did vary was the nature of the planar carbon, more precisely the angle drawn between the –CHO group of the carbonyl group.

The nature of students' drawings in this manner fell into three categories, examples of which can be seen in Figure 6.8:

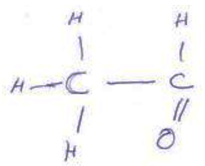
- Linear with approx. 180^{o} angle in CHO group;
- Linear with approx. 90^{o} angle in CHO group;
- Linear with approx. 120^{o} angle in CHO group.

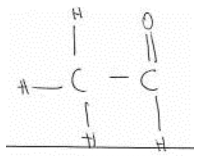
Table 6.7 details the number of students who drew structures which fell into each category. Structures with the correct approximate 120^{o} angle in the CHO group were drawn by 13 students. The majority of students (24) drew structures with 90^{o} angle in the CHO group while five students drew structures with a 180^{o} angle in the CHO group. These five students came from different implementation classes, so this was not a teacher/class led conception.

Table 6.7: Number of students who drew structures with different bond angles in CHO group

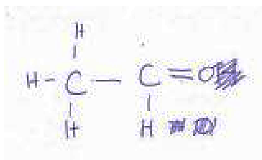
Structure	# of students
120 degree angle between H and O in CHO group (correct)	13
90 degree angles in all bonds	24
180 degree angle between H and O in CHO group	5

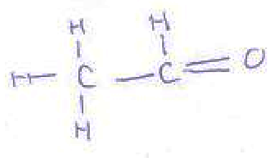
180 degree angle between H and O in CHO group



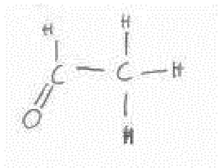


90 degree angle between H and O in CHO group





120 degree angle between H and O in CHO group



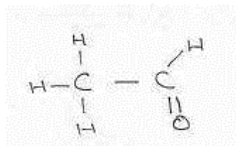


Figure 6.8: Examples of different bonding angles drawn by students.

6.2.3.2 Student Models

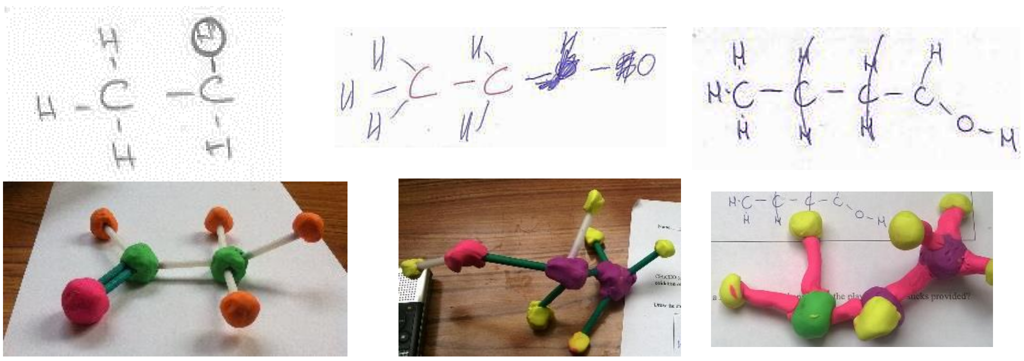
Once students had drawn their structures in 2D, they were given a kit with modelling clay to construct their structure in 3D. Students were instructed to make their 3D structures as accurately as possible. No corrections were given to students who drew an incorrect structure.

As in Table 6.5, students’ models were coded under the following headings:

(a) Relationship between model and 2D structure: did they match?
(b) Differentiation between atoms of different elements;
(c) Geometry of the tetrahedral carbon;
(d) Geometry of the planar carbon.

(a) Relationship between model and 2D structure: did they match?

Almost all of the students’ models (42 out of 45) matched their drawn structures. Three students’ models did not match the structures they had drawn, see Figure 6.9. It should be noted that all three students drew an incorrect structure to begin with. S30 drew an incorrect structure with the oxygen only single-bonded to the carbon but corrected the structure when constructing their model and included a double bond. S25 drew a structure with C-H-O bonding but corrected the mistake in the bonding to construct a model of ethanol. S37 drew a structure with incorrect bonding and functional group and actually constructed an even more incorrect model by adding another carbon and hydrogen. It should also be noted that this student did not opt to use sticks to represent the bonds between atoms but moulded the playdough into sticks. This student is the only one in the cohort that constructed their model in this manner.



S30 S25 S37

Figure 6.9: Students models that did not match their drawn structures

(b) Differentiation between atoms of different elements.

All students chose to differentiate atoms of different elements using colour. Most of them (40 of the 45) used relative size to differentiate between atoms of different elements' all with 'hydrogen' as the smallest. The other five students built all atoms in their model approximately the same size.

(c) Geometry of the tetrahedral carbon

The shapes with which students constructed the tetrahedral carbon in their models were coded into four categories. Examples of these can be found in Figure 6.10.

A. Reasonable tetrahedral
B. Adequate attempt at tetrahedral
C. Poor attempt at tetrahedral
D. Flat, 2D: 90 degree angles

Table 6.8 details the number of students whose models fell into these categories. Students' models which were completely flat were almost direct translations of 2D structures simply constructed with balls and sticks; no 3D element was introduced to the structures. This geometry of the carbon was constructed by 13 students.

Table 6.8: Results of student construction of the tetrahedral carbon

Geometry of Tetrahedral Carbon	# of students
Reasonable tetrahedral	14
Adequate attempt at tetrahedral	12
Poor attempt at tetrahedral	6
2D and linear, approx. 90 degree angles	13

Models which were categorised as an inadequate attempt at a tetrahedral carbon were almost completely flat with the exception of one bond slightly oriented out of the plane that the rest of the molecule is in; two examples of this are shown in Figure 6.10(C). Six students made inadequate attempts at the geometry of a tetrahedral carbon.

Students whose tetrahedral carbons were categorised as an adequate attempt oriented three or all of the bonds out of the plane of the C-C bond. Examples of models in this category are shown in Figure 6.10(B). These students have indicated that they are aware of the 3D nature of the tetrahedral carbon but were unsuccessful in correctly displaying this.

A reasonable tetrahedral carbon was constructed by 14 students. Reasonable tetrahedral shaped models were categorised as being as close to tetrahedral as possible, with only one bond angle slightly ‘incorrect’, as shown in Figure 6.10(A).

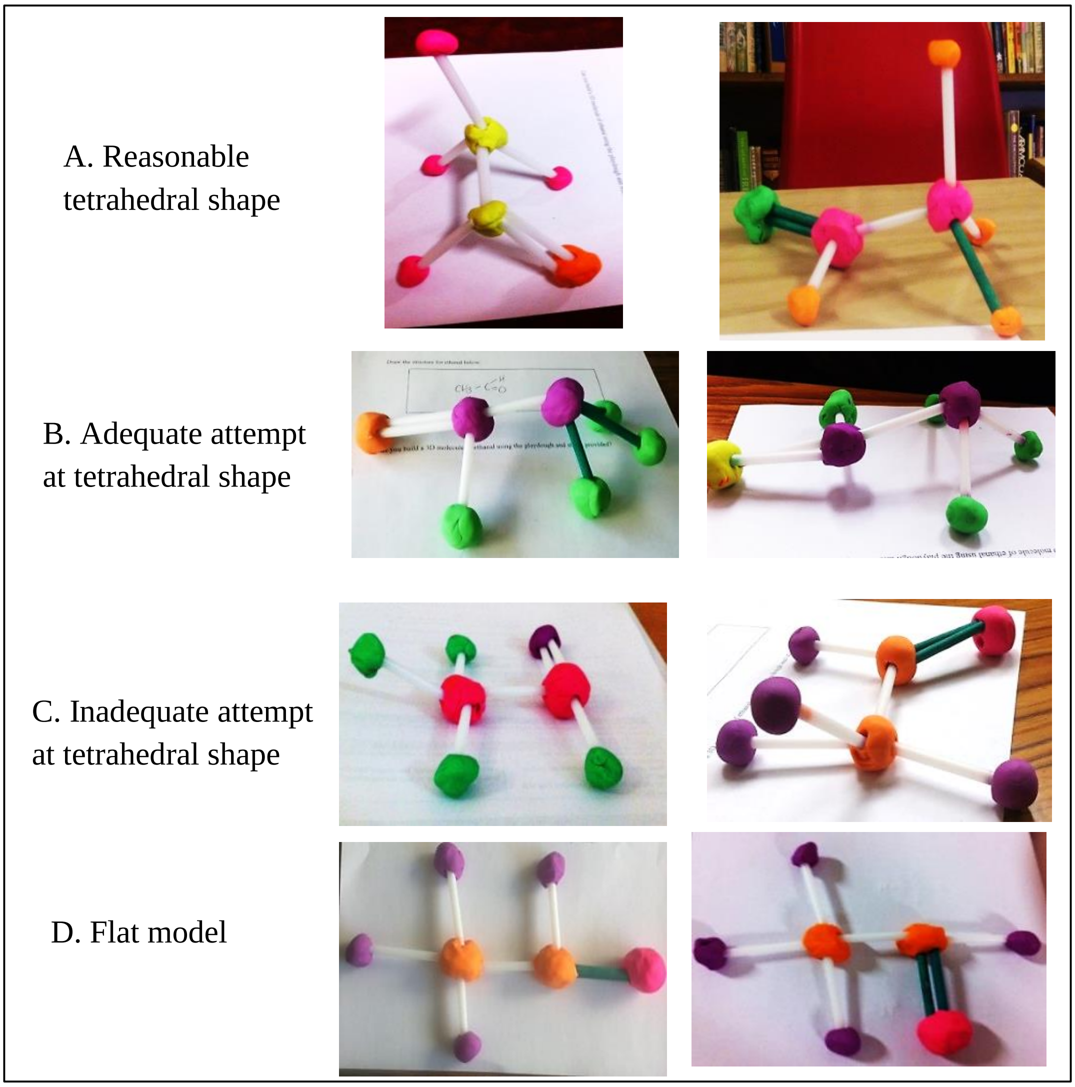


Figure 6.10: Examples of models from each of the four categories of tetrahedral carbons constructed

While not all students were successful at constructing a fully tetrahedral carbon, 32 students made an attempt. This indicates that the majority of students were at least aware of the 3D nature of carbon.

(d) Geometry of the Planar Carbon

The shapes with which students constructed the planar carbon in their model fell into three categories. Examples of these can be found Figure 6.11.

A. Approx. 120^{o} angle in O=C-H
B. Approx. 90^{o} angle in O=C-H
C. Approx. 180^{o} degree in O=C-H

Table 6.9 details the number of students whose planar carbons fell into each category. A planar carbon with an approximate angle of 120^{o} in the CHO group was constructed successfully by 24 students, while 15 constructed a planar carbon with an approximate angle of 90^{0} in the CHO group. Four students constructed an approximate angle of 180^{0} in the CHO group.

Table 6.9: Number of students who constructed the different angles in their planar carbon

Geometry of Planar Carbon	# of students
Approx. 120^{o} angle O=C-H	24
Approx. 90^{o} angle O=C-H	15
Approx. 180^{o} angle O=C-H	4

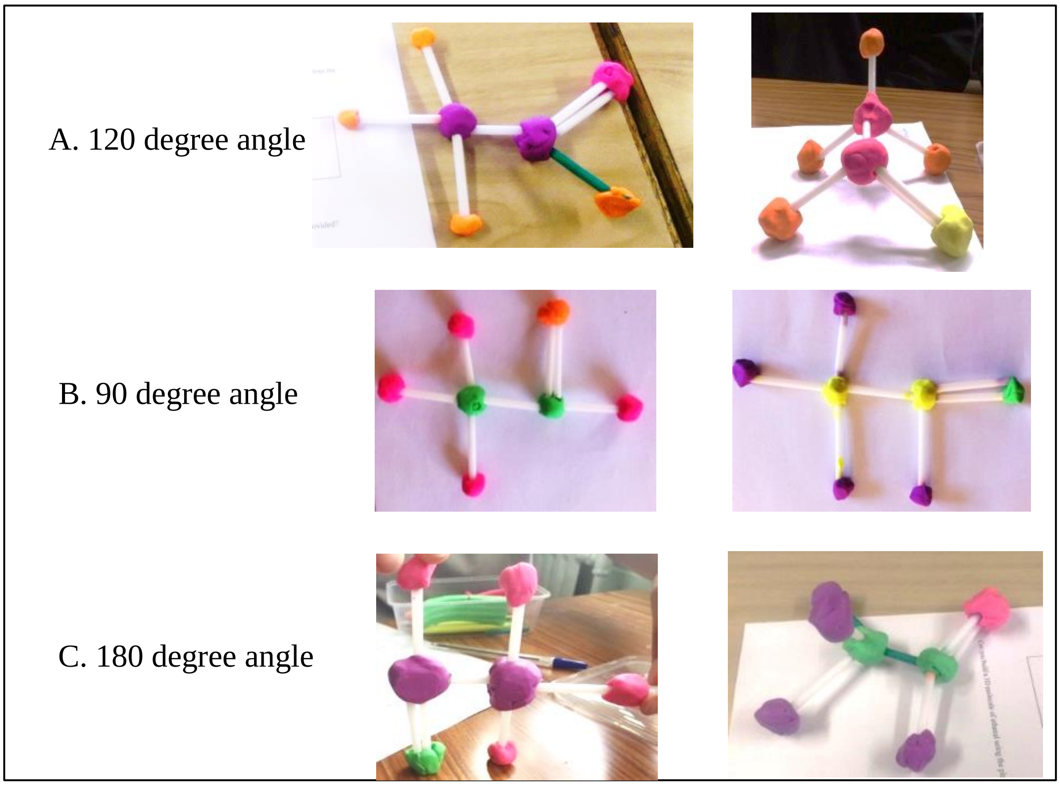


Figure 6.11: Examples of models from each of the three categories of planar carbons constructed

A larger proportion of students constructed an accurate planar shape than constructed a reasonable tetrahedral shape. Interestingly, students who constructed an accurate tetrahedral shape also constructed an accurate planar shape. However, not all students who constructed an accurate planar shape could construct an accurate tetrahedral shape. This suggests that the planar shape of carbon was internalised from the Molymod kits more successfully by students than the tetrahedral shape was.

Other elements of the Molymod kits that appear to have been successfully internalised by students are the use of colour to differentiate between atoms of different elements and the use of size to differentiate hydrogen as the smallest atom.

The majority of students could translate the structure of ethanal from its molecular formula into a 2D structural representation (translate from molecular formula to structure).

All but three students could successfully translate their structure into a model, whether it was accurately 3D or not. Even students who struggled translating from molecular formula to structural formula could transform their 2D structure into a 3D model. Two students who drew an incorrect structure initially actually corrected their structure when translating their 2D drawing into a 3D model.

Students were questioned on their models following their construction to assess their ability to verbalise their understanding of different components of their models.

6.2.4 Modelling Test Follow-up Discussion.

The purpose of the follow-up discussion with students after the modelling test was to investigate students' ability to verbalise their understandings and ability to 'talk chemistry'. As discussed in Chapter 3, student discussions were conducted in pairs and two independent researchers conducted these discussions as well as the researcher.

Students were asked questions which related to four main attributes of their models; the physical representation, the geometry of the model, electron density within the molecule and the solubility of the molecule. The questions asked are summarised in Table 6.10. The full protocol for this discussion can be found in Appendix H.

Table 6.10: Questions asked in relation to each attribute of students' models.

Attribute of model	**Questions Asked**
(a) Physical representation	Describe: • What each colour represents • Why some atoms are different sizes (if they were constructed that way) • What the sticks represent
(b) Geometry of the model	Describe: • The difference between double and single bonds • The shape of the tetrahedral carbon • The shape of the planar carbon
(c) Electron density	Can you identify an area of high electron density within the molecule?
(d) Solubility in water	Do you think this molecule would be soluble in water?

(a) Physical Representation

All students constructed their models using colour to differentiate between atoms and all of the students could identify the atoms represented by each colour. As with their models, all students identified hydrogen as the smallest element, identifying its position on the periodic table as the reason for this. All students also identified the sticks used in the models as representing bonds between atoms.

Carbon and oxygen were identified as the same size by 19 students. The position on the periodic table was a common explanation for students who identified carbon and oxygen as different sizes. Oxygen was suggested as the largest atom by 22 students as it 'contains more protons, neutrons and electrons'. A further four students went on to suggest that carbon is the largest atom because it 'holds everything together'.

(b) Geometry of the model

The difference in flexibility of single and double bonds is a concept which was explicitly highlighted in the OCV. It is encouraging then, that all students identified double bonds as being more rigid compared to single bonds, which are flexible and can be rotated.

> '*Like this, the single bond can go anywhere around there but the double bond can only go that way, do you see?'*
> (the student demonstrates using their model) (S12)

Students' identification of the tetrahedral and planar shapes was not as successful. In total, 26 students could provide a reasonable explanation of the tetrahedral shape. Seven of the 14 students who constructed the tetrahedral shape could describe and explain the shape. An example of a reasonable explanation is described below:

> R: *Can you explain the shape of that carbon for me?*
>
> S12: *Well the bonds are evenly distributed, like pushing apart from each other so it's not flat, like they're all pushing out like that.*
>
> R: *Does the bonding contribute to that shape?*

> S12: *Yeah because the electrons in the bond…what's the word? Retractions? No repulsion that's the word. There is repulsion so you get this shape.*

Of the 18 students who attempted the tetrahedral shape, whether making an adequate or poor attempt, 11 could describe and explain the shape. Interestingly, of the 13 students who constructed flat, linear structures, eight identified the carbon as tetrahedral and could give an adequate description of the shape and how it arises. More importantly, these eight students recognised that they had in fact not constructed tetrahedral but could describe it and demonstrate it with their model.

Only one incorrect explanation arose from students; three referred to lone pairs within the tetrahedral carbon. The rest of the students who did not explain the shape simply did not make an attempt at an explanation.

While more students were successful at constructing the planar carbon in their models than the tetrahedral carbon, they were less successful at describing it. Twelve students identified the planar carbon as 'flat' but could not name it and these students were capable of describing the tetrahedral shape.

(c) Electron density

Oxygen was successfully identified by 23 students as the area of high electron density in their molecules. Incorrect areas of electron density identified include the double carbon-carbon bond (6 students) and the $–CH_3$ group (2 students), and 14 students were unsure and could not make an attempt. These are similar proportions to that obtained in Implementation 1, where 19 students out of 31 were capable of identifying areas of electron density. It is interesting to note the difference in relative complexity between these two molecules, and yet, similar results were obtained.

(d) Solubility in water

While 24 students suggested ethanal would be water soluble, their explanations were incomplete. Most of them (20) identified IMFs within the molecule but could not describe interactions between the ethanal molecule and water molecules. Eight students could not make a prediction.

Incorrect explanations for insolubility focused on repulsion of like charges:

> *'I'm not sure but I would have said that because there's a delta minus in the oxygen and there's a delta minus on that oxygen, that they would repel each other so it wouldn't be soluble.'* (S13)

These results are similar to students' explanations in Implementation 1; the majority of students were capable of identifying areas of high and low electron density and IMFs but could not link these to the physical properties.

This follow up discussion following the modelling test has demonstrated that some students have difficulty communicating their understandings. Even of those who could construct a tetrahedral shape, only half could explain it.

6.2.5 MDS Analysis of Student Data

As there is a range of sources of data collected from students in the form of the Assessment 2, the modelling test and interview, it was considered interesting to determine if the range of responses were similar or dissimilar. Therefore, all data was coded and Multi-Dimensional Scaling (MDS) analysis was run on the data. Students' responses were coded on a numerical scale in which the most correct answer being the highest number, 1 being the most 'incorrect' response and with 0 being no attempt.

MDS graphically represents similarities and dissimilarities between objects. Objects that are considered similar to each other are represented by points that are closer together. In this case, the 'objects' are the students. The 'ideal' response, which is the most correct response, for each question was included in this analysis. This made it possible to see if students were clustering in their responses and if these were closer or far away from the 'ideal' response. All of data presented are compared to an ideal response, where all of the answers to all questions asked are correct. Therefore, the closer to the ideal the more similar the students' answers are to being completely correct. Examples of how student responses were ranked from 'most correct' and 'most incorrect' for comparison with the ideal can be found in

Appendix J. Figure 6.12 shows the MDS plot of student data. It should be noted that the dimensions labelled on an MDS plot are not a scale on which to measure the data. When looking at an MDS plot, one only needs to look at the distances between the data points.

In Figure 6.12, there appears to be two clusters of student responses- one group close to the ideal (red star) and cluster Y, with a number of more scattered responses.

The similarities between cluster Y and the more scattered responses appears to be their poor attempts at Question 5 in Assessment 2, while it is their attempts at the modelling test that differentiates them. The scattered points seem to reflect poor attempts at Question 5 in Assessment 2. In addition to this, all made significant mistakes in the modelling test and were primarily working in 2D. Students in Cluster Y answered Question 5 in Assessment 2 poorly but all at least attempted it. Students in this cluster could draw a correct structure but made poor attempts at 3D models.

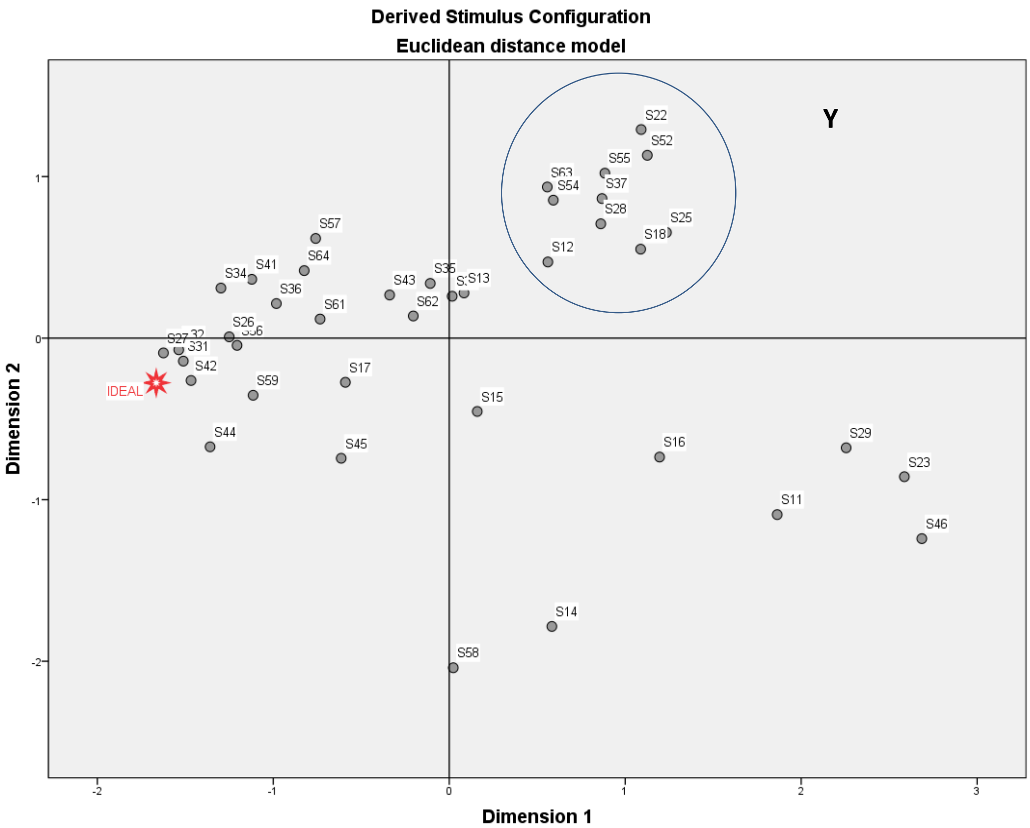


Figure 6.12: MDS analysis on all student data from final implementation- Assessment 2, modelling test and interview.

There were two questions on Assessment 2 that required only theoretical knowledge and so these questions were removed from the data set and the MDS was rerun, meaning this MDS analysis focused on only the questions which require a spatial and structural understanding. The MDS plot for this data set can be seen in Figure 6.13. A number of students are very close to or on the 'ideal' (red star) and there appear to be two main directions away from the ideal for students to lie: students are either directly to the right of the ideal or directly below the ideal.

As you move to the right of the ideal, the nature of students' drawings and structures moved from 3D to primarily 2D. For example, S22 and S11 worked primarily in 2D in the modelling test, drawing a linear structure for ethanal with approximately 180^{o} angle in the CHO group. These students also constructed completely flat models of their structures. It should be noted that these students were successful in all other aspects of Assessment 2 and modelling test. Meanwhile, S61, who is about half way between S22 and the ideal drew a correct structure in the modelling test and attempted to bring a 3D element to their model, albeit inadequately.

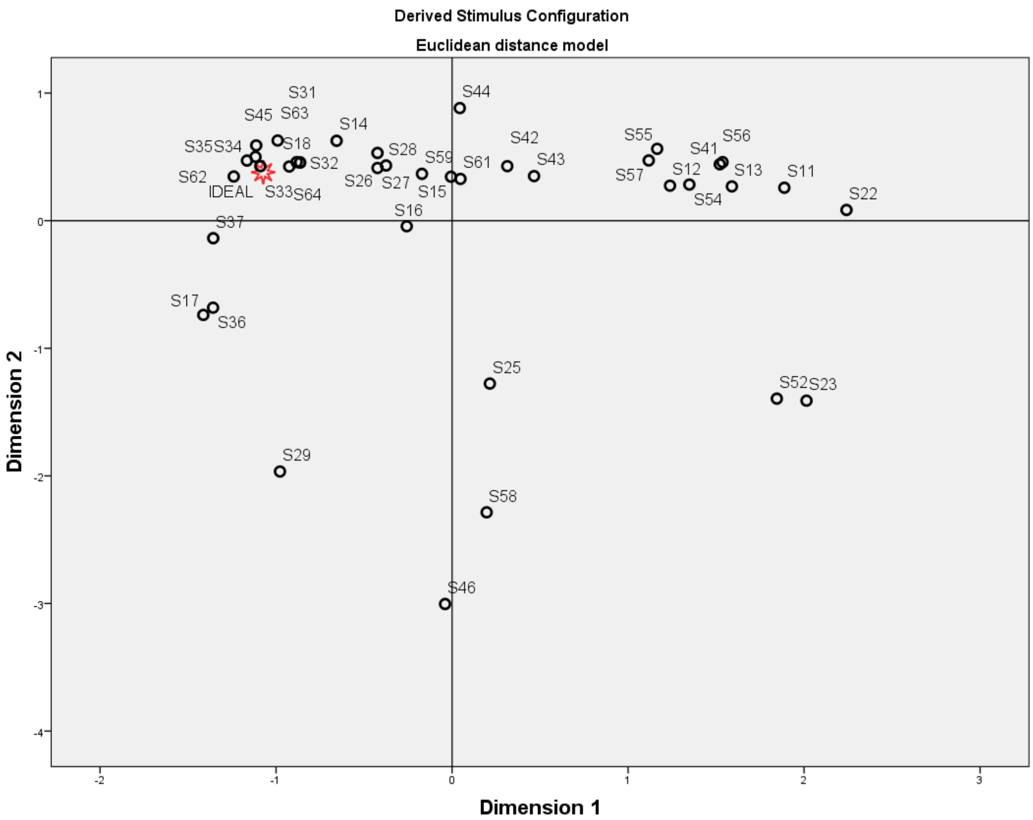


Figure 6.13: MDS analysis on spatial and structural student data only.

As you move below the ideal in this plot (Figure 6.13), students have made mistakes in their modelling test, primarily in the structures drawn at the start of the test. S37 and S16 drew a structure for ethanol instead of ethanal while S17 and S36 made mistakes in the bonding of their structures, i.e. hydrogen bonded to two other atoms or carbon bonded to five other atoms. However, all made good attempts at a 3D model.

To summarise this plot, as you move to the right of the ideal, students are working more in 2D; these response types will be called Category A. As you move below the ideal, students are making mistakes translating from a molecular formula to a structural formula, thus have more 'incorrect' structures. These response types will be called Category B (see Fig 6.14). Thus, if you move in a diagonal from the ideal towards the bottom right corner, students are giving responses with elements of Category A and Category B. It should be noted that Category A responses are not incorrect but are a measure of the nature of students' representations (2D/ 3D).

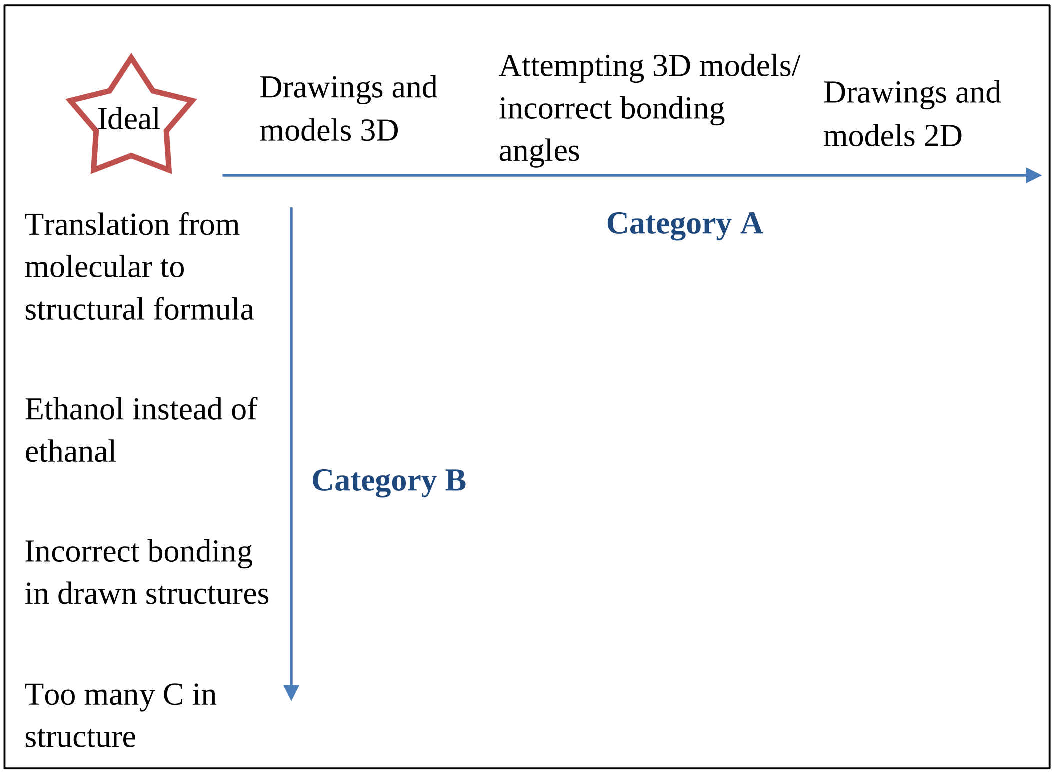


Figure 6.14: Summary of positions of response types on MDS plots of student data

As a point of interest, the spatial ability of students who fell along the Category A line and the Category B line were compared. No pattern was found and students along both of these lines had varying pre- and post- spatial abilities.

This analysis has shown that while the majority of students were able to make the translations required in both the Assessment 2 and modelling test, a number of students are still working in 2D, both drawing and modelling. A small number of students were unable to make the translation from molecular formula to structural formula but despite that, could still construct an accurate 3D model. Only five students in the cohort were making mistakes both in the translations and in constructing a 3D model.

6.3 Conclusions from Implementation 2

Observations allowed the researcher to gain a deeper insight into the implementation of the OCV programme. Students were observed to be highly engaged during activities and engaging in meaningful discussions and collaborations, regardless of the dynamic of the class. Teachers involved were very successful in facilitating discussion and leading students through the OCV activities.

Evaluation of data collected from students indicated that the majority of students are capable of translating between 3D and 2D representations; however some students are still modelling in 2D. The modelling test was a useful tool to gain an understanding of students' mental models of the 3D nature of organic structures following the use of Molymod kits. While some students struggled in constructing accurate shapes of models, a number of elements from the models were internalised, namely, the differentiation of atoms of elements by colour, the relative size of hydrogen as the smallest atom and the explicit representation of the bonds using sticks.

The results of Implementation 2 have important implications for the teaching of organic chemistry. The data collected in Implementation 2 will be used to develop a suggested sequence for learning organic chemistry through the use of physical models. The development of this sequence and its comparison with another suggested sequence in the literature will now be discussed in Section 6.4.

6.4 Implications for Student Learning

As discussed in Section 6.2, students did not achieve all assessment tasks of Implementation 2 successfully, indicating the tasks have different levels of complexity. In order to suggest a learning sequence by which to introduce students to organic chemistry through modelling activities, the data collected from students following Implementation 2 (Assessment 2, modelling test and paired follow-up discussion) will be compared and ranked in order of student achievement.

6.4.1 Identifying a Learning Sequence

The combination of data from Assessment 2, the modelling test and follow-up discussion questions allowed for a deeper investigation into the learning achievements and difficulties that students experienced. Table 6.11 has broken Assessment 2 (A), the modelling test (MOD) and the follow-up discussion (DISC) into their component questions. The questions have been grouped into the type of tasks asked, for example: translating from one representation to another has been assessed through Question 1 and Question 3 in Assessment 2 (A1 and A2), and part A and B of the modelling test (MODA and MODB). There are six task types, labelled A-F in Table 6.11. Students success in each task is plotted in Figure 6.15.

It is clear from Figure 6.15 that students were not able to carry out the tasks within each category equally. Therefore, redrawing Figure 6.15 by placing each task in order of success (as in Figure 6.16) and by removing the follow-up discussion questions (as in Figure 6.17) creates different patterns. There is then a progression of achievement, with students getting fewer questions correct progress from left to right. Re-examining this sequence of the tasks suggests a learning sequence which may be followed.

Figure 6.17 shows that task A1, of Type A, ranked the highest, with all students in the cohort able to achieve this fully. A1 required students to translate from a 3D representation of a hydrocarbon to a 2D representation. The second highest ranked is also of Type A: MODB. This task was the second part of the modelling test which asked students to construct a 3D model of the structure which they drew in the initial part of the modelling test. The other Type A tasks are found several steps below these tasks.

The next four highest ranked tasks all require students to be able to read structures, three of which involve the concept of isomers. Task A4 required students to identify a pair of isomers from four structures, A4E required an explanation of isomers and A5E and A5A required an identification of an isomer of a molecule within the communication grid.

It is interesting that these questions ranked quite high, while the only other question which required a reading of structures, A5C, ranked several steps down. This question asked students to identify an alternative structure of a hydrocarbon. Thus, it appears that students could recognise isomers more successfully than they could recognise alternatively arranged structures of the same molecule. This was already identified in Section 6.2.2.

The least achieved tasks were those in the post-assessment which involved identification and discussion of physical properties (A5GA, A5GE, A5HA, A5HE). This is not surprising as only a small amount of time was spent on Part B of the OCV programme by classes in this implementation in comparison to the time spent on Part A.

Table 6.11: Grouping of student tasks in Implementation 2 by type

Type	Description	Student Task
A	Translation from one representation to another	Assessment 2 Q1 (**A1**) Assessment 2 Q3 (**A3**) Modelling test Part A (molecular – structural formula) (**MODA**) Modelling test Part B (structural formula – 3D model) (**MODB**)
B	Reading structures-identifying isomers	Assessment 2 Q4 (a) (**A4A**) Assessment 2 Q5(a), (c) and (e) (**A5A, A5C, A5E**)
C	3D geometry: construction	Modelling test Part B – tetrahedral (**MODD**) and planar carbon (**MODE**) construction
D	Explanation required	Assessment 2 Q4(b) (**A4E**) Assessment 2 Q5 (g) and (h) (**A5GE**, **A5HE**) Explanation of these shapes and components of model (**DISCA**, **DISCB, DISCC, DISCD, DISCDE**) Explanation of electron density (**DISCEE)** Explanation of solubility (**DISCFE)**
E	Knowledge of IUPAC and naming rules required	Assessment 2 Q2 (**A2**) Assessment 2 Q5 (b), (d) and (f) (**A5B**,**A5D**, **PA5F**)
F	Physical property identification	Assessment 2 Q5 (g) and (h) (**A5GA**, **A5HA**) Identification of areas of electron density (**DISCEA)** Identification of solubility of molecule (**DISCFA**)

		S11	S12	S13	S14	S15	S16	S17	S18	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31	S32	S33	S34	S35	S36	S37	S41	S42	S43	S44	S45	S46	S52	S53	S54	S55	S56	S57	S58	S59	S61	S62	S62	S64
A	A1	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	A3	×	✓	×	✓	✓	✓	✓	✓		✓	✓		✓	×	×	✓	✓		✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓
	MODA	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	✓	×	✓	✓	✓	×	×	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓
	MODB	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
B	A4A	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	A5A	✓	✓	✓	✓	✓	✓	✓	✓		×	✓		✓	×	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	×	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓
	A5C	×	×	×	✓	×	✓	✓	✓		×	×		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	✓	×	×	✓	×	✓	✓	✓	×	✓	✓	✓	✓
	A5E	✓	✓	✓	✓	✓	✓	✓	✓		✓	×		×	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	×	×	✓	×	✓	✓	✓
C	MODD	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	✓	✓	✓	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓
	MODE	×	×	✓	×	✓	×	✓	✓	✓	×	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	×	×	×	×	✓		×	✓	×	✓	×	×	✓	✓	✓	✓	✓	✓
D	A4E	✓	✓	✓	✓	✓	✓	✓	✓		×	×		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	✓	✓	×	×	✓	✓	✓	✓	✓	✓	✓
	A5GE	×	×	×	×	×	×	✓	×		×	×		×	×	✓	×	×		×	✓	×	×	×	×	×	×	×	✓	✓	×	×	×	×	×	×	✓	✓	×	×	×	✓	✓	✓
	A5HE	✓	×	×	✓	×	×	×	×		×	×		×	✓	✓	×	×		✓	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	✓
	DISCA	✓	✓	✓	✓	✓	×	✓	×	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	×	×	✓	×	×	×	✓	✓	✓	×	×	✓	×	✓	✓	✓	✓
	DISCB	×	×	✓	✓	✓	×	✓	✓	✓	×	×	✓	✓			✓	✓	✓	✓	✓	×	✓		×	×	✓	✓	×	✓	✓	×	×	✓	✓	×	×	✓	✓	✓	✓	✓	✓	✓
	DISCC	✓	✓	✓	×	×	×	×	×	×	✓	×	×	×			×	×	×	✓	✓	✓	✓		✓	✓	×	✓	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	DISCD	✓	✓	×	×	✓	×	×	✓	✓	✓	×	×	✓			×	✓	✓	×	✓	×	×		✓	×	×	×	×	×	×	✓	✓	✓	✓	×	×	×	×	✓	✓	✓	×	✓
	DISCEE	×	✓	×	✓	×	×	×	×	×	✓	×	×	×			×	×	✓	✓	✓	✓	×		×	×	×	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	×	✓	✓
	DISCFE	×	✓	✓	✓	✓	×	✓	✓	×	✓	✓	×	✓			×	✓	×	✓	✓	✓	✓		×	×	×	×	✓	✓	×	×	×	✓	✓	×	×	✓	×	✓	×	✓	×	✓
E	A2	✓	✓	✓	✓	✓	×	✓	✓		×	×		✓	×	×	✓	×		✓	✓	✓	×	✓	✓	×	×	✓	×	×	×	×	×	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓
	A5B	×	✓	✓	×	×	×	×	✓		✓	×		✓	✓	✓	✓	×		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓
	A5D	✓	✓	×	×	✓	✓	✓	×		✓	×		✓	✓	✓	✓	×		✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	×	×	✓	✓	×	✓	×	✓	×	✓	✓	✓	✓
	A5F	×	×	✓	×	×	×	✓	×		✓	×		×	✓	✓	×	×		✓	✓	×	✓	×	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	×	✓	✓	×	✓	×	×	✓	✓
F	A5HA	×	×	×	×	×	×	×	×		×	×		×	✓	✓	×	×		✓	✓	×	✓	×	✓	×	✓	✓	×	✓	×	×	×	×	×	✓	×	×	✓	×	×	×	×	✓
	A5GA	×	×	×	×	×	×	✓	×		×	×		×	×	✓	×	×		✓	✓	✓	✓	✓	×	×	×	✓	×	✓	×	×	×	×	×	✓	✓	✓	×	✓	×	×	✓	✓
	DISCEA	×	✓	×	✓	×	×	×	×	×	✓	×	×	×			×	×	✓	✓	✓	✓	×		×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	DISCFA	×	✓	×	✓	✓	×	✓	×	✓	✓	✓	×	✓			×	✓	×	✓	✓	✓	✓		✓	✓	×	×	✓	✓	✓	✓	×	✓	✓	×	×	✓	×	✓	×	✓	×	✓

Figure 6.15: Achievement of student tasks. Coloured boxes with a ✓ symbol were fully achieved. White boxes with a x symbol were not fully achieved

		S64	S32	S31	S66	S62	S33	S34	S53	S59	S61	S44	S54	S58	S14	S12	S17	S42	S56	S15	S36	S27	S45	S18	S28	S57	S13	S35	S43	S25	S26	S29	S55	S11	S37	S41	S52	S16	S23	S46	S22	S21	S30	S24
A	A1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
A	MODB	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	×	✓
B	A4A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	✓	×	✓			
D	A4E	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	×	×	×			
B	A5E	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓			
B	A5A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	✓	×	×			
A	MODA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	✓	×	✓	×	✓	✓	×	✓	×	×	✓	×	✓	✓	×	✓
A	A3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	✓	×	✓	×	×	×	✓	✓	✓	✓	×	✓			
D	DISCA	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	✓		×	×	✓	×	✓		×	✓		✓	✓	✓	✓	✓	×	×	✓	×	✓	✓	✓	✓
E	A5B	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	×	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓	✓	✓	✓	×	✓	×	✓	✓	✓	×	×	×	✓			
B	A5C	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	✓	×	×	✓	✓	×	✓	×	✓	×			
E	A5D	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓	×	✓	×	×	✓	✓	✓	✓	×	×	✓	✓	✓	×	✓	×	×	✓			
D	DISCB	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	×		✓	✓	✓	✓	✓		×	✓		✓	×	×	×	✓	×	×	×	×	×	✓	✓	✓
C	MODD	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	×	✓	×	×	✓	✓	✓	✓	✓	✓	×	×	✓	×	×	✓	✓	×	×	✓	×	×	✓	×	✓	×	×	✓	×
C	MODE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	×	✓	×	×	✓	×	✓	✓	✓	✓	×	✓	✓	×	×	✓	×	✓	×	×	×	×	×	✓		×	✓	✓	✓
D	DISCC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	×	✓	✓	×	✓		✓	×	×	✓	✓		×	×		×	✓	✓	✓	×	✓	×	×	✓	✓	×	×	×
F	DISCFA	✓	✓	✓	×	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	×	×	✓	✓		✓	×	×	✓	×		✓	✓		✓	×	×	✓	×	×	×	✓	✓	✓	✓	×	×
E	A2	✓	✓	✓	✓	✓	✓	×	✓	×	✓	×	✓	×	✓	✓	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	×	×	×	×	×	×	×			
F	DISCEA	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	×		✓	×	×	✓	×		✓	×		×	✓	×	×	×	✓	×	×	✓	✓	×	✓	×
E	A5F	✓	✓	✓	✓	×	×	✓	✓	✓	×	✓	✓	×	×	×	✓	✓	✓	×	✓	✓	✓	×	×	✓	✓	×	×	×	✓	×	×	×	✓	✓	✓	×	×	×	✓			
D	DISCEE	✓	✓	✓	✓	×	✓	×	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	×	×		✓	×	×	✓	×		✓	×		×	✓	×	×	×	✓	×	×	✓	✓	×	✓	×
D	DISCFE	✓	✓	✓	×	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	×	×	✓	×		×	✓	×	✓	✓		✓	✓		✓	×	×	×	×	×	×	✓	×	✓	×	×	×
D	DISCD	✓	✓	×	×	✓	×	×	✓	✓	✓	×	✓	×	×	✓	×	×	×	✓	✓		×	✓	×	×	×		×	✓		✓	×	✓	×	×	✓	×	×	✓	✓	✓	✓	×
F	A5GA	✓	✓	✓	✓	×	✓	✓	×	✓	×	✓	×	×	×	×	✓	✓	✓	×	×	✓	×	×	×	✓	×	✓	×	×	×	×	✓	×	×	×	×	×	×	×	×			
F	A5HA	✓	✓	✓	×	×	×	✓	×	×	×	✓	×	✓	×	×	×	✓	×	×	✓	✓	×	×	×	×	×	×	×	×	✓	×	✓	×	×	✓	×	×	×	×	×			
D	A5GE	✓	✓	×	✓	✓	×	×	×	×	×	✓	×	×	×	×	✓	×	✓	×	×	✓	×	×	×	✓	×	×	✓	×	×	×	×	×	×	×	×	×	×	×	×			
D	A5HE	✓	×	✓	×	×	×	×	×	×	×	×	×	✓	✓	×	×	×	×	×	×	✓	×	×	×	×	×	×	×	×	✓	×	×	✓	×	×	×	×	×	×	×			

Figure 6.16: Student tasks ranked in order of achievement by students. Coloured boxes with a ✓ symbol were fully achieved. White boxes with a x symbol were not fully achieved

		S64	S32	S31	S66	S27	S34	S62	S35	S33	S58	S26	S53	S59	S61	S44	S54	S17	S42	S56	S36	S18	S14	S15	S45	S28	S12	S13	S43	S55	S11	S41	S57	S37	S16	S25	S46	S22	S52	S23	S21	S29	S24	S30
A	A1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
A	MODB	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	✓	✓	✓	✓	✓	×
B	A4A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	×	✓		✓		
D	A4E	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓	×		✓		
B	A5E	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	×	✓	✓	×		✓		
B	A5A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	✓	✓	×	×	✓	✓		✓		
A	MODA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	×	✓	×	✓	✓	×	✓	×
A	A3	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	×	✓	✓	×	✓	✓	✓		✓		
E	A5B	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	✓	✓	×	×	×	✓	✓	✓	✓	✓	×	✓	×	✓	×	✓	×	✓	✓	×		×		
B	A5C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	×	×	×	×	×	✓	✓	✓	✓	✓	✓	×	×	×		✓		
E	A5D	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	×	×	×	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	✓	✓	×	✓	×	×		×		
C	MODD	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	×	×	✓	✓	✓	✓	✓	✓	×	×	×	×	×	×	×	✓	✓	×	✓	×	×	×	×	✓	×	✓
C	MODE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	×	×	✓	×	✓	✓	✓	×	✓	×	✓	×	×	×	×	×	×		×	×	✓	✓	×	✓	✓
E	A2	✓	✓	✓	✓	×	×	✓	✓	✓	×	×	✓	×	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	✓	×	✓	×	×	✓	×	×	×	×		×		
E	A5F	✓	✓	✓	✓	✓	✓	×	×	×	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	×	✓	×	×	✓	×	×	×	✓	✓	✓	×	×	×	✓	✓	×		×		
F	A5GA	✓	✓	✓	✓	✓	✓	×	✓	✓	×	×	×	✓	×	✓	×	✓	✓	✓	×	×	×	×	×	×	×	×	×	✓	×	×	✓	×	×	×	×	×	×	×		×		
F	A5HA	✓	✓	✓	×	✓	✓	×	×	×	✓	✓	×	×	×	✓	×	×	✓	×	✓	×	×	×	×	×	×	×	×	✓	×	✓	×	×	×	×	×	×	×	×		×		
D	A5GE	✓	✓	×	✓	✓	×	✓	×	×	×	×	×	×	×	✓	×	✓	×	✓	×	×	×	×	×	×	×	×	✓	×	×	×	✓	×	×	×	×	×	×	×		×		
D	A5HE	✓	×	✓	×	✓	×	×	×	×	✓	✓	×	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	×	×	×	✓	×	×	×	×	×	×	×	×	×		×		

Figure 6.17: Student tasks with modelling follow-up discussion questions removed and ranked in order of achievement by students. Coloured boxes with a ✓ symbol were fully achieved. White boxes with a x symbol were not fully achieved

The final ranking of tasks in Figure 6.17 has revealed a learning sequence which may be followed when teaching students to engage with the variety of representations used in organic chemistry (Figure 6.18). Due to the limited time spent on Part B of the OCV programme by the classes in Implementation 2, physical properties are not included in this learning sequence.

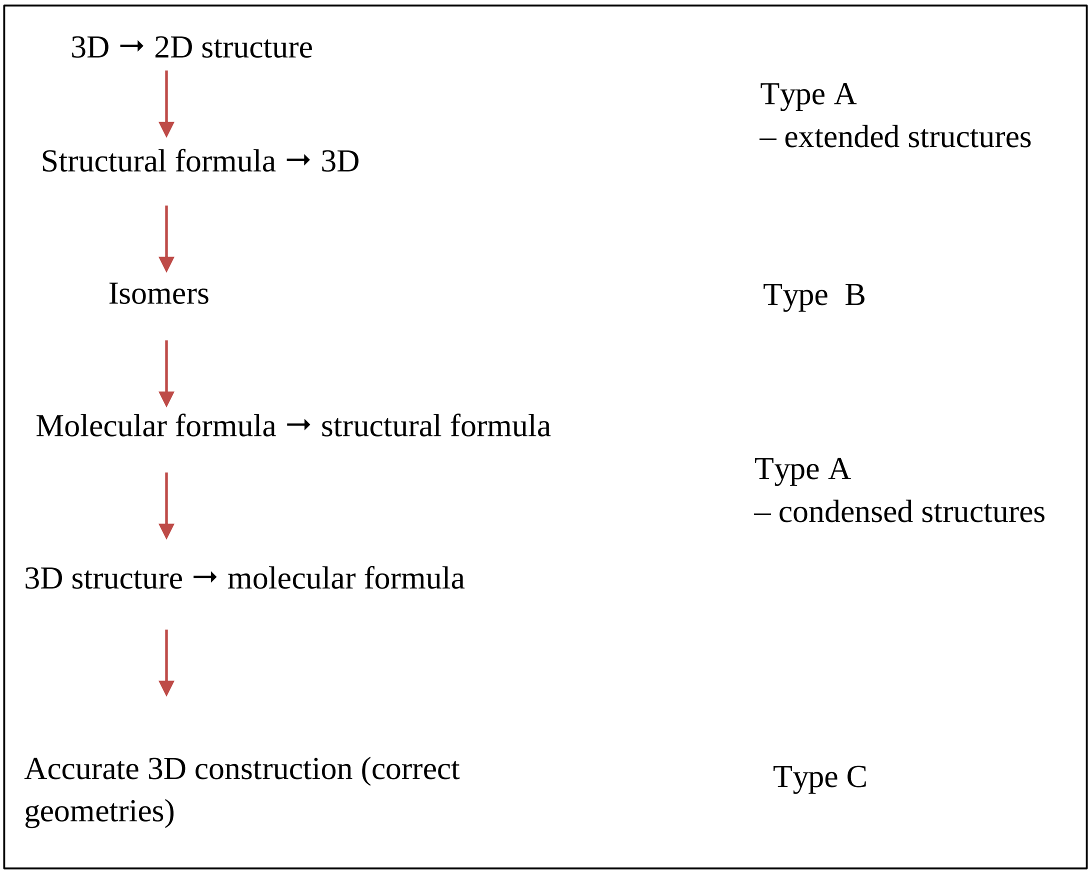


Figure 6.18: Learning sequence for organic chemistry representations which has emerged from the OCV programme.

It should be noted that Type A tasks, which require a translation between representations, have been split into translations between representations of extended structures and translations between representations of condensed structures. This makes sense in that students should be introduced to extended structures before engaging with condensed structures. Anderson and Bodner (2008) recommended the use of extended structures rather than condensed structures by teachers; extended structures that show the atoms, bonds and non-bonding electrons make more space available in the students' working memory to engage with the more important conceptual aspects of organic chemistry.

While there are many suggestions in the literature for teaching organic chemistry as a whole, this learning sequence is far more detailed in relation to the types of representations and tasks which students should be introduced to. Dori and Kabermann (2012) presented a hierarchy of modelling tasks, however our sequence does not quite match theirs. These will now be compared.

6.4.2 Hierarchy of Representational Tasks

The ranking of student tasks in the previous section has allowed for a hierarchy of representational tasks completed in this module to be created, see Figure 6.19 below.

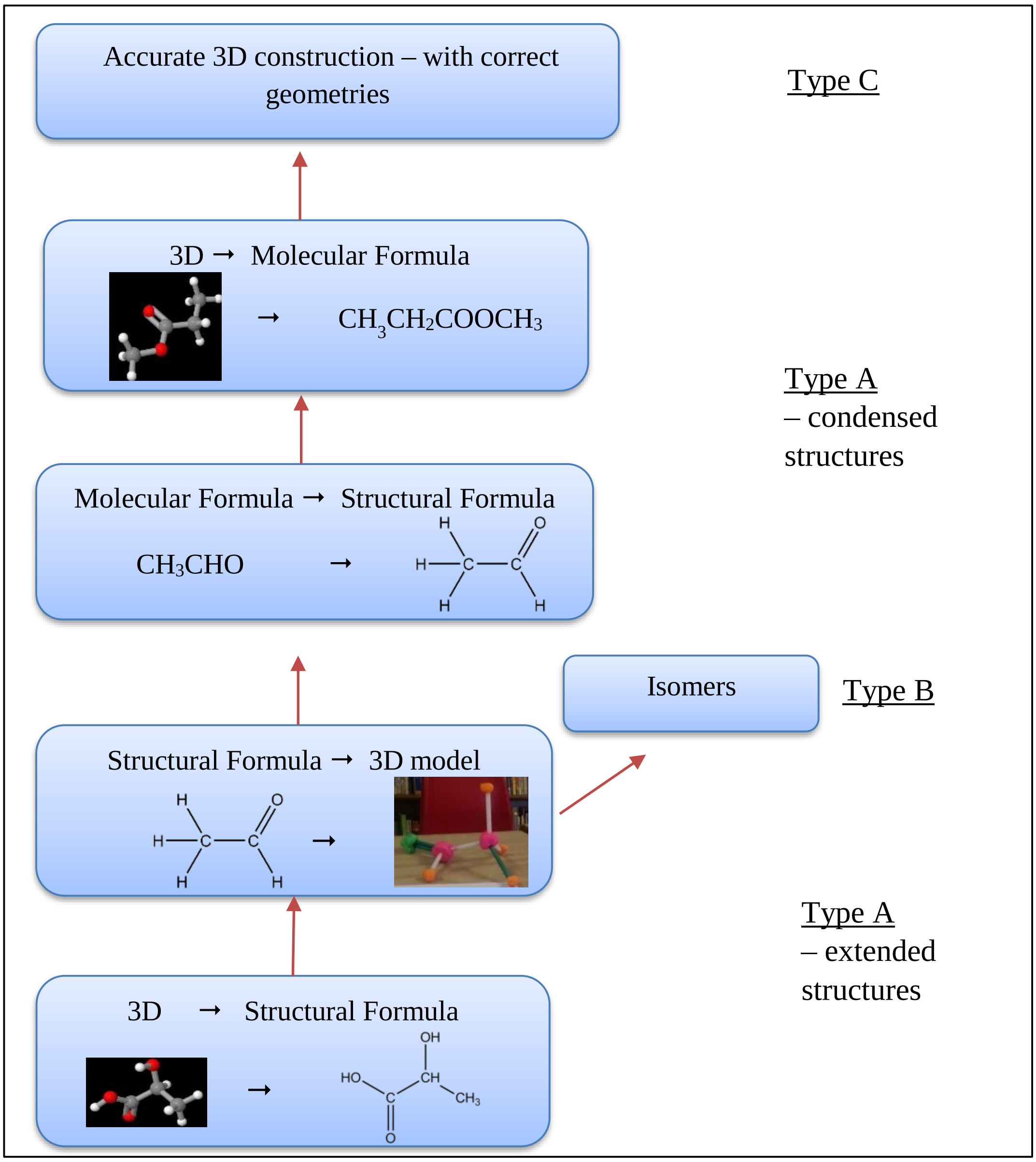


Figure 6.19: Hierarchy of representational tasks

The first two steps of this hierarchy are Category A tasks in which the required translation is between structures that are extended, i.e. all atoms and bonds are represented explicitly. This translation required students to be able to read a structure, identify the components represented by either coloured balls or symbols and translate each component into an alternative representation.

The ability to engage with the concept of isomers could have been included as Step 3, however, it was decided to keep it as a 'branch' from this hierarchy as it does not necessarily involve a translation and you could continue straight to the next step.

The more difficult Category A tasks are the next two steps and require an extra mental processing step. The third step involves representations in which the structural arrangement of components in the representations are not explicit and students have to elucidate the extended structure using a knowledge of bonding and structure. The fourth step requires students to work backwards and represent an extended structure in a condensed manner.

The final step in the hierarchy is the ability to build a geometrically accurate 3D model from any materials given.

The tasks completed by students during the evaluation of the OCV programme fall into Category A modelling sub-skills as proposed by Dori and Kabermann (2012). Their hierarchy can be summarised as in Figure 6.20 below.

STEP 3	Simple and complex 2D representations → model drawing
STEP 2	3D model → molecular AND structural formula
STEP 1	Molecular formula → structural formula

Figure 6.20: Summary of hierarchy of Type A Modelling Sub-skills defined by Dori and Kabermann (2012)

Comparison of the hierarchy which has emerged from this project and that of Dori and Kabermann (2012) reveals conflicting steps (Figure 6.21). Five steps emerged from this research compared to three from Dori and Kabermann. This is possibly due to the types of tasks selected in the projects. Dori and Kabermann's project also involved a computerised molecular modelling environment while this project utilised a physical molecular modelling environment.

Dori and Kabermann (2012) identify the translation from 3D to molecular and structural formula as one step, the second in their hierarchy. However, results from this programme indicate that the translation from 3D to structural formula and 3D to molecular formula need to be treated as two different steps. Moreover, they are two steps apart in the OCV hierarchy, indicating the significant difference in complexity of these tasks. The translation from 3D to structural formula involves reading the structure, identifying the components and translating each component into an alternative 2D representation. However, translating from 3D to molecular formula requires the structure to be read, components identified and the condensing of the structure while translating the coloured balls into 2D symbols or representations. Thus, it seems incorrect to include these translations within the same step.

Dori and Kabermann (2012) assumed the translation from molecular formula – structural formula to be the first step in their hierarchy as their participants (12^{th} grade high school students in Israel) were regularly required to transfer between these representations in their organic chemistry classes in previous years (in 10^{th} and 11^{th} grade high school). Their results reflected this. However, this translation is the third step of the OCV hierarchy, indicating students in this project found this translation more difficult, despite activities in the programme which specifically addressed the molecular formula.

It is probable that the translations on the first step of each hierarchy were the translations which students found easiest due to the design of each project, i.e. the OCV programme was designed to focus on students' inter-relation between 3D and 2D representations; thus students were more comfortable with this specific translation. Likewise, the participants in the research by Dori and Kabermann (2012) were more practised in the translation from molecular to structural formula, thus answered these tasks better, resulting in this translation being the first step of their hierarchy.

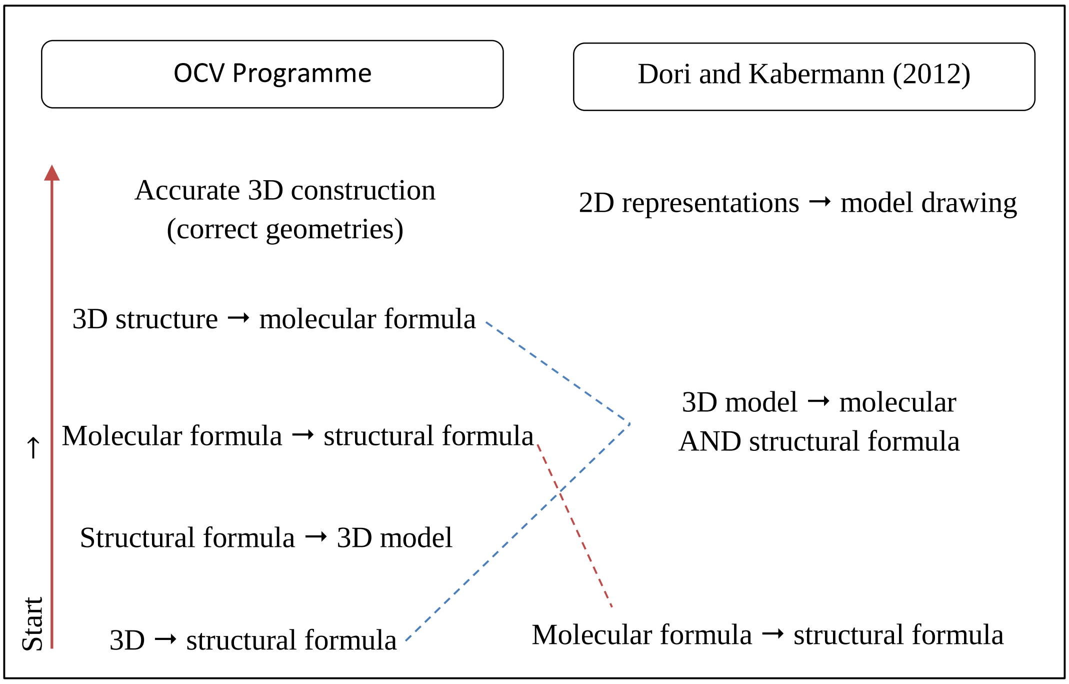


Figure 6.21: A comparison of the representational skills hierarchy of the OCV programme and the research of Dori and Kabermann (2012). The dashed lines link similar tasks to demonstrate the different locations of each task in the respective hierarchies.

It is important for teachers of organic chemistry to be aware of this hierarchy of representational tasks and tailor their lessons to ensure that students are not being asked to complete tasks that are too far up the hierarchy without having mastered previous steps. As Nicoll (2003) found, the hierarchy would suggest that while students can translate 2D structures into free-form models, they struggle with the accuracy of their geometries. While the study by Nicoll only contained a planar carbon, this study has shown that students in particular struggle with the 3D geometry of the tetrahedral shape of carbon. Thus, a stronger emphasis needs to be placed on making this shape more explicit to students.

6.5 Summary

Observation of student conversation played a larger role in evaluation of the OCV programme during Implementation 2. Students were observed to be highly engaged during activities and engaging in meaningful discussions and collaborations, regardless of the dynamic of the class. Teachers involved were observed to be very successful in facilitating discussion and leading students through the OCV activities.

Evaluation of data collected from students indicated the majority of students were capable of translating between 3D and 2D representations. However, the free-form modelling test demonstrated that some students were still modelling in 2D. The modelling test was a useful tool to gain an understanding of students' mental models of the 3D nature of organic structures following the use of Molymod kits. While some students struggled constructing accurate shapes of models, a number of elements from the models were internalised; the differentiation of atoms of elements by colour, the relative size of hydrogen as the smallest atom and the explicit representation of the bonds using sticks.

Evaluation of students' success at representational tasks following Implementation 2 allowed for the development of a suggested learning sequence for introducing students to organic chemistry through the use of physical models. Our learning sequence contrasted that suggested by Dori and Kabermann (2012) with the addition of further steps and an altered sequence of steps. Our learning sequence can be used to inform the future teaching of organic chemistry at second level in Ireland.

Chapter 7

Static vs Process Models

Introduction

The OCV programme makes use of static models and relies on students' explanations to portray the level of their understanding of physical properties. The link between IMFs and physical properties is a dynamic process. The use of student-generated animations has been shown to be a useful tool in identifying students' understanding of the dynamic chemical processes (Chang et al, 2014; Kozma and Russell, 2005). A virtual modelling environment was not included in the OCV approach as it was felt that the time requirement for students to learn how to navigate the software might be too long within the timescale of the project. However, a process modelling case study was conducted with a cohort of third level pre-service teachers (PST) to examine the potential for use of such an environment within future implementations of the OCV approach, particularly in determining student understanding.

Having examined several options for a virtual modelling software, ChemSense Animator was selected as an appropriate tool to assess student understanding in a virtual manner. The PST were introduced to the virtual modelling software with an animator tool and asked to create an animation of a particular process. A key idea that we wanted to get across to the PST was not simply the idea of using animations to demonstrate chemical phenomena but the power of getting students to create their own animations in order to help identify their level of understanding or the gaps that exist in their conceptual knowledge.

7.1. Why ChemSense?

ChemSense is a free, easy to access and easy to use animation software. It can be downloaded directly from the ChemSense website[1]. ChemSense was created to shape the way students think and talk while using representations to describe,

[1] http://chemsense.sri.com/

explain, and argue about physical phenomena in terms of underlying chemical entities and processes (Kozma and Russell, 2004). ChemSense has been shown to improve students' representational competence, with students demonstrating richer, more complex representations of chemical processes (Schank and Kozma, 2002). While the ChemSense Animator tool was designed to be used as part of the ChemSense Knowledge Building Environment (KBE), it is just as effective a learning tool when used as a stand-alone tool (Pernaa and Aksela, 2009).

An animation is created in ChemSense Animator by building up the animation frame-by-frame, with options to control the speed of transition between frames. A primary reason for selecting ChemSense Animator was the simple drawing tool palette, see Figure 7.1. The palette contains only basic representational components, such as atoms, bonds, charges and organic structures. There are no pre-constructed molecules from which to choose. This means that users have to make critical design decisions as to how they are going to use these building blocks to represent the molecule or the particular process, asking questions such as: what atoms do I need? how many are there? what type of bonds are there? which atoms are bonded? Once the user is happy with the molecule they have constructed, they can group all components together, copy them and paste them as many times as required.

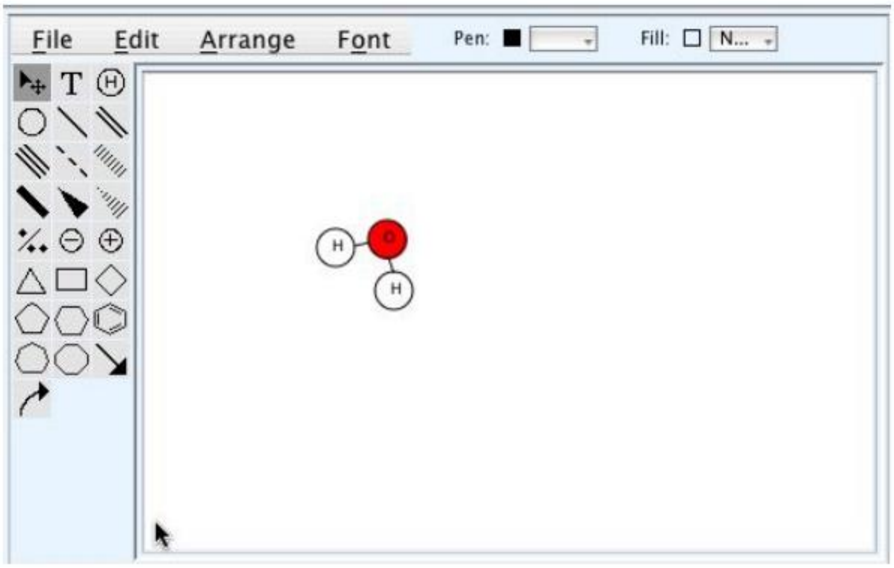


Figure 7.1: ChemSense Animator drawing tool palette.

7.2 Participants in this case study

A group of second year pre-service science teachers were selected as participants in this case study. At the time, these students were taking a module which focused on the role of ICT in science education. Thus, the purpose of selecting these students was two-fold; to use ChemSense to assess their understanding of some core chemical concepts, and to make these PST aware of how to utilise this type of software for assessment of understanding and identification of misconceptions.

The PST were given one hour tutorial on how to use the Chemsense animation and were then given their assignment. They worked on their assignment on their own and then presented it to their groups the following week during a 3-hour session. During this session, the students could modify their animation or not. They then prepared a critique of each animation for submission the following week.

7.3 Assignment

Using ChemSense, the PST were asked to create an animation of a particular chemical phenomena. The topics assigned to students are listed in Table 7.1. These topics were chosen because they require students to be able to represent chemical phenomena at the particulate level. Students were required to create their animation individually. Students then joined with their other group members to critique each other's animation. Each group was required to write a 'critique' of all group members' animations with a discussion on any misconceptions that arose from their animations and recommendations for improving the accuracy of the 'science' presented in each animation. Students were then given the opportunity to revise their animation, however not all students decided to do so.

Table 7.1: ChemSense animation assignments. Chemical phenomena that students were asked to create an animation depicting

Group 1:	**Group 2:**
– Surface tension in water – The process of boiling – Intermolecular forces: comparing strength of IMFs with examples – The neutralisation of excess stomach acid with gaviscon	– Process of dissolving in water – Compare boiling of O2 and Cl2 – Ice cubes melting in a glass of water – Boiling a mixture of ethanol and water
Group 3:	**Group 4:**
– The difference between the properties of copper metal vs the properties of an atom of copper – How do non-newtonian fluids work? – Explain trend in boiling between CH4, SiH4, GeH4 and SnH4 – Rusting of an iron nail	– The process of melting – The formation of a coating of liquid on glass of cold milk - why and how does this happen? – The particulate nature of air – The difference between a concentrated acid and a strong acid
Group 5:	**Group 6:**
– How to dissolve more sugar in tea – Boiling a super-saturated solution of salt and water until half of the water evaporates – The process of evaporation – People climb the tallest mountains in the world carry O_2 tanks to help them breathe due to the 'thin air'. – What is the difference between 'thin air' and air at sea level?	– A closed container of hydrogen gas at shown at room temp, when there is a reduction in volume, increase in temp and decrease in temp – How and why do bond polarities arise, with examples showing varying degrees of polarity – Propane cylinder: why does the cylinder feel like it's full of liquid when you shake it – A tyre is left out on a hot sunny day, what happens to the mass and pressure of the tyre?

7.4 Identification of Misconceptions

The use of ChemSense proved to be a quick and easy method of identifying any misconceptions held by students surrounding the particulate nature of matter, intermolecular and intramolecular forces and the arrangement of atoms in molecules. The peer discussion appeared to be a useful tool to aid students' identification of their own misconceptions and guide the revision of their animations. Tables 7.2 - 7.5 display examples of animations which demonstrate specific misconceptions held by the students and the changes implemented following peer discussion.

Table 7.2 displays frames taken from a students' animation depicting the process of boiling a mixture of ethanol and water and can be taken to show both a level of understanding and alternative conceptions held by the student. It can be seen straight away that the student can draw a reasonable structure for ethanol and water. However, this animation is a clear demonstration of the misconceptions of intramolecular bonds breaking on boiling / evaporating. In the original animation (before peer discussion) the student clearly states '*At 78 degrees the bonds in ethanol break'* and depicts the intra molecular bonds between carbon, hydrogen and oxygen breaking. Likewise, it is stated '*At 100 degrees the bonds in water break*' and the student depicts the intramolecular bonds between hydrogen and oxygen breaking. The final frame depicts all the component atoms from the ethanol and water evaporating out of the container as individual atoms.

Following peer discussion, this student's revised animation shows the breaking of intermolecular bonds between these molecules. Dipole bonds were depicted being broken between water molecules at 100^0C. However, no intermolecular forces were depicted between the ethanol molecules. The peer discussion obviously focused this student's understanding in the right direction but their animation still contained flaws that indicated alternative conceptions; the hydrogen bonds depicted as being broken in the ethanol molecules were in fact the intramolecular bonds between the oxygen and hydrogen in the functional group of the alcohol. Peer discussion obviously was not enough to fully address this student's misconceptions but it appears to have directed it somewhat towards the correct concept.

Table 7.3 displays frames of a student's animation depicting an ice cube melting in a glass of water. The original animation was composed of three slides and depicted the ice cube melting at the bottom of the glass. While the molecules of water in the ice cube are compacted to depict the arrangement of a solid, the process of melting was not demonstrated in any detail. Similar to the pervious student, peer discussion led to a revised animation of a much higher standard. This student's revised animation shows the ice cube on top of the water and also demonstrates the melting of the ice cube over a number of frames. The molecules of ice in the ice cube are shown to be moving further apart and the ice cube losing its shape before the molecules of water in the ice spread to join the liquid water molecules.

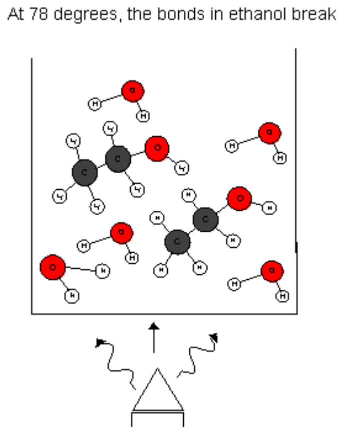
The animation in Table 7.4 depicts the misconception of intramolecular bonds in a solid breaking on dissolving. Sugar molecules are first shown mixed with 'tea molecules' and are then depicted breaking apart into individual atoms once heat is applied. This student did not choose to revise their animation but did acknowledge their mistake in their critique document.

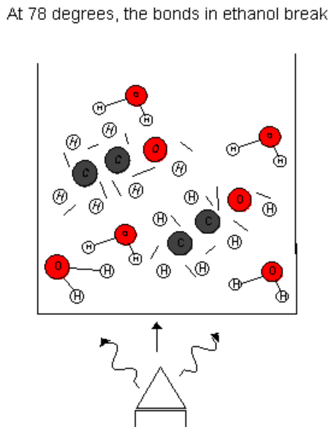
The final example, in Table 7.5, demonstrates a mixture of understanding and misconceptions. This student has drawn their water molecules as O_2H instead of H_2O and depicted hydrogen bonding in water as intermolecular bonds between the hydrogens in water molecules. While it is clear the student knows hydrogen bonding exists between water molecules, it is also clear that this student struggled to represent it. Despite these alternative conceptions, the student then goes on to depict the process of water molecules being heated, moving quicker, breaking intermolecular bonds and eventually evaporating off the surface of the liquid.

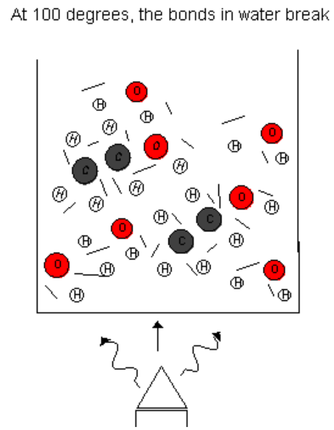
These examples demonstrate the effective use of the ChemSense Animator to identify students' misconceptions, from the ability to produce structurally correct molecules, to describing the process of boiling. Section 7.5 will now address the ability of ChemSense to help students demonstrate a 'deep' understanding.

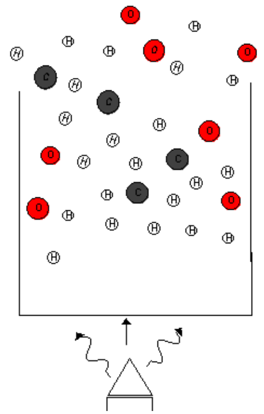
Table 7.2: Frames taken from student animation describing the boiling of a mixture of ethanol and water.
Four frames are shown from the original animation created before peer discussion and the revised animation following peer discussion

Misconception
Intramolecular bonds break on bonding
Frames before peer discussion:

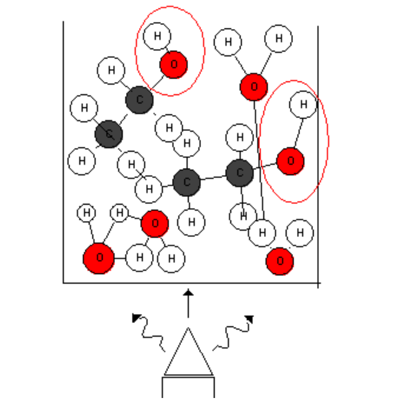


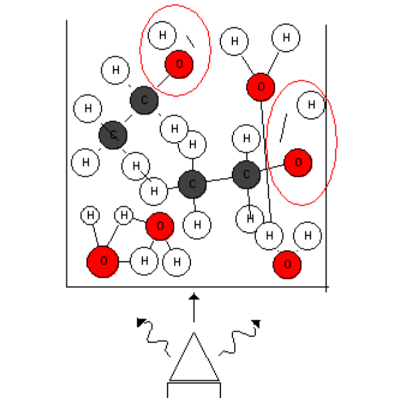


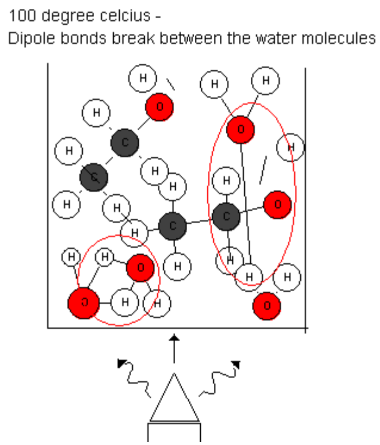




Frames after peer discussion:







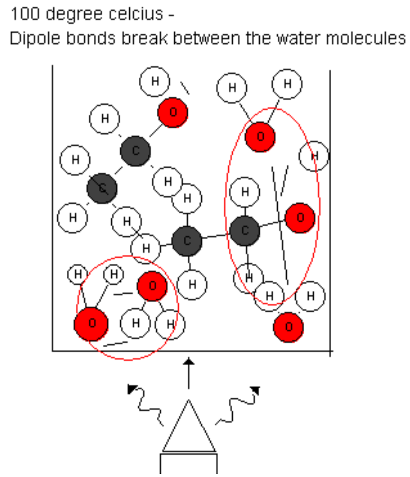


Table 7.3: Frames taken from student animation describing an ice cube melting in a glass of water.
Four frames are shown from the original animation created before peer discussion and the revised animation following peer discussion

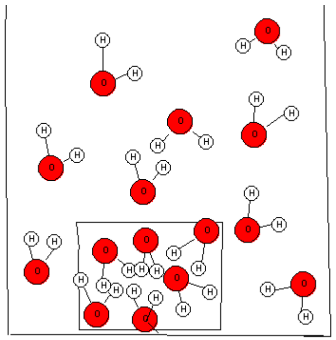
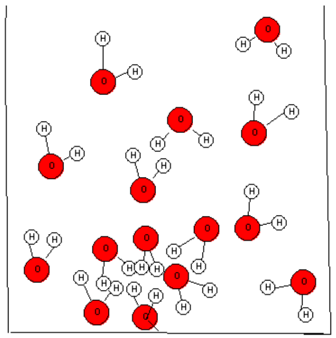
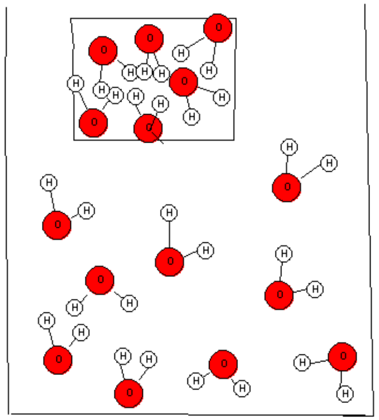
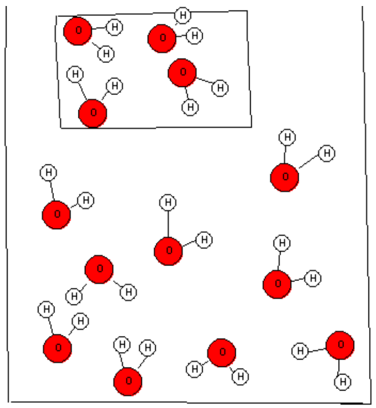
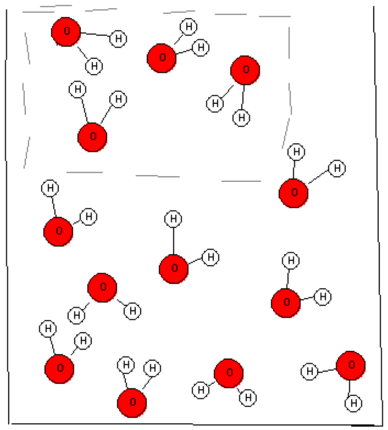
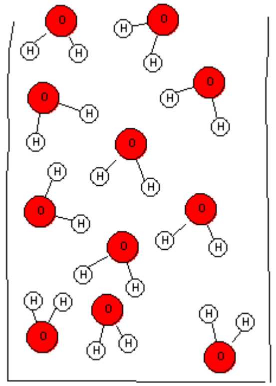
Misconception
Ice sinks
Frames before peer discussion:
 The ice cube is in the glass of water  The ice cube melts
Frames after peer discussion:
  as the ice cube begins to melt in the water, the molecules in the ice cube are not as compacted together anymore  The molecules in the ice are moving so far apart that the cube starts to lose it's shape  As time went on, as the glass was in room temperature The ice cube fully lost its shape and the ice cube melted leaving it as just one glass of water with lots of molecules

Table 7.4: Frames taken from student animation describing the process of dissolving sugar in tea. Original animation shown only as this student did not revise their animation.

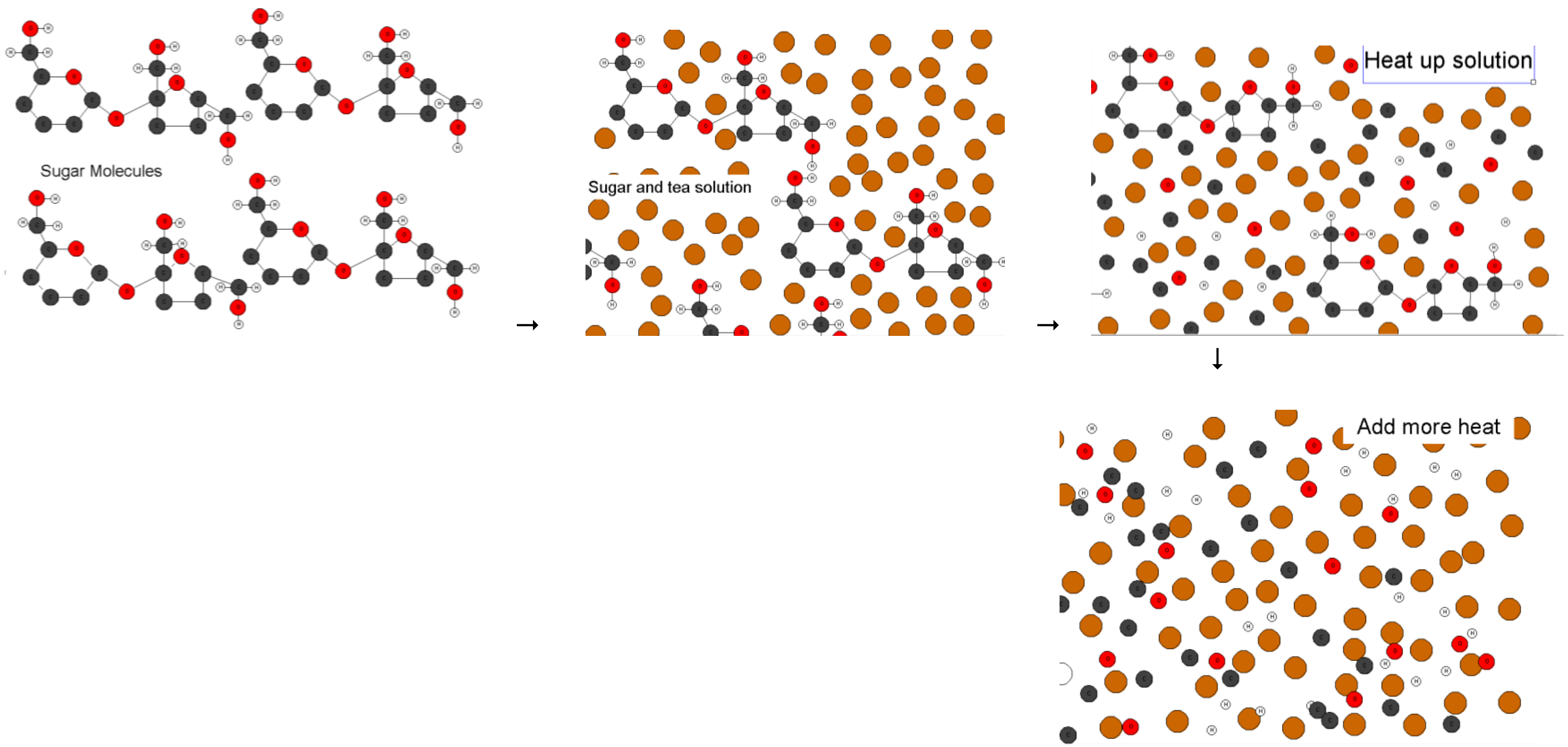
Misconception
Intramolecular bonds break on dissolving
Frames before peer discussion:


Table 7.5: Frames taken from student animation describing the process of boiling water. Original animation shown only as this student did not revise their animation.

Misconception
Hydrogen bonding Structure of water O_2H not H_2O
Frames before peer discussion:

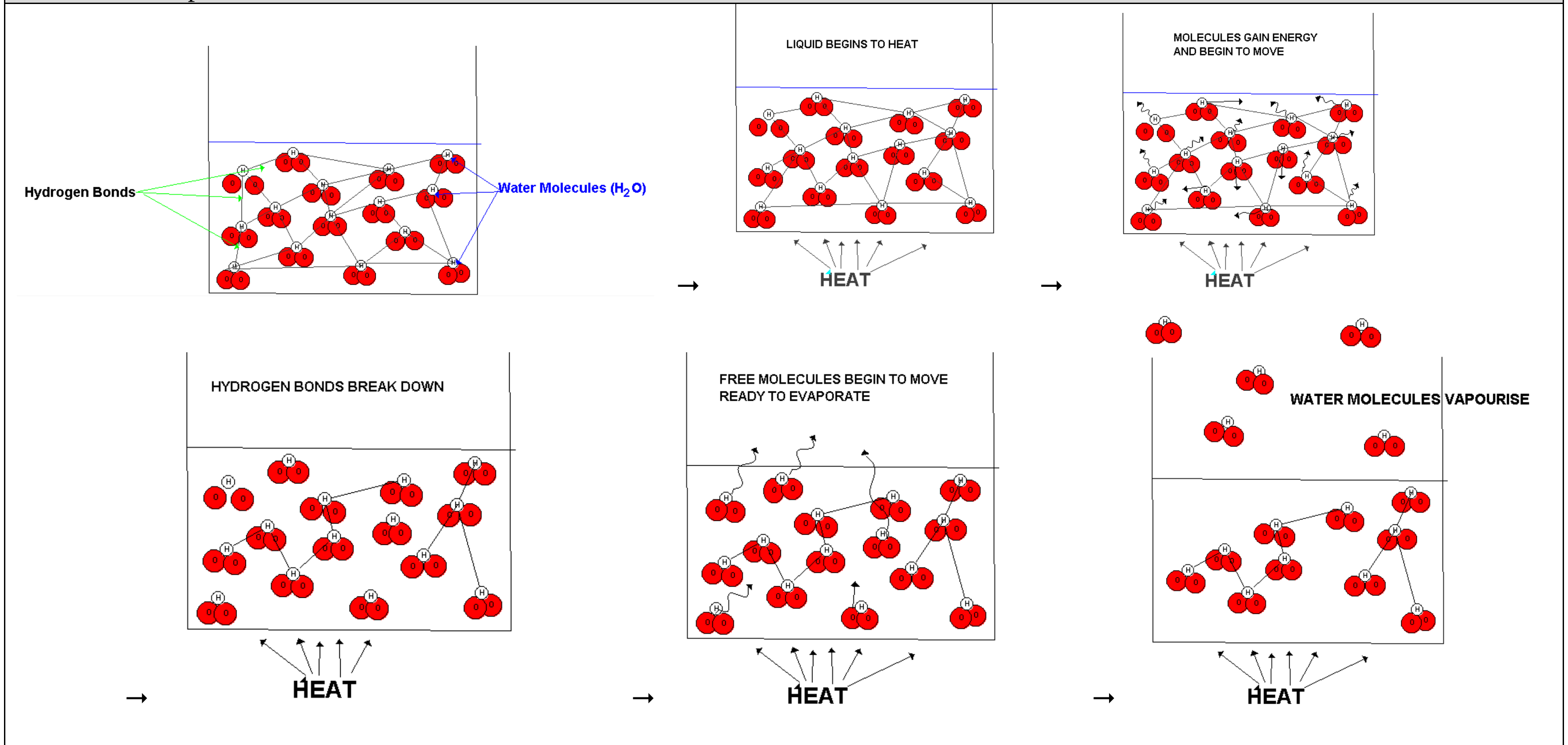
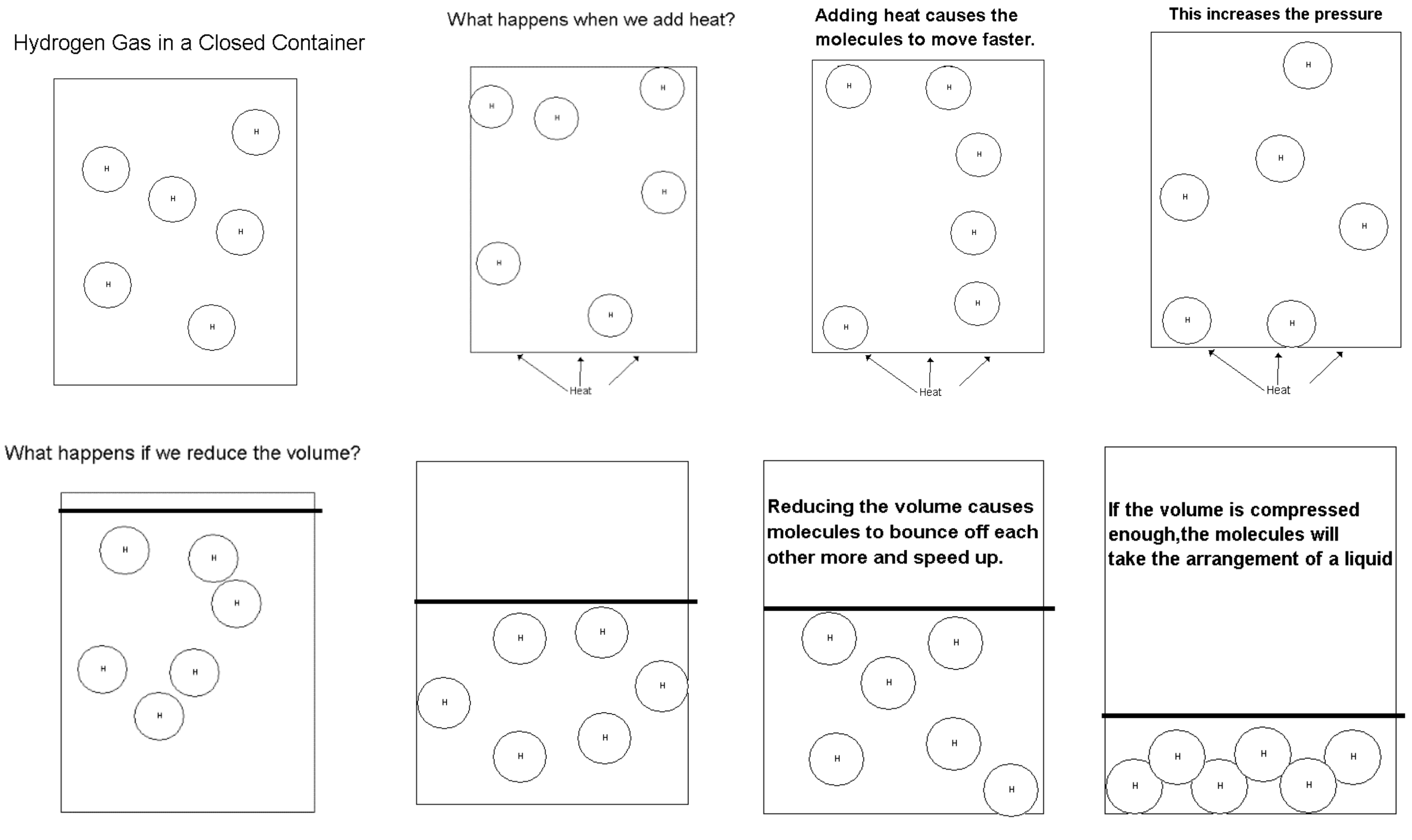


Table 7.6: Frames from animation depicting a closed container of hydrogen gas.

Concept
Closed container of hydrogen gas when heated and compressed
Frames:



7.5 Communication of Understanding

Section 7.4 described several examples of how ChemSense Animator was used to clearly identify students' misconceptions in core chemical concepts. An example demonstrating effective communication of understanding will now be discussed.

Table 7.6 shows frames from a student's animation depicting a closed container of hydrogen gas. A molecule of hydrogen gas is represented as one circle in this representation. In their animation, the student addresses two questions; *what happens when we add heat?* and *what happens if we reduce the volume?* To answer the first question, the student clearly describes that adding heat causes the molecules to move faster and increases the pressure. This is demonstrated over several slides in the animation also.

The second question, was addressed in a similar manner. The reduction in volume is shown while maintaining the same number of molecules. The molecules are shown to bounce off each other more frequently. It is also demonstrated that if the gas is compressed enough, the molecules will be forced into the arrangement of a liquid.

This example demonstrates the scope of ChemSense to allow students to communicate their understanding and the depth of their understanding in a clear manner.

7.6 Summary

Following students' critique of each other's animations, two key points were emphasised to the PSTs. Asking students to create animations themselves can be useful to identify some common misconceptions regarding core chemical concepts. Peer discussion also allowed for identification of these misconceptions and improvement in students' animations. It was emphasised to the PST initially that if they wanted to generate animations to use in their own teaching, that there were (probably) better simulations available on web; however, the power of ChemSense was in 'getting into the student's head' to determine their mental images.

While this trial was at a very small scale, it has demonstrated the value of student-generated animations as an educational tool, both for teachers and students. It is a simple and, perhaps more importantly, a quick method for teachers to assess student understanding and identify misconceptions held by students. Its design forces students to make important representational decisions that challenge their understanding and ensure they are thinking deeply about concepts.

While this type of activity was not included in the OCV programme, this study has demonstrated the power of using student generated drawings to identify students' understanding at the process level. There is certainly potential for inclusion of this type of activity in future implementations of the OCV programme. Where students' explanations failed to reveal the full depth of their understanding in Implementation 1 and 2, student generated animations using ChemSense have been shown to be a very powerful tool for identifying student misconceptions and understandings.

Chapter 8

Conclusions and Recommendations

8.1 Overview of the research

The aim of this research was to develop an approach for teaching organic chemistry which is rooted in the use of physical models to promote a meaningful understanding of organic structures and the development of students' scientific predictions and reasoning.

Chapter 1 identified particular difficulties experienced by students which are related to the abstract nature of organic chemistry and their representations. Students have been shown to have difficulty interpreting formulae (Bernholt et al, 2012; Cooper et al, 2010), translating between different types of representations (Nicoll, 2003) and visualising and performing mental tasks on structures of organic molecules (Tuckey and Selvartnam, 1991; Ferk et al, 2003; Pribyl and Bodner, 1987; Small and Morton, 1983). These give rise to more difficulties relating to structural problems, such as isomers (Hassan et al, 2004) and structure-property relations (Taagepera and Noori, 2000; Cooper et al, 2013). In addition to these difficulties, students also have to learn the 'language' of electron pushing to explain organic mechanisms (Bhattacharyya and Bodner, 2005).

The poor attempts at organic chemistry questions in the LC chemistry exam, discussed in Chapter 2, indicates the perception of organic chemistry as difficult in Ireland. The culture of rote learning organic chemistry material which has emerged suggests the need to rethink how organic chemistry is taught. Thus, this project sought to answer the following research question:

> **Can students learn organic chemistry through an approach where the focus is on meaningful understanding of (a) molecular structure, and (b) the basis of chemical reactivity?**

The Organic Chemistry through Visualisation (OCV) programme was developed for introductory organic chemistry at second level. Chapter 3 detailed the structure of the research project, placing it in the context of the current LC chemistry syllabus, the new Key Skills Framework as set out by the NCCA (NCCA, 2009) and the new chemistry syllabus (currently under revision). The development of the OCV approach was outlined in Chapter 4. The core values around which the OCV programme was developed were: (i) the use of physical models, (ii) inter-relating between 3D and 2D representations, (iii) discussion-led activities, (iv) engaging with relevant organic molecules, (v) engaging with relevant compounds, (vi) predicting and comparing physical properties and reactivity of organic compounds using electron density, and (vii) phenomena-oriented experimental work.

Two additional studies were conducted to further inform the approach. The Representations Exploratory Study demonstrated that students coming into third level education in Ireland are able to engage with the depth cues in different types of representations but are unable to translate between them. The Process Modelling Exploratory Study demonstrated the potential for the inclusion of a virtual modelling environment within the overall OCV approach.

8.2 Key results from evaluation of the OCV approach

The OCV approach underwent a 4-week pilot and two trial implementations. Both qualitative and quantitative data were collected from the participating teachers, students and by the researcher to ensure rigour.

Evaluation of Implementation 1 and 2, results detailed in Chapters 5 and 6 respectively, indicated the majority of students were capable of completing the translations asked of them in the written assessments. While a large proportion of students could predict and compare the physical properties of a variety of compounds, students' explanations were found to be lacking the detail necessary to demonstrate a deep understanding of the link between IMFs and physical properties.

Feedback from teachers indicated a positive engagement by students and this was further observed by the researcher. Observation played a much bigger role in Implementation 2 than in Implementation 1. This, for the most part, is due to my development as a researcher; my focus shifted from <u>getting</u> students to an end-point of understanding towards <u>the process of how</u> students get to an end-point of understanding. Thus, more student conversations and activities were recorded to identify where and how learning was taking place. The case study design of the project allowed for this close observation to take place, while the action research inspired process allowed for this redevelopment of data collection.

While the evaluation tool used to assess students in Implementation 1 identified some key areas of achievement and misunderstandings, it did not assess students' ability to work in 3D. Thus, a second implementation was required to assess this element of the OCV approach. A free-form modelling test was developed for this purpose.

The majority of students could translate a molecular formula into a 2D structural representation. All but three students could successfully translate their structure into a model, whether it was accurately 3D or not. Even students who struggled translating from molecular formula to structural formula could transform their 2D structure into a 3D model. While some students struggled constructing accurate shapes of models, a number of elements from the models were internalised: the differentiation of atoms of elements by colour, the relative size of hydrogen as the smallest atom and the explicit representation of the bonds using sticks.

Despite the small number of students who completed the assessment of Part C: Reactivity of Organic Molecules, the results are extremely encouraging and demonstrate the potential for including this type of teaching approach at second level. This type of task would previously have been considered too complex for second level students studying organic chemistry. However, the students' answers indicated that students at this level are capable of not just predicting reactive centres in the presence of nucleophiles and electrophiles but also of predicting the reactivity of organic molecules. This is extremely encouraging and suggests the need to consider including this type of learning in the new chemistry syllabus for Leaving Certificate.

Where students' explanations failed to reveal the full depth of their understanding in Implementation 1 and 2, student generated animations using ChemSense have been shown to be a very powerful tool for identifying student misconceptions and understandings.

Evaluation of students' success at representational tasks following Implementation 2 allowed for the development of a suggested learning sequence for introducing students to organic chemistry through the use of physical models. This learning sequence contrasted that suggested by Dori and Kabermann (2012) with the addition of further steps and an altered sequence of steps.

8.3 Recommendations for teaching

The OCV learning sequence can be used to inform the future teaching of organic chemistry at second level in Ireland. Chapter 4 demonstrated the higher order thinking skills required to answer questions from the OCV approach. Student success in both Implementation 1 and 2 illustrates the capability of students at second level in Ireland to both engage with much larger and more complex molecules than those currently set out in the LC chemistry syllabus and also use higher order thinking skills to predict and compare the physical properties of complex molecules.

Having undertaken this research, I would suggest the following recommendations for teachers when teaching organic chemistry:

- Students should be introduced to organic structures in 3D before being shown how to represent the structures in 2D;
- Students need to build their own 3D models and these need to be physically handled and manipulated;
- Kits with correct bond angles should be used before allowing students to build free-form models;
- Students should have a good understanding of identifying areas of high and low electron density before studying physical properties;
- When addressing physical properties and intermolecular forces, several molecules of each compound being discussed need to be shown, not just one.

8.4 Future research

This project has demonstrated the power of both physical and virtual modelling for developing students' mental models. The physical models have proven effective in aiding students' understanding of static representations of organic molecules while virtual modelling can aid understanding at the process level of chemical understanding. Dori and Barak (2001) have shown that students who learn using both physical models and a virtual modelling environment perform better than those who learn from only physical models or only a virtual modelling environment. Due to time constraints of the implementation, it was not possible to use both the physical models and a virtual environment with the trial classes. An option for future research would be to trial the use of a combination both modes of learning within the context of this approach. The student generated animations would be particularly useful for identifying students' level of understanding of chemical processes such as boiling point, solubility in water and chemical reactivity.

The small sample size of both implementations means that the results from the OCV project are not generalizable. Only one trial class reached Part C of the OCV module, which involved the reactivity of complex molecules. These students demonstrated a clear ability to engage with unfamiliar molecules and predict reactive centres within them. Future research will have to involve a larger scale implementation of this particular section of the research, and indeed the whole programme, as it was not possible to fully evaluate the effectiveness of the approach in relation to the reactivity of organic molecules.

Students' spatial awareness was tested pre- and post- OCV Implementation 1 to identify if the use of molecular models correlated with students' spatial ability. It was shown that this programme improved the students' spatial ability. In Implementation2, not all classes did the pre- and post- spatial test, so further research is required to investigate if those students who could not construct accurately shaped 3D molecules in the modelling test are actually of a lower spatial ability than those who were successful. Further research into the link between spatial ability and organic chemistry could identify if there is a minimum spatial ability required to be able to succeed when studying organic chemistry. It could also identify if the use of molecular models and/or virtual modelling environments has any benefit to those students who score very high on spatial tests to begin with. While it was assumed for this project that the students' spatial ability could influence their ability to construct a 3D free-form model, the use of the free-form modelling test as a predictor of spatial ability could also be investigated.

Students' stage of cognitive development has been identified in the literature as a factor which influences their ability to engage with the abstract nature of organic chemistry. While students' spatial ability was shown to improve following the use of physical models, it would be interesting to identify if there was any effect on students' stage of cognitive development.

8.5 Personal Development

This project has been a personal journey as much as it has been an educational journey. The recruitment of teachers to participate in the project was a daunting task. I had to be completely confident that my approach to teaching organic chemistry was a valuable and effective approach in order to convince teachers to take part.

When I began this project, I was very much focused on where I wanted students to be at the end of completing the programme. Thus, my research and data collection tools were focused on assessing students at the end of the programme. Having evaluated Implementation 1, I realised that I didn't have a clear idea of how students arrived at the end of the OCV programme. I had to reconsider my evaluation tools to enable me to gain a better insight into the learning that took place.

Undertaking a PhD is a daunting task when the final hurdle is far away and you have no idea what it looks like until it is right in front of you. I have learnt to have faith in my own research abilities and my capabilities as an educator.

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Appendices

Appendix A:

Representations Exploratory Study with 3rd level students

A.1 Study Aim

To further inform the research, the third level students' understanding and use of symbols associated with chemical structure was determined. The cohort selected consisted of 151 students taking a 1st year Chemistry Laboratory module, which lasted 24 weeks (2 x 12 week semesters). These students were from a variety of science programmes, including Biotechnology, Analytical Chemistry, Pharmaceutical Chemistry and Environmental Science. Approximately 50% (76) had studied chemistry for the Leaving Certificate.

A.2 Methodology

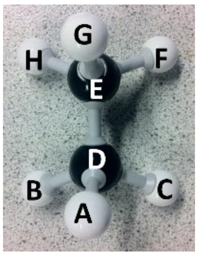
These students were examined twice; once in the first week of their first semester and then in the 9th week of their second semester. Two different tests were used. Test 1 given to these students was a basic structural visualisation test that was modelled on the CVT (Chemical Visualisation Test) created by Ferk et al (2003). This test can be found in Section A.4. Example questions are shown in Figure A.1. Students were shown a variety of molecules using a variety of representations and asked to perform several types of tasks; identify atoms that were closest / furthest away from them, draw mirror images of molecules, identify different representations of the same molecule or identify what a molecule would look like if it was rotated. This test was created to test students' ability to engage with these representations

Unexpectedly, the vast majority of students were successful in all questions on this test, indicating students are able to engage with these representations and perform the necessary tasks, whether or not they have studied chemistry for the Leaving Certificate.

Test 2 given to these students consisted of two questions that were actually part of the chemistry laboratory end-of-semester 2 assessment. The students had attended the same modules in chemistry and at this stage had almost a full academic year of chemistry studies. The focus of these questions was on translating between representations of organic compounds. The first question asked students to write the molecular formula of two compounds, diethyl ether and butanoic acid, from their 2D skeletal structure, thus assessing their ability to translate from a sub-microscopic representation to a symbolic representation (see Figure A.2).

Q2.

In the molecule B, identify which of the atoms are closest to you, furthest away from you and middle distance away from you.



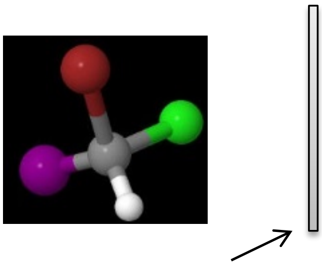
Atoms closest to you: ______________________________

Atoms middle distance away from you: ________________

Atoms furthest away from you: ______________________

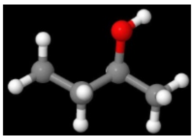
Molecule B

Q6.
Draw the mirror image of the following molecule:

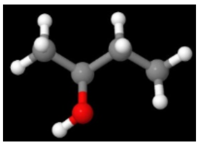


Mirror

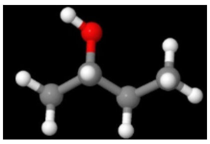
Q11.
Identify the picture that represents what Molecule K looks like from behind:



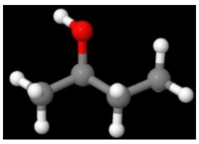
Molecule K



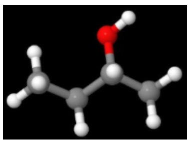
a ☐



b ☐



c ☐



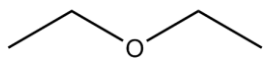
d ☐

Figure A.1: Example questions from basic structural/visualisation test given to 1st year undergraduate students (Test 1)

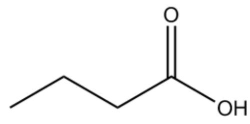
The second question had three elements to it (see Figure A.2) and was actually part of the practical element of the laboratory exam. Students were provided with a container of ‘atoms’ from the traditional Molymod kits. Students were required to construct a model of ethanoic acid using the Molymod kit and show it to their tutor before dismantling their structure. The tutor recorded if the student constructed a correct structure for ethanoic acid.

Q1. Write the molecular formula for the following two compounds:

(a)



(b)



Molecular Formula: ____________________ ______________________

Q2. Write the formula for Ethanoic Acid: ________________

Build the model (show to your tutor and then dismantle)

Sketch the structure:

Figure A.2: Questions from Test 2 given to 1st year undergraduate students

The results of each of these questions will now be discussed.

A.3 Results of Study and Implications for Research Study

Question 1 (Test 2)

As can be seen in Table A.1, 44% of students were unsuccessful with both translations and only 30% of students were able to correctly read both structures and translate them into molecular formulae. These are alarming figures from students who have been studying chemistry for almost a full year at university. Sixty-six of the students were unable to translate either structure into their respective molecular formulae.

Table A.1: Breakdown of students results in first organic question on 1st Year Laboratory exam (N=151)

	% of students	% with LC Chem	% without LC Chem
Both Correct	30	19	11
A correct	18	9	9
B correct	8	6	3
Both Incorrect	44	16	28

A further 26% of students could translate one but not the other, with more students (18%) being able to translate the diethyl ether structure into its molecular formula than the butanoic acid (8%).

The majority of students who could successfully translate both structures into a molecular formula had studied LC Chemistry. The majority of students who could not translate either structure had not studied LC Chemistry. It appears, despite students without LC Chemistry undergoing a full year of chemistry instruction, they were unable to make these translations.

Despite butanoic acid being on the LC Chemistry syllabus, students who studied LC Chemistry were less successful translating butanoic acid than they were translating diethyl ether.

There were two common mistakes when writing the molecular formulae; students' formulae had either: (i) an incorrect number of carbons, indicating a difficulty reading the skeletal structure or (ii) incorrect number of hydrogens. Examples of these are shown in Figure A.3.

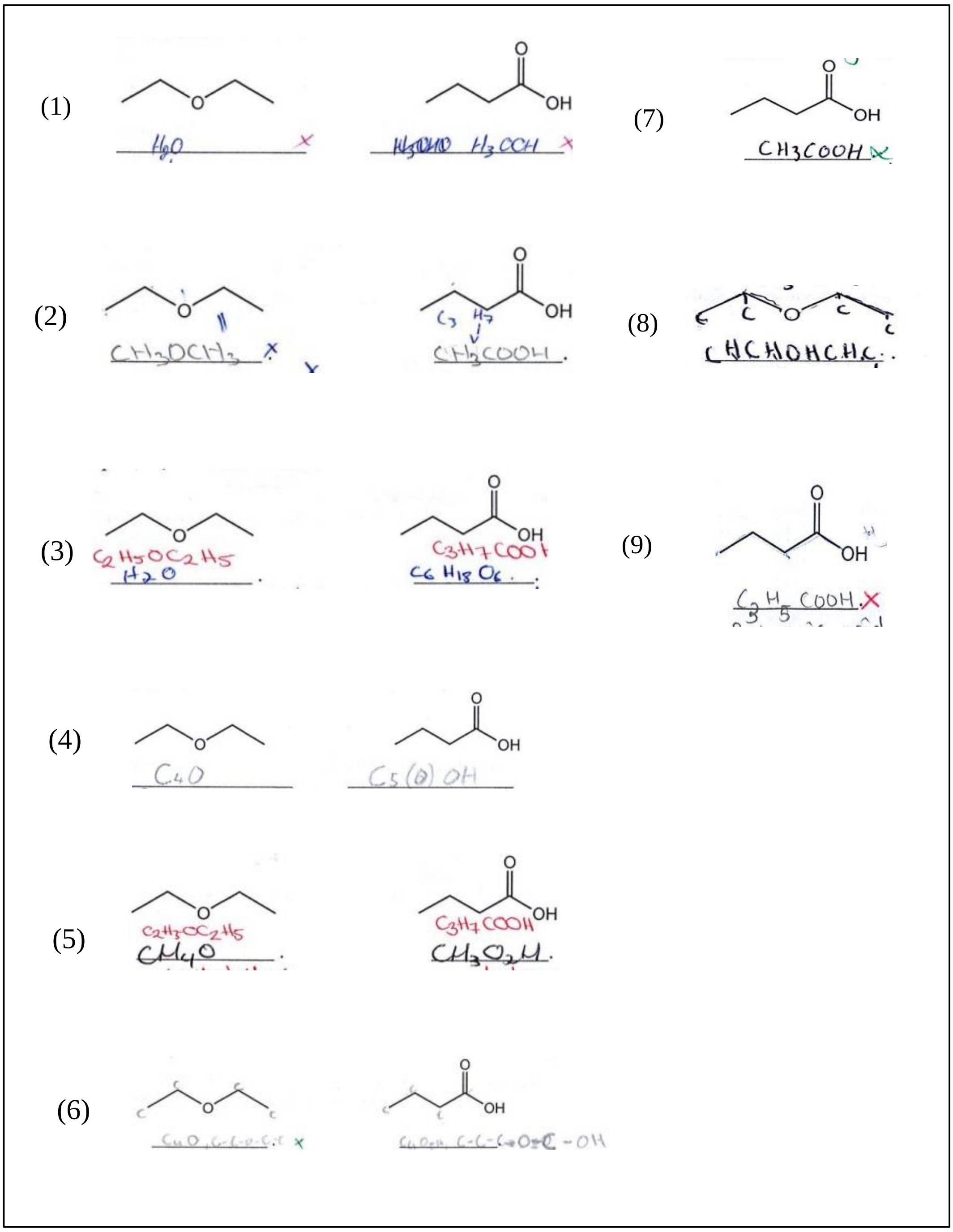


Figure A.3: Examples of students who could not translate from structure to molecular formula. Students 1-6 were unsuccessful at translating both structures. Students 7-9 were unsuccessful translating butanoic acid.

Question 2 (Test 2)

Students were asked to give the formula and structure for ethanoic acid and construct a 3D model. As this data was collected 'after-the-fact' it was not possible to photograph students' models or to gain information as to what element of the structure was incorrect, only if it was correctly constructed or not.

Table A.2 provides a summary of students' results from Question 2 in Test 2. As can be seen, a larger proportion of students successfully completed this question.

Table A.2: Summary of results of Question 2 on 1st Year Laboratory exam. (N=151) ✓ symbol means correct and x means incorrect.

Formula	**Model**	**Structure**	**# of students**	**# with LC**	**# no LC**
✓	✓	✓	54	35	19
✓	✓	x	6	3	3
✓	x	✓	3	2	1
✓	x	x	20	5	15
X	X	x	11	1	10
X	X	✓	3	1	2
X	✓	x	0	0	0
X	✓	✓	3	2	1

54% of students could complete this question successfully; 9% of students could write the molecular formula but could not translate that into its structure, with 6% of these students unable to draw the structure and 3% unable to construct the model. A further 20% of students could write the molecular formula but could not translate that into either a 2D or 3D structure. See Figure A.4 for examples of student work where they wrote the correct molecular formula but drew an incorrect structure. Students (a) to (g) made mistakes expanding the molecular formula to a structure due to incorrect bonding, such as expanding the COOH to C-O-O-H. This type of mistake is consistent with that identified in the literature by Kieg and Rubba (1993), Arasasingham (2004) and Bernholt et al (2012). Students (h) and (i) attempted to construct skeletal structures but were unsuccessful.

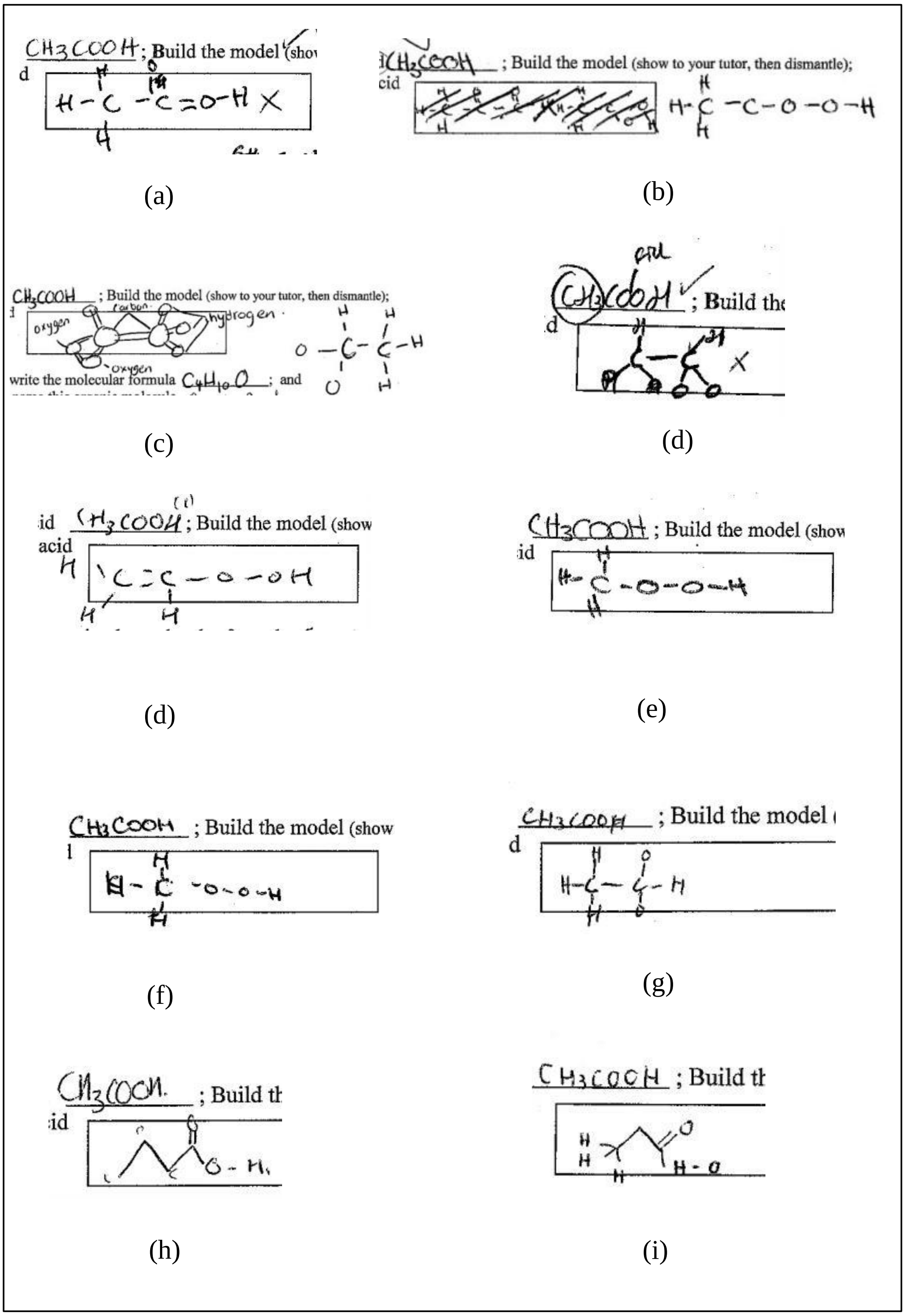


Figure A.4: Examples from student work showing errors in structure for ethanoic acid

In total, 17% of students could not write the correct molecular formula, with 11% being unable to construct a correct structure or model.

Despite the trends that arose from the first question, it is clear that these students, whether they studied chemistry for the LC or not, are not sufficiently proficient in translating between these 2 particular types of representations. While it is expected that having studied chemistry for the LC would be an advantage for students when beginning their studies at third level, it would be hoped that students would be at a similar level by the end of their first year of study, particularly in a concept as foundational as reading skeletal structures and writing a molecular formula for them. This is a worry for future lecturers, as skeletal structures are the traditional method of representing organic structures at 3^{rd} level and these results show that only 30% of this year's cohort of 1^{st} Year science students are able to read these representations correctly. Skeletal structures are an abstract representation as a significant proportion of the information is implicit.

The higher proportion of students who were successful in Question 2 could be explained by the fact that students have engaged with this molecule in several experiments throughout the year and so were familiar with its structure.

Despite difficulties translating between representations, these students were successful in the first test given at the beginning of the year. This test asked students to read a variety of representations and perform tasks such as mentally rotating a model.

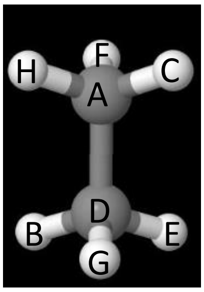
These findings have clear implications for this research project; students in 1^{st} year of a chemistry laboratory were able to engage with different types of representations of structures but not translate between them. Thus, an emphasis needs to be placed on facilitating students' ability to do this when designing the teaching approach of the OCV programme.

A.4 Copy of Test 1- Visualisation Test (3rd Level Students)

Note: Black/grey atoms = carbon, Red atom = oxygen, Green atom = halide (Cl, Br)

Q1.

In the molecule A, identify which of the atoms are closest to you, furthest away from you and middle distance away from you.



Atoms closest to you: ________________________________

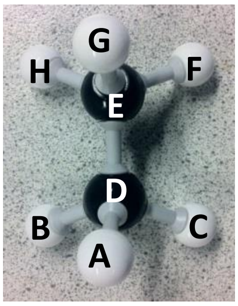
Atoms middle distance away from you: ________________

Atoms furthest away from you: ________________________

Molecule A

Q2.

In the molecule B, identify which of the atoms are closest to you, furthest away from you and middle distance away from you.



Atoms closest to you: __________________________________

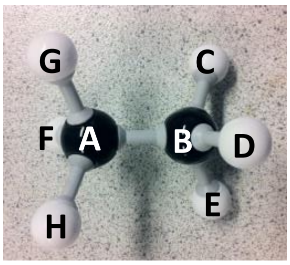
Atoms middle distance away from you: ___________________

Atoms furthest away from you: _________________________

Molecule B

Q3.

In the molecule X, identify which of the atoms are closest to you, furthest away from you and middle distance away from you.



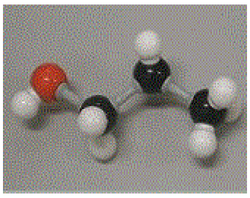
Atoms closest to you: ________________________________

Atoms middle distance away from you: ________________

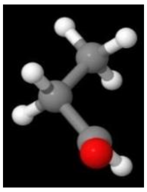
Atoms furthest away from you: ______________________

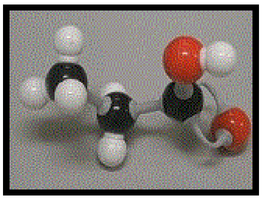
Molecule C

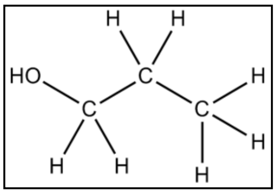
Q4.
Match the representation of Molecule D with its corresponding representation below (a, b or c). (Tick the box)



Molecule D

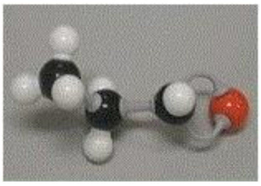




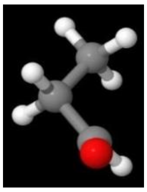


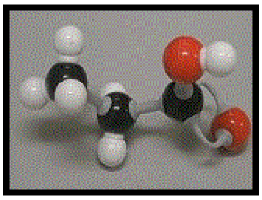
a ☐ b ☐ c ☐

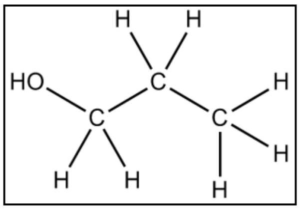
Q5.
Match the representation of Molecule E with its corresponding representation below (a, b or c). (Tick the box)



Molecule E

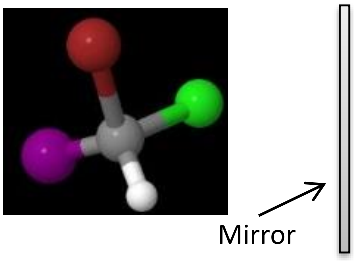




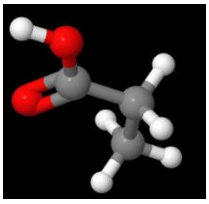


a ☐ b ☐ c ☐

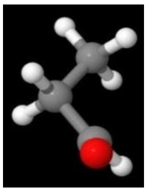
Q6.
Draw the mirror image of the following molecule:

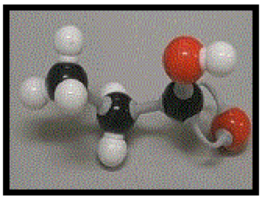


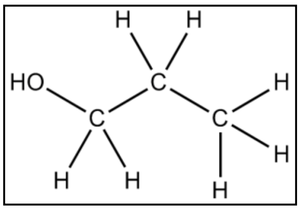
Q7.
Match the representation of Molecule F with its corresponding representation below (a, b or c). (Tick the box)



Molecule E

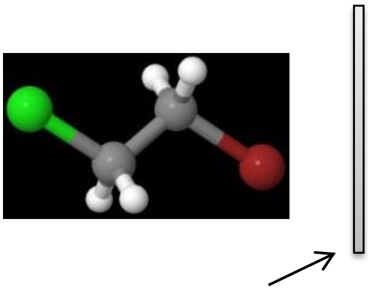






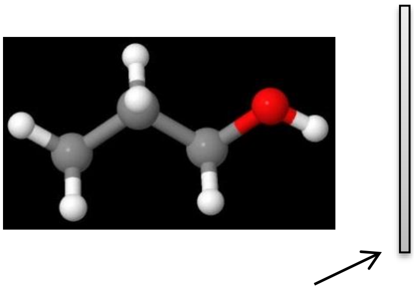
a ☐ b ☐ c ☐

Q8.
Draw the mirror image of the following molecule:



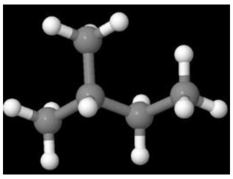
Mirror

Q9.
Draw the mirror image of the following molecule:

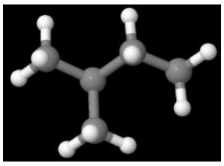


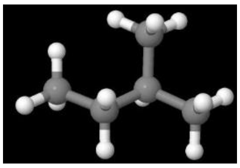
Mirror

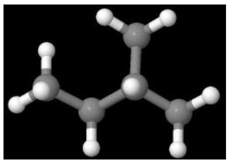
Q10.
Identify the picture that represents what Molecule J looks like from behind:



Molecule J

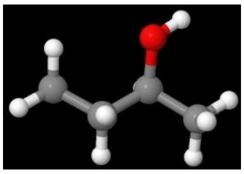




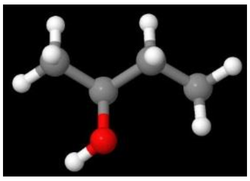


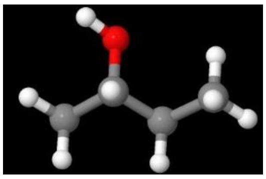
a **b** **c**

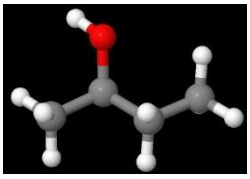
Q11.
Identify the picture that represents what Molecule K looks like from behind:

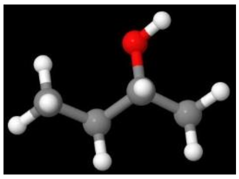


Molecule K



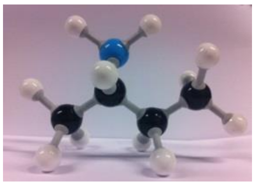




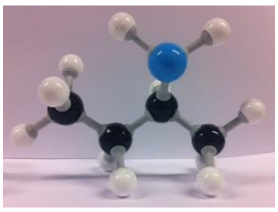


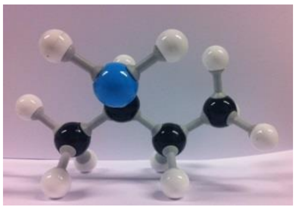
a **b** **c** **d**

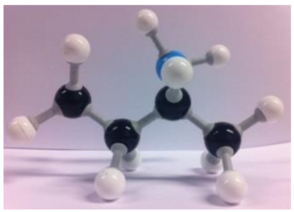
Q12.
Identify the picture that represents what Molecule L looks like from behind:



Molecule L







a **b** **c**

Appendix B:

Letters of Ethical Approval

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

DCU

Ms Laura Rice
School of Chemical Sciences

14th February 2014

REC Reference: DCUREC/2014/010

Proposal Title: **Organic Chemistry through Visualisation – Following the Electrons**

Applicants: Ms Laura Rice, Dr Odilla Finlayson, Dr Kieran Nolan

Dear Laura,

This research proposal qualifies under our Notification Procedure, as a low risk social research project. Therefore, the DCU Research Ethics Committee approves this research proposal. Please note approval is subject to receipt of correspondence from each School confirming their agreement to participate in the study. Materials used to recruit participants should state that ethical approval for this project has been obtained from the Dublin City University Research Ethics Committee. Should substantial modifications to the research protocol be required at a later stage, a further submission should be made to the REC.

Yours sincerely,

DCU Research & Innovation

Dónal O'Mathúna

Dr. Donal O'Mathuna
Chairperson
DCU Research Ethics Committee

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

DCU

Ms Laura Rice
School of Chemical Sciences

30th September 2014

REC Reference: **DCUREC/2014/206**

Proposal Title: **Investigation of First Year Science Students' Cognitive Abilities and Chemistry Conceptions**

Applicants: **Ms Laura Rice, Dr Odilla Finlayson**

Dear Laura,

This research proposal qualifies under our Notification Procedure, as a low risk social research project. Therefore, the DCU Research Ethics Committee approves this research proposal. Materials used to recruit participants should state that ethical approval for this project has been obtained from the Dublin City University Research Ethics Committee. Should substantial modifications to the research protocol be required at a later stage, a further submission should be made to the REC.

Yours sincerely,

DCU Research & Innovation

Dónal O'Mathúna

Dr. Donal O'Mathuna
Chairperson
DCU Research Ethics Committee

Appendix C:

Teacher Reflection Sheet (TRS)

OCV Teacher Reflection Sheet

Class Length (please circle): Single Double

Chapter No.:		Activities Completed:	

Did you make any changes to the lessons outlined above i.e.: the order of activities, additional activities/ examples, skipped questions?

Rate students’ ability to carry out the activities suggested: (1= not able, 5= very able).

1 2 3 4 5

Rate students’ achievement of the anticipated learning outcomes (1=not achieved, 5 =fully achieved) and state evidence for this

1 2 3 4 5

Identify areas where students experienced difficulties or achieved learning outcomes:

Difficulties	Achievement

Was additional instruction/ clarification required for any of the activities?

If you were to repeat this lesson, what changes, if any, would you make?

Appendix D:

Researcher Observation Sheet

OCV Researcher Observation Sheet

Class Length (circle): Single Double

Chapter No.:		Pages in Student Manual Covered:	

Did the teacher make any changes to the lessons outlined above i.e.: the order of activities, additional activities/ examples, skipped questions?

Rate teachers' ability to guide students through activities suggested: (1= not able, 5= very able).

1 2 3 4 5

Rate students' engagement with the activities suggested: (1= not engaged, 5= very engaged) and state evidence for this.

1 2 3 4 5

Rate students' ability to carry out the activities suggested: (1= not able, 5= very able).

1 2 3 4 5

Rate students' achievement of the anticipated learning outcomes (1=not achieved, 5 =fully achieved) and state evidence for this

1 2 3 4 5

Identify areas where students experienced difficulties or achieved learning outcomes:

Difficulties	Acheivement

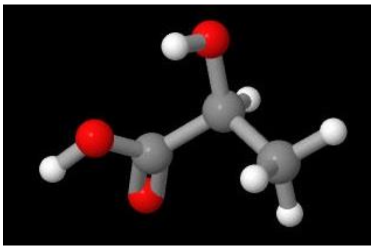
Was additional instruction/ clarification required for any of the activities?

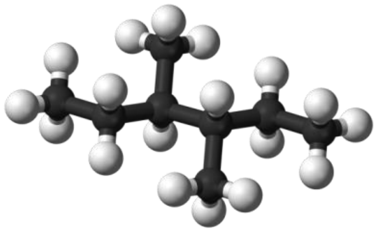
<u>**Appendix E:**</u>

Implementation 1-Assessment 1

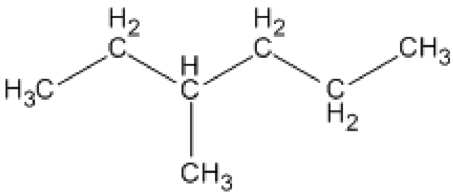
Questions used in Assessment 1 during Implementation 1. For ease of compiling appendices, the answer boxes have been removed.

Q1. Draw 2D structures of the following organic molecules represented by 3D pictures:

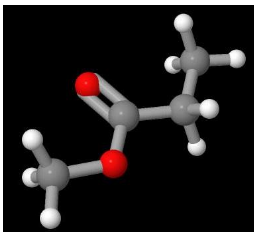


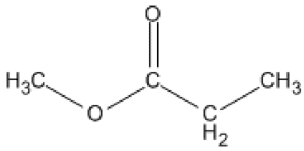


Q2. Draw 2 isomers of the following molecule:

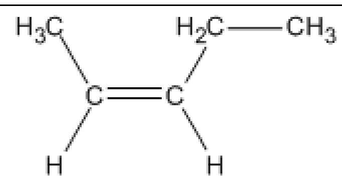


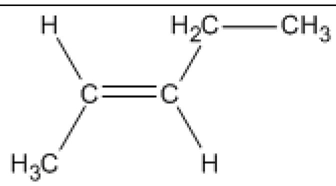
Q3. Write the molecular formula for the molecule represented in both 3D and 2D below.





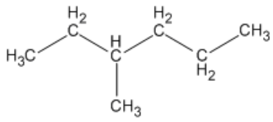
Q4. Label the cis-isomer and the trans-isomer of the following isomer pair:



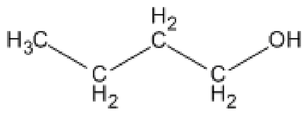


Q5. One of the organic compounds below is a gas at room temperature and the other is a liquid at room temperature. Using your knowledge of inter-molecular forces, suggest which compound is a gas and which is a liquid.

Explain your answer.



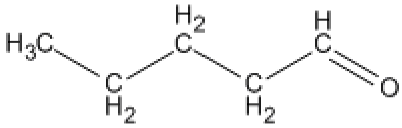
A



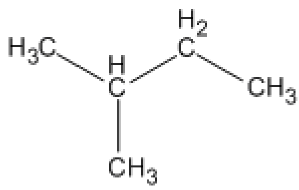
B

Q6. Rank the following molecules in order of *decreasing* boiling point. (i.e.: highest to lowest).

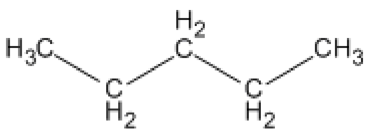
Explain your answer.



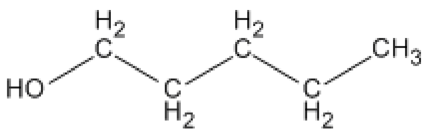
A



B



C



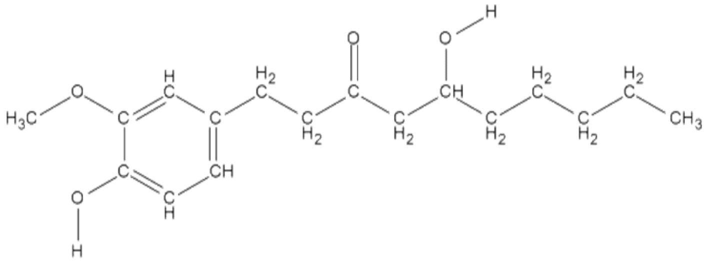
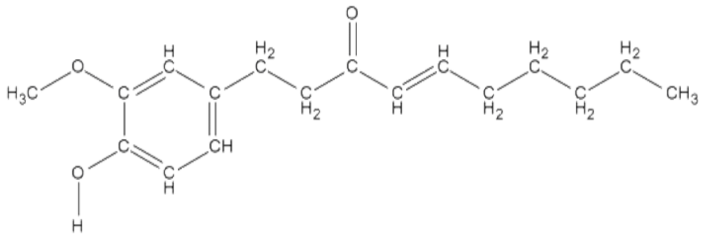
D

Highest BP	
Lowest BP	

Q7.

Gingerol (structure A below) is the active ingredient in ginger.

When ginger is dried or cooked, Shogaol (structure B below) is produced. Shogaol also has a pungent ginger smell.

A Gingerol	
B Shogoal	

(a) Identify areas of high and low electron density in each compound on their structures above (i.e.: assign partial charges)

(b) The boiling point of Gingerol (A) is approx. 453ºC. Would you expect Shogoal (B) to have a higher or lower boiling point than Gingerol?

Explain your answer (consider intermolecular forces and the shapes of the molecules)

(c) Which of these compounds would you expect to be more soluble in water?

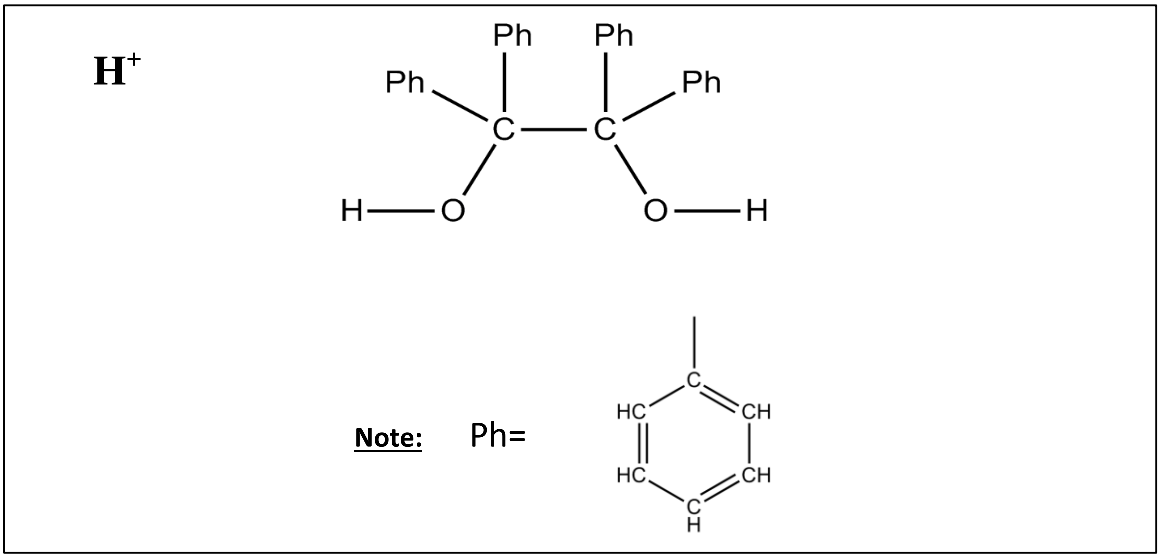
Explain your answer (consider how each molecule will interact with water molecules)

Appendix F:

Implementation 1-Part C: Reactivity Assessment

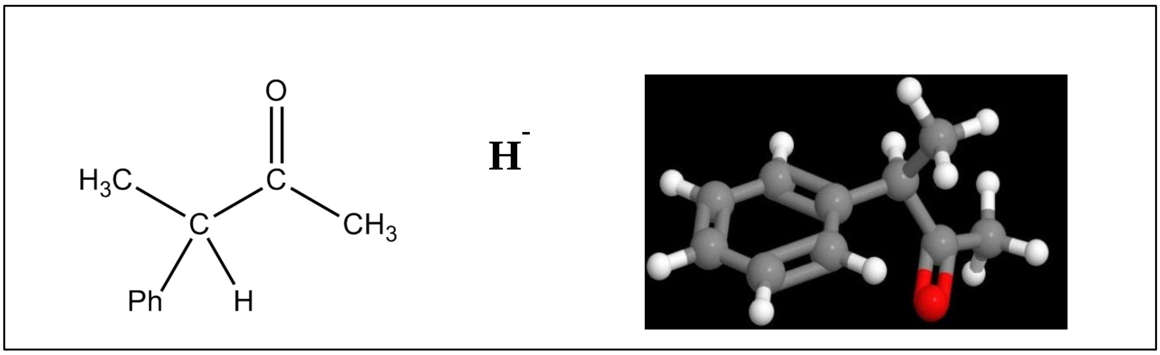
Q1.

Suggest the sites on the molecule below that a H^+ ion is likely to attack. Circle the possible sites on the structure below.



Q2.

Identify the possible reactive centres of this molecule in the presence of H^-. Circle the possible reactive centres on the 2 dimensional drawing of the molecule's structure.

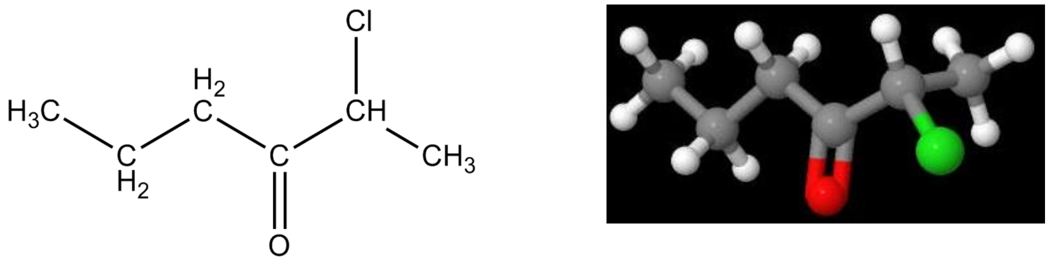


Explain your answer:

Q3.

Predict the possible reactive centres of this molecule in the presence of H^-. Circle the possible reactive centres on the 2 dimensional drawing of the molecule's structure.

$\mathbf{H^-}$



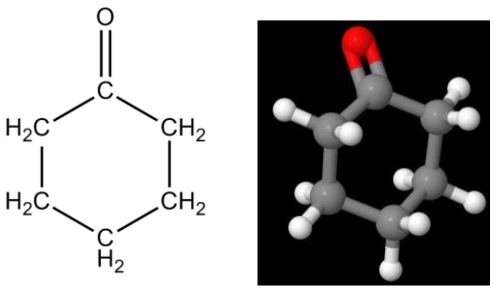
Which of these reactive centres do you think is most likely for the H^- to attack? Explain your answer:

Q4.

Carbon is more electronegative than Phosphorous. As a result, when they are bonded together a polar covalent bond is formed, with the Phosphorous taking a slight positive charge and the Carbon taking a slight negative charge. An example of this occurs in the following molecule:

$$Ph_3\overset{+}{P} \xrightarrow{} \overset{-}{C}H_2$$

What are the two possible ways that this Phospherous containing molecule can attack the cyclic molecule below? Explain your answer

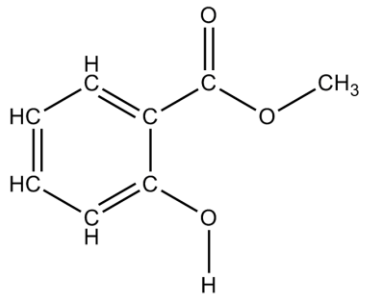


$+ \quad Ph_3\overset{+}{P}—\overset{-}{C}H_2$

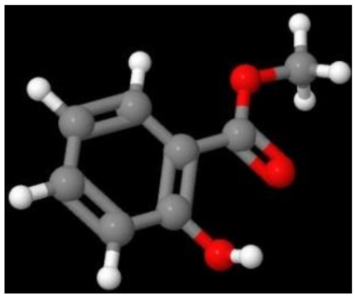
Q5.

Methyl Salicylate, also called Oil of Wintergreen, is a clear organic liquid obtained from Wintergreen plants. It is used as a flavouring in chewing gum and mints.

Identify the possible sites on the Oil of Wintergreen molecule that an OH^- ion might attack. Circle the possible sites on the 2 dimensional drawing of the molecule's structure.



OH^-



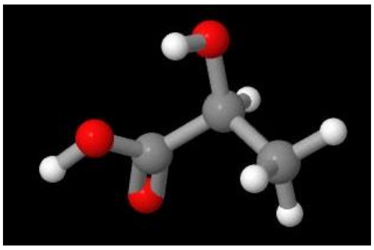
Suggest which of these reactive centres do you think is most likely for the OH^- to attack? Explain your answer:

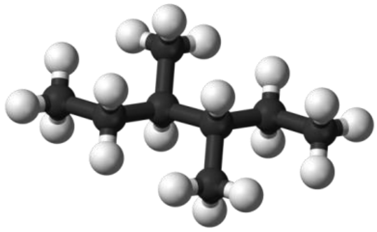
<u>Appendix G:</u>

Implementation 2-Assessment 2

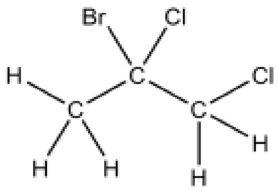
Questions used in Assessment 2 during Implementation 2. For ease of compiling appendices, the answer boxes have been removed.

Q1. Draw 2D structures of the following organic molecules represented by 3D pictures:





Q2. What is the name of the following compound?



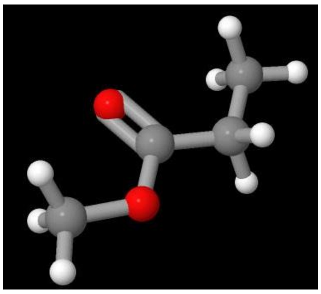
(a) 2,3-dichloro-2-bromopropane

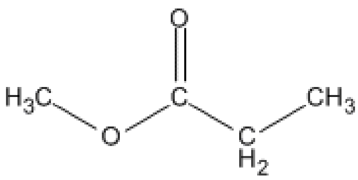
(b) 1,2-dichloro-2-bromopropane

(c) 2-bromo-2,3-dichloropropane

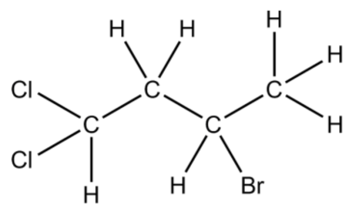
(d) 2-bromo-1,2-dichloropropane

Q3. Write the molecular formula for the molecule represented in both 3D and 2D below.

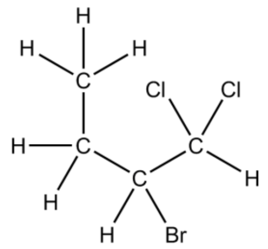




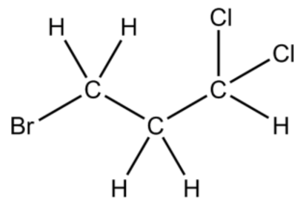
Q4. Four compounds, W, X, Y and Z are represented below:



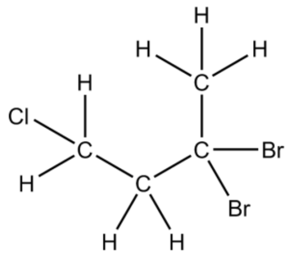
Compound W



Compound X



Compound Y



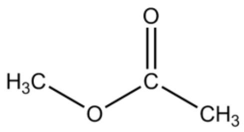
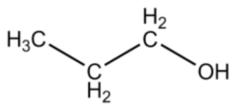
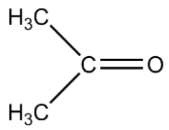
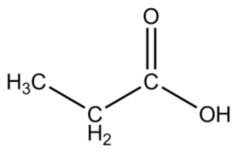
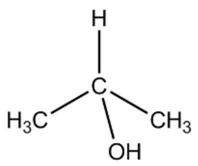
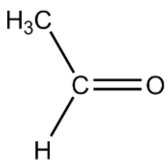
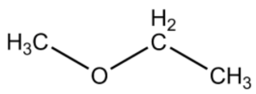
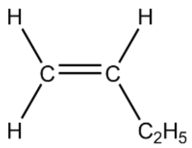
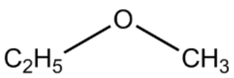
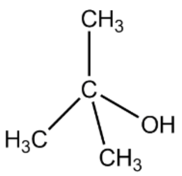
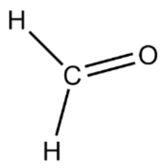
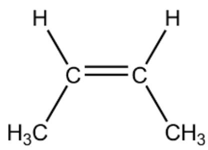
Compound Z

Which of the following is a pair of isomers?

(a) W and Y
(b) X and Y
(c) W and X
(d) Y and Z

Explain how you know these are isomers:

Q5. Look at the boxes below and answer the questions that follow:

A 	B 	C 	D 
E 	F 	G 	H 
I 	J 	K 	L 

Select the boxes which show the structure of:

		Answer
(a)	An isomer of the compound shown in box G	
(b)	An aldehyde	
(c)	A compound which is identical to I	
(d)	An alkene with a cis- arrangement	
(e)	An isomer of the compound shown in box B	
(f)	An ester	
(g)	A molecule which will be insoluble in water	
(h)	A molecule with a higher boiling point than the compound shown in box B	

Explain your answers to (g) and (h):

Appendix H:

Protocol for Paired Interview

The following protocol was followed by researchers during the paired interviews of Implementation 1

- ~ State students' names before beginning
- ~ Have students face slightly away from each other- so they don't influence each other's model
- ~ IF students draw an incorrect structure, don't correct them, let them build what they have drawn

---

1. Students are given the molecular formula for ethanal (CH_3CHO) and asked to draw its structure in the box provided. Ethanal occurs naturally in coffee, bread and ripe fruit.

2. Give students the box of playdough and sticks and ask them to construct as accurate a 3D representation of ethanal as possible.
   - They can use whatever they want to represent each component of the molecule

Example questions to ask students about their models:

Their Model

Colour of atoms	
All the same colours	Different colours for different atoms
- Why did you select the same colour for each atom? - Can you explain to me what each atom is? (e.g: hydrogens, carbons, etc.)	- What does each colour represent? - Why did you choose these colours?

Shape of the molecule – CH_3 part	
- Can you explain the shape that you have constructed for the CH_3 group? (feel free to point to that part of the molecule) - Why did you construct this shape?	
If tetrahedral	Other than tetrahedral
- Do you remember the name of this arrangement? - How does the bonding contribute to this shape? - Why are the hydrogens arranged like this around the carbon?	- Can you explain the arrangement of these atoms? - Why did you arrange the atoms like this/ how did you arrive at this arrangement?

Shape of the molecule – CHO part	
- Can you explain the shape that you have constructed for the -CHO group? (feel free to point to that part of the molecule) - Why did you construct this shape?	
If planar	Other
- Do you remember the name of this arrangement? - How does the bonding contribute to this shape?	- Can you explain the arrangement of these atoms? - Why did you arrange the atoms like this/ how did you arrive at this arrangement?

Size of atoms	
All the same size	Different size atoms
- Are all the atoms the same size?/ Why did you make all the atoms the same size? - What contributes to the size of the atom? - Is there a reason all the atoms would be the same size?	- Which is the largest atom? - What contributes to the size of the atom?

Bonding in the molecule
- What do the sticks represent? - Are all the bonds the same in this molecule? (same type, length, etc.) - Can you point out a single bond? - Can you point out a double bond? (ask even if no double bond present in molecule) - How does a double bond compare with the single bonds in the molecule? - prompt id needed: in terms of rigidity, flexibility

Electron Density
Is there an area of high electron density within this molecule? Is there more than one area of high electron density? What causes areas of high electron density to exist?

Solubility in Water
- Do you think ethanal will be soluble in water? - What makes something soluble in water? - Is there a particular part of the ethanal molecule that will interact with water molecules? **(allow students to sketch this interaction if they are having trouble communicating)**

Appendix I:

Example of Paired Interview Transcript Coding

Tetrahedral Carbon Description	Code
No name, no description	0
Name/ no explanation	1
Attempt at explanation (describes bonding shape)	2
Adequate explanation (repulsion of electrons)	3

The dialogue below is an example of an adequate explanation from a student that received a coding of 3.

R: Yes, do you remember the name of the shape?

S1: Ah…

S2: Tetrahedral I think?

R: Very good. And why does this shape arise?

S1: Like, the angle?

R: Yes, why is it like that?

S1: I…

S2: I think it has something to do with lone pairs forcing them that way I think. Carbon has a lone pair, I think which is kind of em pushing them away. I'm not sure if it's for that one or for another one.

R: Does carbon have a lone pair in here?

S1: No I don't think so

S2: No it's probably not a lone pair because carbon doesn't have a lone pair. Oh…is it because they want to have an equal distance, kind of? Because they are repelling each other equally, so that they have that shape.

Note: R= researcher, S= student

Appendix J:

Example of Ranking of Responses for MDS Analysis

The following are examples of the coding applied to student responses for MDS analysis. The ideal responses are highlighted in yellow. The ideal responses were defined according to the correct answer that I was looking for each question.

Once the student responses were coded, they were input into SPSS software for MDS analysis. This analysis compares each response by each student and graphically represents each student by a data point according to how similar/dissimilar their responses were.

Assessment 2, Question 4: Identifying isomer pairs

Ranking of responses (Ideal highlighted in yellow)

0	No attempt
1	D
2	B
3	A
4	C

Assessment 2, Question 5 (c): Identifying same structure with different presentation

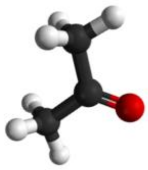
Ranking of responses (Ideal highlighted in yellow)

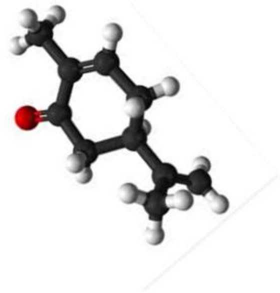
0	No attempt
1	J
2	E
3	G

Appendix K:

OCV Teacher Manual

Front page of OCV Teacher Manual. Full OCV Teacher Manual available on attached CD.





Organic Chemistry through Visualisation

Teacher Manual

Authors: Laura Rice, Odilla Finlayson, Kieran Nolan

School of Chemical Sciences, Dublin City University

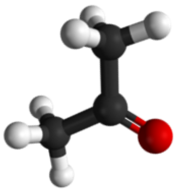
IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

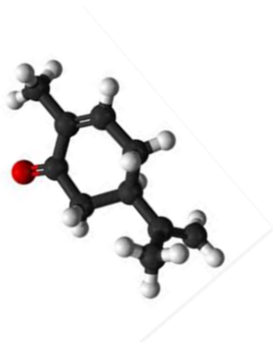
CASTeL

Appendix L:

OCV Student Manual

Front page of OCV Student Manual. Full OCV Student Manual available on attached CD.





Organic Chemistry

through Visualisation

Student Manual

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