Investigating Conceptual Chemical Misconceptions in Atomic Structure and Bonding in Year 12 Chemistry Students

by

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ABSTRACT

This project aims to ascertain the extent and cause of conceptual chemical misconceptions in the classroom and whether they can be rectified within the curriculum. Previous studies have indicated that misconceptions may exist in the subtopic of atomic structure and bonding. A case study on Atomic Structure and Bonding was carried out on a Year 12 cohort through a mixed methods approach; a 10-question Chemical Concept Inventory (CCI), classroom observation, interviews and concept maps. Although initial CCI responses appeared to indicate conceptual misunderstandings were present in the topics of stoichiometry and VSEPR, interview responses indicated otherwise. The stoichiometric incorrect answers were more likely due to terminological misunderstandings rather than conceptual issues. Participants' oral explanations involving formulae and equations were often spoken incorrectly to the researcher, suggesting a potential reason for terminological issues was the ambiguity between coefficients, subscript and superscript numbers when orally stated. Thus, heightening educator awareness of this ambiguity along with the nature of terminology in the classroom can potentially help students fully grasp the chemical conventions. Similarly, VSEPR results suggested a lack of student knowledge rather than misconceptions, potentially due to the structure of how this topic is first introduced, possibly caused by time constraints.

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TABLE OF CONTENTS

SECTION 1: INTRODUCTION

1.1 CONTEXT OF THE RESEARCH

In the UK, education is a right for every child to be able to access up until the age of 16, with varying school leaving ages in the different countries of the UK after this age (Gov.uk, 2017). However, with one in three English students and one in four Scottish students going on to higher education, there is a requirement to provide education at a high enough standard that can allow students have a strong chance of succeeding at university (Kershaw, 2017). For this research, science (and more specifically chemistry) education will be studied.

Science has been a core part of the National Curriculum in England since the proposal of the 1988 Education Reform Act which stated that the National Curriculum would be 'covering the 'core' subjects of English, mathematics and science' (House of Commons: Children Schools and Families Committee, 2009). However there were particular issues in Science, Technology, Engineering and Mathematics (STEM) subjects in the General Certificate of Secondary Education (GCSE) results for 2016 with a recent report in the Telegraph (Kirk, 2017) stating 'the largest falls in A* - A pass rate since 2011 were seen in ICT and chemistry. In a worrying sign for STEM subjects, the five subjects with the largest falls in attaining top grades since 2011 have all been in the science and technology areas'.

Recent examiners' reports for AQA GCSE Chemistry (2014-16) indicate frequent misunderstanding of basic chemistry concepts in both higher and foundation level chemistry, particularly in the topics of Atomic Structure and Bonding, and Stoichiometry. Some examiners' reports even use language such as 'misunderstanding', 'incorrect designation', or 'discriminating question' (when talking about a question that split the students into higher and lower achieving students) and the word 'misconception' when explaining where students were unable to answer a question correctly (AQA, 2014a; AQA, 2014b; AQA, 2014c; AQA, 2014d; AQA, 2014e; AQA, 2014f; AQA, 2015a; AQA, 2015b; AQA, 2015c; AQA, 2015d; AQA, 2015e; AQA, 2015f; AQA, 2016b; AQA, 2016c; AQA, 2016d; AQA, 2016e; AQA, 2016f; AQA, 2016g). These topics have been shown to be difficult to grasp at a deeper level of understanding at all educational stages in the past rather than just at GCSE (Treagust, 1988, pp. 160, 164-165; Taber, 1993). Driver (1983, p. 39) suggested that in order to teach chemistry effectively, teachers must be aware of the possible misconceptions (called 'alternative frameworks') that students could hold stating 'it is as important to help pupils refute their misconceptions as it is to present the accepted view'. This means that in order to help students to fully understand a particular concept, teachers must explain to the students exactly why the students' misconceptions are not usually considered to be correct explanations for what is occurring in the scenario being tested rather than just stating the true framework. The explanation allows the students to come to their own conclusions about the limitations of their misconceptions and, as such, are more likely to accept the view being given by the teacher. Additionally, a study by Coll and Treagust (2003, p. 464) on ionic bonding stating 'learners at all educational levels harbour a number of alternative conceptions and prefer to use simple mental models'. Furthermore, research into chemical misconceptions has been carried out in a number of different countries, suggesting that this is a global issue rather than a problem unique to the educational system in the UK.

As science education is important at multiple different levels, research has been carried out from school levels up to university into both students and teachers. Nakhleh (1992, p. 191) echoed this viewpoint, arguing that one possible reason why students struggle to learn chemistry is that ‘many students are not constructing appropriate understandings of fundamental chemical concepts from the very beginning of their studies.’ This suggests that in order to combat the misconceptions that students have at the higher educational levels, the work must start earlier in the educational timeline.

Therefore, by looking at Advanced Level (A Level) Chemistry, this study aims to identify potential causes of students’ misunderstandings on key chemistry topics in atomic structure and bonding; this should help teachers to identify problem areas which require more guidance, and potentially offer reasons that these issues are introduced.

1.1.1 Research into Atomic Structure and Bonding as a Problem Area

Atomic structure and bonding has been suggested as a difficult topic for students for a number of years, and has been suggested as a ‘threshold concept’. A threshold concept has been defined as a concept which is ‘a transformed way of understanding, or interpreting, or viewing something without which the learner cannot progress’ (Meyer and Land, 2006, p. 3). For example, Park and Light (2009) investigated the understandings of three first-year undergraduate students (chosen from a small sample of 20 interviewees from 633 students) from an introductory chemistry course. Despite the research being focused on whether the different models of the atom (‘Particle model, Nuclear model, Bohr's model, and Quantum model’) could be used to identify whether atomic structure was a threshold concept, the research suggested that the students being interviewed held their own models of the atom, and that one of the three students did not develop his understanding of the atomic model over the course (Park and Light, 2009, pp. 239, 242-250). For example, this student started and ended with a Bohr model, though he ended with a 'modified Bohr's orbital model considering different shapes of orbitals' where he saw each orbital shape as a set path (Park and Light, 2009, pp. 242-244). This second model left the student with some confusion when drawing the atomic structure including the p orbitals as he stated 'it would be running into the nucleus … it makes no sense' (Park and Light, 2009, p. 244). This suggests that although the course held 'seven chapters [which] were related to the main topic of this study: 'atomic structure'' out of the nine in the core book used, some students in the course failed to fully understand the new models being introduced (Park and Light, 2009, p. 239). Therefore, although the research being carried out by Park and Light (2009) is looking at whether atomic structure and bonding could be seen as a threshold concept, their research suggests that misconceptions could be present in the students' minds.

Furthermore, research carried out by Gonzales (2011) suggests further evidence for the presence of misconceptions (underlined by Gonzales) in atomic structure and covalent bonding between atoms, illustrated by one student mentioning that:

'The <u>electrons are not whizzing around</u> when the [covalent] bond is formed. The electrons would probably stay in one location. The <u>electrons are not moving</u> around the atoms. When the bond is formed, if <u>one electron moves then the other has to move</u>' (Gonzales, 2011, p. 55).

Issues with bonding have also been identified by Metcalfe (1996) when asking Form 6 students (aged 15-17) from New Zealand about the nature of bonding. For example, only '48% of students correctly agreed' with the statement 'All bonding is electrical in nature', and some misconceptions including: ‘No, some bonds are caused by chemical reactions’, ‘No, because a lot of things have no charge’ and ‘No, they're all electrical except Van der Waals’ (Metcalfe, 1996, p. 36).

The presence of these misconceptions suggests that students do not fully understand how bonding occurs between atoms, and these issues could be due to the language used as some students had confusion between ‘molecules, elements and compounds’ when talking about bonding (Metcalfe, 1996, pp. 8, 22, 41-42, 80-81). Therefore, more clarification of terminology is potentially needed at the earlier stages of the chemistry teachings in order to address these issues; with clearer definitions of the language used in chemistry lessons it is likely that some students would be able to fully understand the questions being asked and obtain the correct answer.

Additional research carried out in the Greek secondary educational system into students’ understanding of the atom suggests that even though older children (age 17) who were on a specific ‘science and math direction’ had fewer misconceptions than their younger counterparts (between 13-15) who were on an unspecified course, there were still misconceptions present (Papageorgiou *et al.*, 2016, p. 475). The majority of the students’ misconceptions fell in a task specifically looking at characteristics of an atom (where 42.5% of all students had misconceptions where ‘students were asked to answer whether ‘atoms’ are/could be alive’ with the options being ‘always, sometimes or never’’ with an explanation required (Papageorgiou *et al.*, 2016, pp. 471, 474). Papageorgiou *et al.* (2016, p. 476) state the misconception here is between atoms and cells, with some students stating ‘the atom is the smallest living organism, since cells consist of atoms’. This suggests that despite having a specific programme for science which could dedicate more time to evaluating whether misconceptions exist in the students' minds and correcting them, these students still held incorrect theories about some basic scientific concepts.

1.2 Theory

1.2.1 Importance of Pedagogical Research at the Secondary School Level

Pedagogical research is important at all education levels, due to the fact that carrying out research into how teaching is conducted can aid teachers to identify which approach may be most effective for their class. This research is more important than simply analysing the attainment of their students, as by looking at the teaching methods themselves rather than raw marks, the teacher is able to evaluate whether the methods used in the research would be applicable for their class or whether the introduction of this method may be detrimental (Entz, 2007, pp. 2, 9, 20). However, educational research often does not offer a 'clear unambiguous guidance about the best way to teach' (Taber, 2007, p. 5). Consequently, it is important that pedagogical research is carried out in multiple different scenarios as the conclusions from research into one subject may suggest one teaching methodology is best, whereas this may not be the case across other topics or subjects.

Alongside the research being carried out by specialist researchers into pedagogy, there is also a drive for newly trained teachers and teachers in training to appreciate the importance of 'research-informed and evidence-based' conclusions about how they should carry out or structure their own sessions (Taber, 2007, p. 7). This is also shown by some PGCE courses including separate, isolated modules on pedagogy e.g. Newman University and University of Worcester, as well as courses specifically looking into elements of pedagogy e.g. Education MA at Leeds (Leeds Trinity University, 2017; Newman University, 2017; University of Worcester, 2017). This focus on pedagogy in the teacher training process allows teachers to understand that there are multiple different teaching methods, allowing the teacher the opportunity to try out and identify which methods work more effectively for their own class.

1.2.1.1 Why AS Level Chemistry Students have been Chosen for this Research Project

As this research project aims to identify whether there are misconceptions in the cohort being analysed, Advanced Subsidiary Level (AS Level) students were chosen to be the target population for the research project for two main reasons.

Firstly, all of the students studying AS Level Chemistry would have elected to study chemistry, suggesting that these students would potentially have an increased interest in the subject compared to the students who did not elect to study chemistry at a higher level, although some students may have elected to study chemistry for other reasons. This increased interest may suggest that these students would be more likely to want to understand the reasoning behind their answers (e.g. they have a desire for conceptual understanding rather than simply learning how to answer the questions). This viewpoint echoes similar views around ‘Interest-based Learning’; the idea that if a student has an interest in what is being taught, they are more likely to want to learn more about the topic or subject, compared to if the student was forced to learn something they had little or no interest in at all (Nordmark, 2017). Therefore, if there are common misconceptions present in the cohort being tested in this project, this is more likely to be representative of an issue which needs to be addressed in the student population rather than an example of individuals' issues due to low work ethic.

Secondly, as this research was taking place during school times, it was important to keep the disruption to the students' learning to a minimum. As there has recently been a change into reverting the AS and A2 exams back into a two year A Level rather than having formal exams at the end of the AS year as AS and A levels are now 'decoupled' (Office of Qualifications and Examinations Regulation, 2018), this means that carrying out the research during the AS year should have limited impact on the students (in regards to any other formal exams that they may have).

1.2.2 Accepted Definitions for Misconceptions Used in this Research Project

A misconception is commonly defined as 'an idea that is wrong because it has been based on a failure to understand a situation' (Cambridge Dictionary, 2018). In the educational context, misconceptions are often seen by teachers (see Section 1.1 Context of the Research) at the beginning of a topic as students have adapted their own understandings of the world, and typically part of the job of the teacher is to help the students identify and correct these misconceptions (Lucariello and Naff, 2018).

Misconceptions in science teaching were categorised by the National Research Council (1997, p. 28) into several different types:

- ‘Preconceived notions’ which are ideas that people hold due to their own personal experiences.
- ‘Nonscientific beliefs’ which are ideas that people hold through learning outside of science lessons.
- ‘Conceptual misunderstandings’ which are incorrect scientific ideas held by the student as the concept being taught is taught in a way that is confusing to the student. This is normally due to the fact that the concept doesn't fit in with the previous ideas that the student held, and as the science behind it is not explained enough for the student to be able to refute their previous understanding, an incorrect model which contains both their previous knowledge and the new knowledge being taught is created by the student.
- ‘Vernacular misconceptions’ which are ideas that arise by terminological differences as words in science have specific definitions which may be different to the same word used in another scenario outside of a science lesson.
- ‘Factual misconceptions’ which are ideas which have been learnt incorrectly at an early age and have not been challenged previously - these ideas could have been taught by anyone to the student, both inside and outside of academia.

For this research project, it is anticipated that the misconceptions being analysed fall mainly in the ‘conceptual misunderstandings’ area, with the ‘vernacular misconceptions’ and ‘factual misconceptions’ areas potentially also being common as the research takes place in a school, so the environment that the research is taking place in is in the scientific and academic environment. However, as the research project is looking at all misconceptions, anything which falls into the main category of a misconception in atomic structure and bonding will be analysed rather than discriminating between the different categories.

1.2.3 Current Theories about Learning and Potential Implications for how Misconceptions May Arise

Please note: As the research project carried out followed an inductive approach, the researcher did not adopt any of the learning theories stated below to apply to the research project before any data collection had occurred in order to limit unconscious bias from being introduced.

Multiple different theories are currently in place to try to understand why students learn in different ways. These theories include: Behaviourism, Cognitivism, Constructivism, Humanism and Social Constructivism. However, these theories are rarely applied as standalone approaches to teaching, as there is often a lot of overlap between the theories. This overlap is especially evident when looking at the subdivisions of theories e.g. Social Constructivism and Constructivism. Therefore, by analysing the main points of each theory and evaluating whether misconceptions could be introduced by applying the theories to a cohort, it may become evident through this project whether the teacher applied any of these theories in their lessons, and so if the application of the theories was potentially a factor into any misconceptions that the students may have.

1.2.3.1 Behaviourism

Behaviourism is the theory that students will learn information by responding appropriately to the stimulus given (Klinger, 2010, p. 156). This suggests that there is a greater importance in the teacher giving reinforcement (either positive or negative) to the students' answers so that the student learns which answers will give them the positive reinforcement rather than teaching the theory behind why the student's answer is correct or incorrect. However, this practice does not always work in all subjects. The behaviourist teaching methodology is more effective in topics and subjects where there are precise rules to learn and a “skill and drill” approach can be used e.g. formulae, as there is a “correct” response for these types of question (Klinger, 2010, p. 156; Berkeley Graduate Division, 2018).

Misconceptions can potentially arise using this style of teaching as the student learns to give an answer that they believe the teacher wants as this allows a positive response, however this means that they may not understand why the answer is correct. This could potentially cause problems if the students are asked questions which are related to the questions that the teachers have been asking, though are not exactly the same. As the “skill and drill” questions do not work as effectively for instilling more complex ideas into the students’ understanding, there may be issues arising if the students have to use types of skills based on these complex ideas e.g. more analytical techniques.

1.2.3.2 COGNITIVISM

Cognitivism is a theory more focused on ‘how information is received, organised, stored and retrieved by the mind’ (Ertmer and Newby, 2013, p. 51). This suggests that there is a high importance on how the teacher is able to present the concepts to students, as in order for the students to understand a topic, the concepts must be presented in easy to follow steps. This practice is occasionally viewed as a development from behaviourism as cognitivism is seen as an active process as 'the learner [is shown] as an active participant in the process of knowledge acquisition and integration' (Yilmaz, 2011, p. 205).

Misconceptions can potentially arise if the student is unable to compartmentalise the concepts in the correct order e.g. they attempt to jump ahead to the answer without properly evaluating their route. This can potentially mean that the students miss out a valuable step in their thought process, as although this step may not be needed in all cases, it could be vital in other scenarios leading to students being confused when their method fails to work in certain scenarios. In this situation, misconceptions are present when students question whether the theory of what the teacher taught was wrong rather than question the method the student used.

1.2.3.3 Constructivism

Constructivism is the theory that the student learns concepts by building on existing knowledge relevant to the concept that is being taught (Bada, 2015, pp. 66-67). This theory works on the idea that the student has to be able to relate the new concept to something meaningful to them; the idea has to be linked in some way to the student in order for the concept to be learnt. This in turn means that constructivism is quite a subjective theory, as the understanding for each student is different. As each student has a different background of experiences, each student will link the new concept to different experiences, rather than everyone making the same links.

Misconceptions can potentially arise if students attempt to link the concepts being taught with their own understanding on this topic, and there is an incompatibility between the two (see ‘conceptual misunderstandings’ in 1.2.2 Accepted Definitions for Misconceptions Used in this Research Project above). This potentially causes the student to get confused as to how to approach or answer the questions being asked, as they are unsure as to why their constructed model (encompassing both their previous experience and the teaching around the subject) is not able to answer the question.

1.2.3.4 Humanism

Humanism is the theory that learning is ‘a personal act to fulfil potential’ (Gravells and Simpson, 2014, p. 94). This approach is based on the belief that the ‘student is central and the learning is personalised’, and as such the teacher works more as an assistant to the students’ learning, rather than being the lead in the lesson (Parsons, 2013, p. 2). Additionally, humanism works on the belief that all students want to learn, and that they are able to set their own targets and goals for learning, however this must occur in a suitably supportive environment for this to be able to take place (David, 2015).

Misconceptions can potentially arise if the students’ targets are not suitable with the overall subject matter of what is being taught. Although the humanist approach emphasises the importance of the students being able to take control of what they individually wish to learn and how to do this (to a certain extent), this does not often coincide with what happens in the classroom, as most of the sessions will take place in groups (Verial, 2010). This suggests that if humanism is followed completely, the discussions in the groups could veer away from the subject matter the teacher wants the class to focus on, or stick to the correct topic but accidentally share misconceptions with their group through these discussions (see Section 1.2.3.5 Social Constructivism).

1.2.3.5 Social Constructivism

Social Constructivism is the theory that ‘understanding, significance and meaning are developed in coordination with other human beings’ (Amineh and Asl, 2015, p. 13). This means that the student learns more information as well as developing the ability to communicate their understanding or topics where they feel they may need more support through working with other people (both peers and teachers) in order to construct a better knowledge base of the subject being taught. A key theorist in social constructivism was Vygotsky, who came up with the idea of the ‘zone of proximal development’, which was stated as “the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peer” (Shabani *et al.*, 2010, p. 238). In other words, this is an idea that there are three zones of a person's knowledge: one of what they already know or can learn by themselves, one where they could learn though they require guidance or assistance to do so (the zone of proximal development), and one which they could not attempt to learn yet as the scaffolding had not been created yet for the student to build upon (see Figure 1).

Figure 1: A figure to show the different zones of student's knowledge according to Vygotsky's Zone of Proximal Development. The zone of proximal development is shown as the middle ring in the figure. Adapted by the author from Janevski *et al.* (2013, p. 23).

Similarly to constructivism, misconceptions can potentially arise if students attempt to link the concepts being taught by either the teachers or their peers with the students' own understanding on this topic, and there is an incompatibility between the two (see 'conceptual misunderstandings' in Section 1.2.2 Accepted Definitions for Misconceptions Used in this Research Project above). This can also potentially lead to the students questioning whether their existing knowledge was correct (if their peers seem to be disagreeing with what the student believes), or creating a poorly constructed model based on all the information they are receiving from teachers and peers which may not be sufficient to answer any questions being asked.

1.3 PREVIOUS METHODS USED TO IDENTIFY MISCONCEPTIONS

Research has been ongoing for several years into identifying whether misconceptions are present and to use this research to develop teaching aids to help staff identify if/where students have these misconceptions. Time has been argued as one of the larger obstacles to teaching students effectively as teachers are not able to spend as much time as is needed helping students understand the importance of the lesson (Driver, 1983, p. 49). As such, different resources (e.g. questionnaires, interactive activities) have been developed to facilitate the identification of these misconceptions (Treagust, 1988, pp. 159-161; Peterson and Treagust, 1989, p. 459; Bethard *et al.*, 2012, p. 12), and have been refined over time.

1.3.1 Interactive Activities

There are a number of interactive activities that can be used by the teacher either inside or outside the classroom. An example of a technique that can be used for instant feedback of the class' understanding of a topic is the use of 'classroom response systems' or 'clickers' in the classroom (Sevian and Robinson, 2011; Keough, 2012). By integrating multiple choice questions into the classroom that students can anonymously respond to using the clicker, the teacher is able to see whether the students are able to answer the question, or whether more work is needed for the class to understand the correct answer (Keough, 2012, p. 831). This allows the teacher to gain real time knowledge of the class including: 'the progress of our students; readily identify their misconceptions; easily tell if they are struggling with concepts' (Sevian and Robinson, 2011, p. 14).

However, using the clickers in this way does have some disadvantages when trying to identify misconceptions. The main issue is that the students do not have the ability to ask the teacher clarifying questions while keeping their anonymity (as using the clickers allows the students to answer without the teacher knowing who gave which response) (Addison *et al.*, 2009, pp. 84-85; Bojinova and Oigara, 2011, p. 179). This means that the students may not feel comfortable asking for clarification if they were unsure about a particular question; students have stated they ‘liked clickers because they allowed them to participate in class while remaining anonymous’ as there was a reduced pressure when answering the questions (Bojinova and Oigara, 2011, pp. 172, 176-177). Additionally, even though high performing students have reported that using the clickers was beneficial for their performance as the students were able to identify where they were going wrong, potentially addressing their own misconceptions, lower performance level students were less satisfied with the use of clickers and the impact on their marks (Addison *et al.*, 2009, p. 84). Therefore, there is a chance that using the clickers will have different effects on different ability groups, though as research suggests the impact of using clickers in the classroom on performance is positive (Keough, 2012, pp. 825-828), this suggests that the benefits of using clickers in the classroom outweigh any disadvantages.

Another form of interactivity used to identify misconceptions is an ‘interactive tutor’ (Bethard *et al.*, 2012, p. 12). Though typically used for developing essay writing skills, and aiding teachers in providing formative feedback in the classroom (Ramaswamy, 2012, pp. 17-19) a specific interactive essay writing tutor was proposed and developed by Bethard *et al.* (2012, p. 12) to ‘[analyse] student essays for misconceptions and [recommend] science web pages that correct those misconceptions’. The model created by Bethard *et al.* (2012, p. 17) aimed to predict what conclusions students would come to given the information available to them, and also whether a ‘student sentence can be concluded from any combination of the sentences in the domain knowledge’ which would be evidence of conceptual understanding, whereas a sentence which could ‘not be concluded from the domain knowledge is likely a misconception’. In other words, if the student sentences were shown to link back to the domain knowledge (that being the initial information given to them), it was likely to be evidence of conceptual understanding, though a sentence which had no link back to the domain knowledge would likely be a result of external knowledge, and could indicate a misconception. By evaluating the model's ability to identify the misconceptions, it was found to be effective at both identifying the test misconceptions as well as suggesting resources relevant to the particular misconception at a rate higher than at random (32% rather than 9%) (Bethard *et al.*, 2012, p. 20).

However, although these initial results suggest that computer models could be used to both identify and correct students' misconceptions, there are still disadvantages. The major issue is that the computer program created was only in the testing phases and had not been applied to the real world environment, and as such would require a lot of time and resources to be adapted for real students' answers (Bethard *et al.*, 2012, pp. 14-15, 20; Ramaswamy, 2012, pp. 7, 66-68). Discipline specific programs would need to be developed and then used together in an integrated format in order for all misconceptions to be identified (as the programs perform better at identifying and suggesting resources in the 'domain that it was originally developed for, but poorer on more distant domains') (Bethard *et al.*, 2012, p. 20). This suggests that once interactive tutors are created to a high enough standard in the science subjects these resources could be valuable to quickly identify misconceptions and to point students to an area where they could discover the correct framework, though at the moment the online tutors are not advanced enough to be used in the classroom for the sciences.

1.3.2 Concept Inventories

There have been a number of pedagogical studies to try to evaluate the conceptual understanding of students at a number of different educational levels. An increasingly commonly used resource to evaluate the students' understanding in chemistry is the Chemistry Concept Inventory (CCI) (Undersander *et al.*, 2017, p. 45). Even though this report focuses on chemistry, it is worth noting that there have also been concept inventories for physics - labelled the Force Concept Inventory - which has been in use for a number of years (Savinainen and Scott, 2002, p. 45) and the Biology Concept Inventory which is currently being developed (The University of British Columbia, 2015). This suggests that there has been a desire to identify whether the students are learning concepts effectively across all of the sciences, and that there is not a particular science that requires extra analysis.

Chemistry Concept Inventories (CCIs) have been used for a number of years, first being put forward as a method of analysing students' conceptual understandings in 1996 (Mulford, 1996): the idea was developed, evaluated and the results were published in 2002 (Mulford and Robinson, 2002, p. 739). CCIs are multiple choice questionnaires which have been used to evaluate teaching and learning many times since their first publication, with a review of the effectiveness of the CCIs in education being carried out over a decade since its first application (Barbera, 2013, pp. 546, 548-552). The questions have been developed and evaluated many times via a number of methods to make sure that the questions could not be misinterpreted, including using interviews to identify potential misconceptions that are held by the students not covered by the questions (Krause *et al.*, 2004, pp. 1-5). The multiple choice questions in the CCI undergo rigorous testing multiple times as each question is evaluated to determine whether it can be utilised correctly in the CCI, with questions being replaced or reworded if it is determined to be unclear for the students 'until acceptable reliable results are attained' (Pavelich *et al.*, 2004, p. 3). Typically, CCIs are issued to test 'one topic or subtopic only', allowing the staff to understand and evaluate where the majority of the class's issues lie (Pavelich *et al.*, 2004, p. 3). Due to the specificity on only one topic, the questionnaire can also be designed so there can be a clear distinction between the students' performance (e.g. as a discrimination questionnaire to separate out different ability levels of 'good students and poor students') (Krause *et al.*, 2004, p. 2). Therefore CCIs can be used to identify where both individual and class wide misconceptions occur by looking at the questions with high discrimination scores (Krause *et al.*, 2004, pp. 2, 4).

Due to the fact that the CCI is comprised entirely of multiple choice options, theoretically this should negate any chance that the marker will have difficulty deciding how many marks should be awarded to an answer; there is only one correct answer. However, a risk of using a multiple choice questionnaire to test understanding is that hypothetically students could guess the correct answer without fully understanding the concept being tested (Peterson and Treagust, 1989, p. 460). This effect is limited slightly with the CCI being designed so that many of the questions are in pairs, with the first testing a concept, and the second asking for an explanation of the thinking behind the student's answers (e.g. *'What is the reason for your answer?'* followed by four potential answers which included distractor answers as well as the correct answer) (Mulford and Robinson, 2002, p. 742). By placing the questions in pairs also limits the effects of question order on the students' ability to answer the questions (Lund, 2013, pp. 29, 36), as the second question prompts the students to think about each set of questions rather than guessing an answer and moving on to the next concept. This structure of the questions potentially allows the marker to both evaluate where problem areas lie in the topics being tested (as these questions would have a lower percentage of students being able to answer these questions correctly). Additionally, this format can also assist a teacher in evaluating whether there has been a misunderstanding of the teaching, as all of the multiple choice answers could potentially seem sensible if there had been a misconception in the student's mind (see Appendix 1: The Chemistry Concept Inventory Issued to all Students).

SECTION 2: RESEARCH QUESTIONS AND AIMS

Due to the strong evidence of chemical misconceptions being present at various educational levels (Driver, 1983; Treagust, 1988; Peterson and Treagust, 1989; Metcalfe, 1996; Park and Light, 2009; Gonzales, 2011; Papageorgiou *et al.*, 2016), the main aim of this research is to ascertain the extent and cause of conceptual chemical misconceptions in the classroom and whether they can be rectified within the curriculum.

This main aim can be broken down into several different research questions to explore potential factors to students' misunderstandings of key chemical concepts in Atomic Structure and Bonding:

2.1 ARE TEACHERS INFORMING STUDENTS OF THE CONCEPTS BEING COVERED IN EACH LESSON/ARE STUDENTS AWARE OF THE CONCEPTS BEING COVERED IN THE CLASS?

Due to the different constraints involved with the teaching process as stated previously, the lack of time is most commonly the reason that teachers are unable to effectively evaluate whether the students have fully understood the topic being taught (Driver, 1983, p. 49). Therefore, it is up to the teacher to be mindful of whether the students are actually informed of what is being taught, the importance of what is being taught, and the distinction between different aspects (facts, skills and concepts) that the teacher is implementing in regards to which would be the most effective for the students' learning (Téllez, 2018). These are defined by Téllez (2018) who states that facts are 'verifiable pieces of specific information' e.g. that electrons have a negative charge, concepts are 'a much broader, deeper type of knowledge' which 'involve relationships or processes' e.g. a group of rules that can be applied to understand other situations, such as atomic structure and skills are 'a type of learning that gets better with practice' e.g. how to approach a problem solving question. This means that students can learn facts within a particular concept, but cannot learn concepts within facts, though concepts can be applied to help explain facts.

If the teacher is not aware of the difference between facts and concepts, or does not explicitly state the difference to the students, the students may fail to be able to generalise their factual knowledge to different situations as facts are specific to the context that they are taught in, and cannot be applied outside of that context easily (Téllez, 2018). Additionally, conceptual understanding allows the student to understand why the topic or lesson is important, and suggests a deeper understanding of the overall topic as concepts can be generalised to many different scenarios as they are not context specific. Therefore, if the teachers believe they are teaching concepts, but instead teaching facts, the students may fail to apply similar principles to other situations (Ehrenberg, 1981) which could potentially explain why some students struggle with exams as different questions are being tested.

Therefore, it could be argued it may not be as important that the student understands they are learning concepts compared to whether the teacher is aware they are teaching concepts rather than facts. However, if a student is not aware of the difference between concepts and facts, they may have difficulties working out why some "facts" they learn are generalisable to different situations (actually concepts), whereas others are not (actually facts). This can cause issues in exams if the student has to answer questions that are not exactly like they have encountered before as they may unsuccessfully attempt to apply facts to different contextual situations. Consequently, it is important that students understand what concepts are being taught, and the importance of being able to apply these to other situations in the subject which may not have been addressed in the lessons when the concept was originally taught.

2.2 Do teachers aim to identify and rectify misconceptions in the classroom?

As the teacher has many different students in their class at once, it is essential that the teacher first identifies what level of understanding the students have. If the teacher does not follow this step, the teacher may accidentally overlook issues that the students could have; each student may have a different understanding of the topic being taught prior to the lesson. If the class does have multiple different understandings of the same topic (or there are misconceptions in the class) it may be a lot harder for the teacher to be able to effectively teach the whole class at the same time without addressing these misconceptions (National Research Council, 1997). This means that if the teacher makes no attempt to identify whether the class has any misconceptions at any point in the lesson, it may lead to further misconceptions for the students (partially dependent on the learning theory being applied by the teacher in the lesson – see Section 1.2.3 Current Theories about Learning and Potential Implications for how Misconceptions May Arise). Therefore, it is important for the teacher to analyse whether there were any misconceptions in the class to begin with, and then to work on rectifying them.

Similarly, even if the teacher is attempting to identify whether the students in their class have misconceptions, if the teacher is not attempting to rectify these, this could also be detrimental to the class. Although the teacher is aware of the misconceptions in the class, if the teacher does not try to rectify these before teaching another topic this could mean that the students are left with more misconceptions at the end of the lesson; both introduced from the new topic and their original misconceptions remaining. However, if the teacher is attempting to rectify the misconceptions of their class, it is important that the attempt to rectify the misconceptions does not unintentionally introduce any more misconceptions to the students. For example, if the teacher identifies that there is an issue by a student giving an incorrect answer to a question, and the teacher attempts to rectify this by merely stating the correct answer to the question, this is still not tackling the root cause of the misconception. Even though the teacher may be able to teach the student the correct response to the question being asked, the student may have only learnt how to give the correct answer to that particular question and does not fully understand why that answer is correct. This suggests that the teacher may be attempting to rectify the misconception by teaching the student facts rather than the concept which, as stated previously, could cause problems for the student when attempting to answer exam questions which are not the same as the one posed in the class by the teacher as the facts are not generalisable to different scenarios.

On the other hand, if the teacher is attempting to rectify the misconceptions by teaching the students the process behind both why their answer was incorrect, and also explaining the concept fully, this could be a better method of rectifying misconceptions in the students' minds. For example, the teacher could use a variety of different questions in varying scenarios, or use multiple models when explaining the concept to show how the concept can be applied in different contexts, and be utilised in different ways rather than only being relevant in a specific circumstance. If the teacher is making an attempt to both identify the misconception that the student has, as well as address to the student why their misconception is not an accepted way of tackling the question being posed or cannot be applied in varying scenarios, this may effectively tackle any preconceived misconceptions the students have before the teacher attempts to teach any new content. Additionally, the teachers should analyse whether the students have any misconceptions after the topic or lesson, and if so, again an attempt at rectifying the misconceptions should occur as soon as possible to reduce the chance that the misconceptions continue into other levels of education; e.g. A Level, degree level and potentially even higher. Therefore, it is important that the teachers aim to both identify and rectify any misconceptions that the students may have, and to do this both before and after the lesson in order to prevent any misconceptions from continuing unopposed.

2.3 What techniques/resources do teachers use to illustrate and explain concepts?

Teachers are able to use many different techniques and resources to illustrate and explain any concepts they are teaching to the class in an effort to make the content easy to understand by all of their students. These resources can vary from one teacher to another, and which are used depends a lot on the class being taught as the different experiences in the class may affect which resources may be the most useful for the students. However, previous research has shown that some methods of teaching or resources used by the teachers could end up accidentally introducing misconceptions into the students' minds (in the worst case) or confuse the students more.

Research carried out by Cherif *et al.* (2015) suggests that if a teacher uses analogies that the students do not understand, the students could end up more confused after the introduction of the story as the students have to come to their own understanding of what the teacher means by the analogy and how that can be applied to what the teacher is meaning in this instance. This means that the students have to make two assumptions when attempting to understand the concept; firstly, what the concept is that the teacher is trying to teach, and secondly, how this concept is applied in the analogy the teacher is describing.

Additionally, if the teacher is relying too heavily on a resource that is inherently flawed (e.g. a textbook with a mistake in it) and this mistake goes unnoticed or the students are not made aware of this by the teacher, this could introduce further misconceptions into the students' minds as they have to decide how the mistake in the resource matches up with the information that the teacher is saying. Furthermore, some textbooks have been written with mistakes, and then these mistakes have been copied by other textbooks (Young, 2012), suggesting that some mistakes may have accidentally been accepted as fact across many generations as well as in different countries. For example, the number of mistakes in textbooks has now reached the point where some teachers are rejecting some textbooks; Kenyan secondary school teachers found multiple issues in a variety of textbooks including STEM subjects and have refused the new books due to concerns that 'using these books may cause damage to learners either through omission of some content or overload' (Oduor, 2018). Additionally, a two year study carried out across middle schools in America discovered that 'none of the 12 textbooks [that the researchers looked at] has an acceptable level of accuracy' which suggests that there is a widespread issue about the accuracy of the information in the textbooks that students are using to learn from (ABC News, 2006). This is further evidenced by the multiple different instances that people have discovered mistakes in the textbooks over multiple years; these mistakes have been found both in science textbooks as well as in science exam papers throughout the years (Elgot, 2015; Pells, 2017; TNN, 2018). This issue with the exam papers containing mistakes will be discussed further in Research Question 5 (Section 2.5).

Therefore, it is important to analyse which techniques and resources are being used by the teachers in order to critique whether these methods or resources utilised could accidentally be introducing any additional issues into the students' understanding.

2.4 Do the concepts that students find important or essential for answering questions correlate with what is covered in the lessons?

For a student to be able to apply the concepts being taught in the classroom to different scenarios, the student firstly has to be aware of what the concepts are. If the students are not fully aware of the concepts being covered in the lesson, then this could cause more issues when the students are trying to apply these concepts to other situations (see Section 2.1 Research Question 1) as the students cannot be expected to fully understand the concept and work out why the procedure being applied works (Biggs, 1999).

However, assuming that the students do understand the concepts being taught in the classroom, if the students are not able to draw out these concepts in other situations outside of the classroom (e.g. in an exam setting) then the students may not have fully understood the use and application of the concepts (Millar, 2004). This stance is reinforced by a report done by Atkin (1968) cited in Millar (2004, p. 16) where it is stated: "There seems to be no explicit recognition of the powerful role of the conceptual frames of reference within which scientists and children operate and to which they are firmly bound.” This suggests that students are being taught these scientific concepts in an isolated situation, and as such may not be able to fully appreciate or understand how these concepts can be applied to different situations, or which concepts should be drawn upon to answer questions which seem similar in content to what was covered in the lesson.

Additionally, it is important to identify what the students believe are concepts, and whether these concepts have been taught in the class or have been uncovered by the students outside of the lesson via their own knowledge or work outside the classroom. Research carried out by Condon (2017) looking at when students were using their digital resources suggests that students are working for many hours outside the classroom, both in the evenings and weekends. Homework is aimed to support the subject matter taught in the lesson, and as such ‘homework for secondary students consolidates the key concepts covered in the classroom’ (Silvester, 2017). Silvester (2017) argues that the homework helps the students to ‘[increase] the likelihood of a student remembering and being able to use those skills in a variety of situations in the future’, which is a key component of a concept (the ability to apply it in a variety of situations rather than it be fixed in a specific context). This means it is potentially possible for the students to discover different concepts, or even decide which concepts are most useful/applicable to different questions outside of the classroom when doing their own research when attempting to answer homework questions.

Therefore, it is important to analyse whether students are able to identify concepts outside of the lessons in order to work out whether students are both aware of what the concepts relating to the topic of atomic structure and bonding are, as well as whether they can draw upon the concepts outside of the lesson (which would indicate the students have understood the concepts being taught as important outside of the classroom context).

2.5 Are students able to answer questions testing conceptual understanding in different circumstances (for example when asked questions not in the typical exam style)?

For a student to fully understand a concept, they must be able to apply the concept to a number of different scenarios, not just the examples given in the classroom when teaching the concept to the student. If a student is rote learning, or learning how to answer exam questions (though not understanding why the answers they give are correct), the student may struggle later on when answering questions which are not in the same format as the examples given in class.

Previous research suggests that rote learning for exams will be disadvantageous in the long term, as students fail to fully understand the science behind why their answer in the exams was correct, and so struggle to apply their knowledge to different situations (Frey *et al.*, 2017), even if the short term results of a good grade in the exam are positive. Frey *et al.* (2017, p. 1185) looked at the difference between two groups of students; 'abstraction learners' who 'focused on learning the functional relationship among points' and 'exemplar learners' who 'focused on learning the individual input-output pairs'. Despite the students' previous chemistry ability, Frey *et al.* (2017, p. 1185) found that the 'abstraction learners' had been able to '[extract] underlying principles, encouraging a relatively deep understanding of content', whereas 'exemplar learners' had '[failed] to learn the functional relationship; consequently, these students could not successfully solve novel inputs'. Therefore, this research further evidences that students who have conceptual understanding will outperform rote learning students, suggesting that by teaching students the benefits of linking different ideas together rather than relying on rote learning may aid in their ability for deeper conceptual understanding. However, research carried out by Oloruntegbe and Ikpe (2011, p. 268) by a survey across 10 Nigerian government secondary schools suggests 'the inability of a significantly high percentage of students to relate chemistry concepts learned in school to home activities' although there was an 'emphasis placed by school curricula on connecting science to students' everyday life experiences'. Therefore, this research suggests that even with an emphasis on creating links for the students in the school curriculum, some students may struggle to come up with these links without additional assistance, and so an effective method of testing and reinforcing conceptual understanding must be used.

The method of testing conceptual understanding is different to testing facts as 'concepts cannot be verified, like facts, as being "right" or "wrong"' (Ehrenberg, 1981, p. 39). As stated earlier in Research Question 1 (Section 2.1), it has been suggested that for students to fully understand concepts, rather than learning facts, the students should be able to apply the principles they have learnt to different contextual situations (Téllez, 2018). Additionally, in the past, certain mark schemes for exams require exact wordings of the students' answer in order to award the marks to the student, even if the student had given a correct description of the scientific term required. For example, the 2016 Edexcel GCSE Chemistry Paper Mark Scheme states '**Ignore** descriptions of photosynthesis –term is required' (Edexcel, 2016). This stating of requiring the exact terminology in exams (though it does seem to be less frequent in recent years) could incorrectly suggest that the student does not understand the concept as they are not putting down the exact terminology despite the student being able to describe the concept being tested. In order to evaluate whether the students have understood the concepts, these concepts should be tested in a number of different scenarios. Furthermore, by changing both the format and context of the questions, the students are required to ‘transfer knowledge to new situations’, aiding their conceptual understanding (Silvester, 2017). This means that varying the mode of assessment should aid in identifying whether the students have fully understood the concept, without the strict restrictions of anything the students ‘must’ mention to show understanding; with the exception of definitions.

Therefore, it is important that the students are able to link in the concepts they are learning into other scenarios outside of the classroom to show conceptual understanding has taken place as they are able to apply their understanding to a variety of different situations, rather than the student simply learning how to answer exam questions correctly.

2.6 Are students able to see links between different chemical concepts and use a combination of concepts to tackle difficult questions, or are the concepts kept separate in their minds?

In order for a complex chemistry question to be answered effectively, it is possible that a number of different chemical concepts are needed. As most curricula aim to build or expand on the students’ knowledge from the year before, it is important that the students are aware of how the knowledge from each year builds upon their pre-existing knowledge, and also what other concepts can be called in where relevant.

Previous research suggests that prior knowledge (both academic and personal) is important as 'learning ultimately begins with the known and proceeds to the unknown' (Campbell and Campbell, 2008, p. 11), which also reinforces the importance of teachers recognising the students' level of knowledge before teaching (see Section 2.2 Do teachers aim to identify and rectify misconceptions in the classroom?).

Kiliç and Çakmak (2013) argue that 'meaningful learning occurs when complex ideas and information are combined with students' own experiences and prior knowledge to form personal and unique understandings'. This suggests that not only do students need to understand links between the different topics being taught in the classroom, but also how these different concepts can be related to their everyday lives. The linking of knowledge to other scenarios suggests deeper understanding of the concepts (Frey *et al.*, 2017), and can aid students in tackling much more complex questions in situations that the students have never seen before (see Research Question 5, Section 2.5).

Therefore, it is important for students to be able to see links between the concepts being taught to both deepen their understanding of the subject content, as well as to be able to identify which concepts may be applicable to a variety of different situations outside of the normal exam style questions.

As there are many different research questions being investigated in this research, a number of research designs will be utilised in this project.

SECTION 3: METHODOLOGY

This research was proposed as a follow on from previous research carried out by the author to investigate chemical understanding at an undergraduate level (Smith, 2016), though this time carrying out more in depth research investigating conceptual chemical understanding at the school level. Although this research project is a case study, the proposal and methods were planned so that the procedure can be replicated across different classes and schools in the future to evaluate the results collected in this study. Ethical approval was granted by the University of Birmingham Ethics Committee before this research project started with the reference number ERN_18-0072; the full ethics approval form for the proposed research plan is attached as Appendix 6.

The research design chosen for this research is a mixed methods approach. By combining three research designs (a pre-post questionnaire, classroom observation and interviews where the participant creates a concept map), the results gathered allow for a more in depth approach to understanding how and when misconceptions are introduced. Furthermore, by using a range of different methods in this study, it allows for methods triangulation to occur to support any findings gathered; which is the expected norm in fieldwork research (Denzin, 1970, pp. 471-475; Patton, 1999, p. 1192). Additionally, the research here primarily follows an inductive approach (Dudovskiy, 2018), with any hypotheses being theorised after the initial questionnaires have been completed by all of the participants and being verified in the interview stage of the research.

An inductive approach was utilised in this research project to attempt to limit both confirmation bias and unconscious bias held by the researcher as this project follows on from a previous project. As using an inductive approach allows for the direction of the study to change after commencing the research, using this approach provided more freedom to alter and edit the research questions should the data suggest other potential routes to investigate (Dudovskiy, 2018). Seeing as the research should be as objective and unbiased as possible, it is important the data gathered is not being collected to confirm any previous results, but instead to gather data and see what patterns emerged, and to compare these studies only after the analysis has been carried out (Blackstone, 2012). Although there may be a risk of confirmation bias if the researcher actively sought out other data to match up with any theories developed from the data gathered using an inductive approach, there is a reduced risk of this occurring if the researcher alternates between developing theory and hypothesis (e.g. inductive then deductive) which is applied in this research project (Fforde, 2016, p. 14). Therefore, as previous research carried out by the author had suggested a potential area of interest, it was essential that there were no expected results; the data gathered would be analysed as if there had been no previous research in this area, and as such an inductive approach was important to limit the chances that data confirmation bias is present.

3.1 Creation and Use of the Chemistry Concept Inventory (CCI)

The CCI used in this project was developed by looking over previous questionnaires used to identify chemical misconceptions (Nurrenbern and Pickering, 1987; Peterson *et al.*, 1989; Williamson and Abraham, 1995; Mulford, 1996; Mulford and Robinson, 2002; Taylor, 2013; Smith, 2016). As Atomic Structure and Bonding had previously been identified as a common problem area for students at many different educational levels (see Section 1.1.1 Research into Atomic Structure and Bonding as a Problem Area), the CCI was created specifically to test this topic. This CCI covered four subtopics: Stoichiometry (Question 1 and 2), Electronegativity (Questions 3 and 4), Valence Shell Electron Pair Repulsion (VSEPR) Theory (Questions 5 and 6) and Polarity (Questions 7-10). This CCI is mainly concerned with investigating Research Question 5, though the information gathered from these questionnaires also factors into Research Questions 4 and 6. 10 multiple choice questions were selected from the previous publications to investigate various aspects of this topic (see Appendix 1: The Chemistry Concept Inventory Issued to all Students). The questions were not selected in any particular order, apart from questions which were in two parts being placed together; first part asking for a specific answer, and the second being *'What is the reason for your answer to the question above?'*. Each CCI was coded so that the participants' identities would be kept confidential, though the CCI could be issued or referred to as many times as wanted while being able to track the participant to their questionnaire between the various stages of this study.

For the case study of one school, the questionnaire was only issued to the students to fill in once (at the start of a revision session), though the students were asked to keep track of their codes for the interview portion of the research. Participants were informed of the time limit and instructions for completion before the questionnaire was issued, but no other information was given by the researcher while the participants completed their questionnaires. All tests were marked by the same researcher. The results of the questionnaires are used for context in the interviews; the third stage of the research project, and so the advantages and limitations of a pre/post questionnaire are applicable here.

During the interview stage, the students were asked to explain their original answers shown on the questionnaire, and were allowed to change their answer if they believed that they had made a mistake. If the students were incorrect with their original response, the interviewer asked prompting follow up questions. If the student still was unable to come to the correct answer, the interviewer explained the science behind why their answer was wrong before giving the student another opportunity to answer the question (repeated as many times as necessary). All changes to the students' answers were noted on the interview sheets in a different colour or on the interview schedule by the interviewer to see if any changes had occurred either before or after prompting by the interviewer (see Section 3.3 Interviews).

3.1.1 Evaluation of Using the Multiple Choice CCI Compared to Other Questionnaire Types

As stated in Section 1.3.2 Concept Inventories and Section 3.1 Creation and Use of the Chemistry Concept Inventory above, the questionnaire used in this research is entirely multiple choice. Using a multiple choice questionnaire has many advantages over open ended questionnaires for this research, principally that there is only one correct answer; there is no issue over whether marks are allocated for answers which are close to the expected or model answer, but are not exactly what the marker had in mind (Ekbatani, 2011). This would also allow for the marker to easily compare the pre/post responses from a student as there is no ambiguity as to what the participant has answered both times, helping to evaluate whether there has been a change in the students' responses.

Secondly, by providing the students with options to choose from rather than making them create their own answers, the time taken to compete the tests is much shorter for multiple choice questionnaires (Bacon, 2003, pp. 31-33, 35). This allows for the multiple choice questionnaire to be more suited for this project as it will be less obtrusive to the teachers and students who are participating in this project as it will not intrude for as long on the lessons.

However, there are limitations to using multiple choice questions to evaluate a student's understanding. Burton *et al.* (1991, p. 5) state that as the options are presented to the students, these types of questionnaires are 'not adaptable to measuring certain learning outcomes' which are highly explanatory in nature. This is supported by arguments stating that these questions 'cannot assess learners abilities to work at problems or projects over a protracted period of time' (Welsh Assembly Government, 2010, p. 8). However, as the questionnaire is being issued twice in a pre/post method, with interview questions asking the students to explain their answers during the second time the questionnaire is issued (see Appendix 1 and Appendix 3), this should help reduce these limitations slightly.

Additionally, there is a chance that a participant could guess the correct answer to all of the questions on the test (Higgins and Tatham, 2003, p. 4). However, despite the chance that a student could guess the correct answer to all of the questions without any prior knowledge, the chance of this happening is reduced by increasing the number of questions on the test and how many options are given for each question. For example, if the test consists of questions which comprise four answer options, the chance of someone scoring at least 70% just by guessing is 1 in 16 for a two question test, but is 1 in 285 for a 10 question test (Burton *et al.*, 1991, p. 6). As the CCI created for this research comprises 10 questions with an average of four options (mean of 3.8 options per question), it is unlikely that chance will substantially affect the results gathered.

When evaluating the effectiveness of multiple choice questionnaires, research conducted by Bridgeman (1993, pp. i, 24) on comparisons between open ended questions and multiple choice questions (specifically for a quantitative section on a test) suggested that 'total scores for the multiple-choice and free-response tests demonstrated remarkably similar correlation patterns', despite the fact that for individual items 'there were striking differences between the open-ended […] and multiple-choice formats'. This suggests that when generalising the students' results across different schools and classes (rather than only evaluating one class), the inclusion of multiple choice answers is not a distracting factor for the higher performing students as the higher performing students are likely to be ranked higher whether or not the questions are multiple choice. However, as this CCI is not being used to test the students' ability, but more to identify areas in which there are potential misconceptions in the class, the raw score that the students obtain is not as important as the reasoning behind their answers (right or wrong) and so this score is also used for context in the interview part of this study.

Therefore, by taking into account the advantages and disadvantages of using multiple choice questionnaires, for the purposes of this research, they are the most effective question format to use when evaluating the change in the students' knowledge.

3.2 Classroom Observations

In order to gain a better understanding of how the topic of Atomic Structure and Bonding is presented and taught to the students who were participating in the research project during lessons, a classroom observation took place on a session covering Atomic Structure and Bonding to see how the teacher interacted with the class. This observation was used to investigate Research Questions 1, 2 and 3, as well as to give context for Research Question 4. An observation schedule was created by the researcher to limit the degree of observer bias as relevant criteria were observed before the session took place (see Appendix 2). The observation schedule is split into four sections: Background (which is concerned with exploring Research Questions 1 and 4), Planned Resources (which is concerned with Research Question 3), Teacher Interactions (which is concerned with Research Questions 2 and 4) and Other Notes. These four sections allow for the recording and investigation of what was covered in the classes so that when marking the CCIs, the researcher can evaluate whether there should be any change in the students' results, as well as being able to record the content covered by the teacher for reference or clarification in the interview phase of the project.

3.2.1 Effectiveness of Classroom Observations

Classroom observations can be used for a number of different reasons, such as evaluating teaching ability and providing feedback on how the teacher can improve their methods, or detailing what happens in the classroom using an observation schedule (which is the main purpose of the observations carried out in this project; see Appendix 2) (State University, 2011).

Using observations in the classroom has a few different advantages when used for research. Firstly, by having a researcher in the room observing the class teacher means that there is a more detached and external view of the classroom as the researcher is using an observation schedule to evaluate what is happening in the classroom rather than relying on the teachers' self-reflection on the lesson afterwards. This allows for a 'more reliable measurement of […] behaviour rather than self-report metrics' as the evaluation is carried out in real time rather than the teacher trying to remember exactly what happened in the classroom as their focus will be on their teaching (The Upfront Analytics Team, 2015).

Additionally, the observer can look for anything which may not be classed as important by the teacher as the teacher may classify something as not worth reporting to the researcher, but is important for the researcher in the context of the research (The University of Sheffield, 2014). This means that by the researcher being present in the session, there is a higher chance that the observer will be able to gain an overall view of the lesson, and to write down information that they view important even if the teacher may not view the same information as important to report. This allows the researcher to gain a 'real-world perspective' to reduce any unconscious bias that the teacher introduces by not fully reporting everything of relevance that occurred during the lesson (The Upfront Analytics Team, 2015; Steber, 2017b).

However, there are also disadvantages to using classroom observations. The classroom observations only look at a particular lesson or set of lessons, meaning that what is observed in the classroom for those lessons may not be accurate to the teachers' techniques over the whole subject (e.g. they may use different techniques to teach the topic being observed compared to another topic) (Wile, 2011). This is particularly relevant if the teacher knows the lesson will be observed, as there is a risk of the teacher preparing a lesson specifically for the observer which is not truly accurate to what would happen without the observer there (Stigler *et al.*, 1999, pp. 6, 14). On the other hand, as classroom observations are common as a formative and summative assessment to develop teachers' skills (Lengeling, 1996, pp. 15, 17-18), there is a reduced risk of this occurring as the teachers will have experienced observations in the past and so will be less likely to develop a new plan specifically for the research. Additionally, authors discuss the importance of using observations alongside other research methods in order to triangulate the results due to findings discovering 'what teachers say they believe and what they actually do in the classroom can be very different things' (Wile, 2011; Schoenfeld, 2013, p. 619). This means that the results gathered from the classroom observations will be used in tandem with other techniques which could reduce the risk of the observational results being affected.

Furthermore, as well as deliberate changes to the teachers' behaviour occurring due to knowing the observations will be happening, there is a chance of unconscious changes to the way the teacher (and potentially the students) behave in the classroom purely due to the presence of someone else in the classroom (State University, 2011). However, this potential change in behaviour of the students and staff is due to anxiety about their performance being assessed (The University of Sheffield, 2014). Consequently, this anxiety can be reduced slightly by reassuring all participants that the research project is not evaluating their abilities in the classroom, but is being used to provide context for the other research methods utilised.

The researcher can also have observer bias, defined by Mahtani *et al.* (2018, p. 23) as 'systematic discrepancy from the truth during the process of observing and recording information for a study' as they observe the lesson as their point of view, and a different observer could record different notes. However, as stated earlier, an observation schedule was created before any observations were completed (see Appendix 2: The Observation Schedule Used in this Research) to try to provide structure to the observations and increase objectivity by not participating in the session apart from taking notes. Although Sapsford and Jupp (2006, p. 87) argue that using an observation schedule may introduce more bias into what is observed as the 'preconceived categories of an observation schedule may be unsuitable or inadequate for describing the actual nature of the behaviour that occurs', no presumptions were made that the categories were an exhaustive list, hence the inclusion of the 'Other Notes' section. This means that although observer bias will be present, steps have been taken to limit any preconceived ideas about what would be observed in the lesson and so the impact of this observer bias is reduced.

Therefore, although there are many disadvantages to using classroom observations as a research technique, as the observations are being used alongside other techniques (and are used primarily as a reference for what happened in the classroom in case students mention any teaching techniques in the interview), the classroom observations can be used effectively in this research.

3.3 Interviews

The final phase of the research project was individual interviews with volunteers from the student participants who completed the CCIs earlier on in the project. All interviews were completed outside of lessons, with the student's Chemistry teacher not being involved in the interview to relieve any pressure the student might have been feeling, and lasted 30 minutes. These interviews were concerned with Research Questions 4, 5 and 6, with the various sections of the interview being related to different research questions. The interviews were tailored to the students (see Appendix 3), as the second part of each interview included interview questions specifically on the CCI questions that the student could not answer at all e.g. by leaving the question blank without circling an answer where applicable, followed by questions the student answered incorrectly, then finally questions that the student could answer (these interview questions are related to Research Question 5). Individual interviews were carried out rather than group interviews in order to be able to tailor the interviews to the individuals, and to increase the chances of hearing all participants' thought processes rather than having a potential issue where participants would not feel confident sharing their thought processes if these differed to that of their peers which could skew the data obtained. The first section of the interview included the creation of a concept map (related to Research Question 6; discussed further in Section 3.4 Using Concept Maps), as well as direct questioning on what concepts the students found were important and which concepts were needed to answer the different questions on the CCIs (which relates to Research Question 4). The same questions were issued to all students with the exception that the questions being referred to on the CCI were tailored to what the participants managed to answer correctly or incorrectly (See Appendix 3). If the participants were achieving an incorrect answer on the CCI the same prompt was used; praising the thinking or methodology that was correct first, and then using the phrase 'However, that is not the right answer for this question because [an explanation of why their reasoning was incorrect was given here]. Knowing that information, what answer would you select to answer the question and why?'. By using the same broad interview schedule on each participant, and only altering questions about the CCI in the interview, there is a possibility for common themes across pupils (and schools if this research project is continued in the future) to emerge about both the whole topic of Atomic Structure and Bonding as well as a deeper understanding of how students approach each individual question.

In this case study, 9 students agreed to take part in an interview out of the 11 who completed the questionnaire, meaning that there was a very high representation of the students' opinions being evaluated in this part of the project. All participants were given the information sheet relating to the interviews (see Appendix 4) before the CCI had been issued, and were allowed to change their minds about their willingness to participate up to two weeks after the interviews had taken place. An opt-in and signed consent approach was used at all stages, including a separate consent form to participate in the interviews; all consent forms and information were issued on the day of the CCI completion, and reissued and shown to the participants prior to the interview. Although using this opt-in approach introduces self-selection bias as the pupils are choosing whether they want to be participants in the interviews as stated by Olsen (2011), the number of interviewees shows a high representation of the participants who completed the CCI as only two student participants did not participate in the interview stage of the project.

3.3.1 Evaluation of In-Depth Interviews

There are many different types of interviewing methods which can be used in varying situations, though for this research project individual interviews will be used. Oppenheim (1992, p. 65) states that there are essentially two kinds of interviews: 'exploratory interviews' and 'standardized interviews'. For this research, exploratory interviews are used as these 'develop ideas and research hypotheses rather than to gather facts and statistics' unlike the standardized interviews which are normally used in large scale surveys (Oppenheim, 1992, p. 67).

Exploratory (or in-depth) interviews are useful for being able to explain the reasoning behind participants' responses and can collect much more detailed information than other types of data collection methods (Boyce and Neale, 2006, p. 3). Additionally, using an in-depth interview rather than a standardized interview allows for the interviewer to adapt to the participants' answers e.g. to ask follow up questions, or request clarification (Steber, 2017a). This flexibility also allows the interviewer to make the interview questions more accessible for the participants, e.g. to reword or explain a question that the participant did not understand (Alshenqeeti, 2014, pp. 40, 43). These adaptations allow for exploratory interviews to have fewer incomplete answers than other methods of data collection, with a higher chance of answers being reflective of the questions the researcher is truly asking as there is a reduced chance of a miscommunication between the researcher and the participant (Alshenqeeti, 2014, pp. 40, 42-43; Morris, 2015, pp. 5-7).

Therefore, interviews are commonly used alongside quantitative research methods (e.g. questionnaires) to better understand the participants' reasoning behind their questionnaire answers (Boyce and Neale, 2006, pp. 3, 8; Brinkmann and Kvale, 2015). This means that by using the mixed methods approach of conducting interviews alongside the questionnaire will allow for increased validity as the participants will be able to articulate their thought process, rather than the researcher inferring what the participants may have thought (Zohrabi, 2013, pp. 254, 259).

However, there are some limitations with using the exploratory interview in this research. Firstly, the sample size for the interviews is small compared to the population as it would be unfeasible to interview all AS Chemistry students, meaning that any conclusions made using the small sample will not be generalisable to the whole population of all AS Chemistry students across the country even if apparent patterns begin to emerge (Boyce and Neale, 2006, p. 4; Morris, 2015, p. 7). On the other hand, many authors report reaching saturation in a relatively small sample. Guest *et al.* (2006, pp. 61, 76, 79) state that for a homogeneous population, saturation could occur within 12 interviews, though they do argue that this is not a definite number to reach saturation as many factors could affect the saturation point. This suggested saturation point is similar to that posed by Francis *et al.* (2010, pp. 1234, 1241) of 13 or 14 interviews, though this number is based on their criteria for saturation; 'after 10 interviews, when three further interviews have been conducted with no new themes emerging, we will define this as the point of data saturation'. Furthermore, Marshall *et al.* (2013, pp. 15, 20) reviewed 83 qualitative studies (in information systems) to evaluate the 'number of interviewees, interviews and length of interviews' and suggested that 'single case studies should generally contain 15 to 30 interviews'. At the lower end of the spectrum put forward by Marshall *et al.* (2013, pp. 19-20), all three of the studies listed above recommend fewer than 20 interviews to reach saturation. Although the number of interview participants is slightly lower than these recommendations (9 out of 11), there is a high proportion of participants who agreed to interview. Therefore, even though the results will not be generalisable to the whole population, the results gathered by the interviews should be sufficient to create reliable assumptions for the data set (Mason, 2010, p. 4).

Additionally, as the interview is being conducted face-to-face, there is always an element of bias in the results as the participant may not fully explain the answers to the question that the interviewer is asking (Morris, 2015, p. 7). This can either be deliberate or subconscious as the participant either deliberately withholds information, or does not realise that they are not fully answering the questions being asked. Furthermore, if the questions that the researcher is asking are unclear, there is a possibility that the participant will not be able to answer them the way that the researcher intended, further adding bias into the results (Ziniel, 2014, pp. 14-16). However, these elements of bias can be reduced by a number of factors. Although subconscious bias is almost impossible to remove altogether as the participant is unaware that they are introducing the bias into the results, the deliberate source of bias can be reduced by training the interviewer properly to develop methods to overcome this. If the participant is deliberately not answering the question being asked, the interviewer must identify what the possible cause of this obstructive behaviour is, and then attempt to deal with that appropriately. For example, Ziniel (2014, p. 16) states that if the participant is unwilling to answer the question, the interviewer may simply need to reassure the participant about the confidentiality of their answers, or restate 'the importance of the research and how important their participation is'. Also, as mentioned earlier, in-depth interviews allow for the interviewer to clarify any questions which may be confusing for the participant meaning that the possibility of adding in bias through unclear questions is reduced for the exploratory interview over the standardised interviews (Alshenqeeti, 2014; Steber, 2017a, pp. 43-44). These simple techniques can help reduce the deliberate bias as the participant becomes better informed about the importance of the research as well as what exactly the research is about, so they are less likely to be deliberately obstructive if they have volunteered for the study.

Therefore, despite the disadvantages that exploratory interviews have, as these interviews are being used in a mixed method approach, the ability to gather in depth information to explain the participants' answers to the questionnaire outweighs the disadvantages for this research.

3.4 USING CONCEPT MAPS

During the interview, the participants were asked to develop a concept map on the topic of atomic structure and bonding. The process of creating the concept map was explained twice to the students; firstly written down in the Interview Information Sheet (Appendix 4) issued to all participants, and then explained orally in the first three interview questions (see Appendix 3).

The process of the formation of the concept maps broadly followed the steps stated by Trochim (1989, pp. 2-14):

'1. Preparation' which comprises selecting the concept to be used to make the concept map (in this case this was Atomic Structure and Bonding) as well as choosing the participants who will be constructing the concept map (the participants who agreed to be interviewed, though they were interviewed individually rather than as a group).

'2. Generation of Statements' which is where the participants begin to develop ideas of what may be related to the chosen concept in a mind mapping activity, without evaluating these ideas.

'3. Structuring of Statements' which is where the ideas the participants have generated are analysed by the participants to develop links between their ideas so they can begin to relate ideas to each other (the participants were prompted to think of links by the researcher if necessary (see Question 2 in Appendix 3)).

'4. Representation of Statements' where the physical form of the map starts to be created, with the ideas and links between the ideas being recorded on paper (though this layout can change in the next couple of steps).

'5. Interpretation of Maps' where the main group of ideas is analysed and labelled based on common themes to show whether there are many different branches of ideas relating to the central concept or whether there is only one large group of ideas - these can be divided into subgroups as well if needed. The participants have to determine 'whether they make sense and what they imply about the ideas which underlie their evaluation or planning task.' This was partially prompted by the interviewer by asking the participants to explain why some of the concepts were important, and which ones were used while answering questions on the CCI (see Questions 3 and 4 in Appendix 3).

'6. Utilization of Maps' where the concept map is then analysed to work out if it fulfils the original aim posed at the start of the concept map's creation. This step was carried out by the researcher after the interview rather than by the participant due to time constraints (discussed in detail in Section 4.4.1 Evaluation of the Concept Maps).

The creation of the concept map mainly addresses Research Questions 4 and 6. In the first stage of the concept map creation, Research Question 4 is addressed as the student is asked to state all concepts they find important in atomic structure and bonding. This is supported by the students' justification in the last stage of questions directed at the concept map creation (though students are encouraged to add to the concept map at any point during the interview if they wish). Research Question 6 is investigated during the second question of the interview, as links between the students' own ideas of important concepts are explained and justified by the student. At the end of the interview, the researcher asked the participant for permission to take a photograph of the concept map created; if permission was granted, the concept map was coded for later analysis with the same code used for the questionnaires before a photograph was taken.

In the case study, many students who made concept maps only put a few ideas down to begin with, and did not create visible links on the paper. However, when asked about specific links between concepts they had put down, the students orally explained the links, and these were noted down in the researcher's interview notes so that a record could be kept (as well as audio recorded if the participant had consented to an audio recording of the interview). Where used in this report to illustrate the points raised, the combined concept map of the students' concepts and orally explained links may have been created by the researcher; this is stated for clarification (see Section 4.4 Results of the Concept Maps).

3.4.1 Evaluating Concept Mapping as a Tool

Concept maps were first created by a team led by Novak in 1972, and are defined as 'graphical tools for organizing and representing knowledge' (Novak and Cañas, 2008). Concept maps have also been identified as being able to help identify misconceptions in the past (Novak and Gowin, 1984, pp. 19-21), and have been shown to be 'effective in identifying both valid and invalid ideas held by students' (Cañas *et al.*, 2003, p. 7) which is the main use of the concept maps utilised in this project.

When finalised, concept maps typically include a hierarchy of the concepts, with 'the most inclusive, most general concepts at the top of the map and the more specific, less general concepts arranged hierarchically below' (Novak and Cañas, 2008, pp. 1-2), though this is not always the case. The 'Rubber Sheet Analogy' (the idea that each concept can be picked as the most important) has also been applied to the concept map to state that 'concept positions on a map can continuously change, while also maintaining the same relationship with the other ideas on the map' (Inspiration Software Inc., 2018). Therefore, this suggests that the map can be constructed with the concepts in any position as long as the links between the concepts are established.

The use of a concept map constructed in an interview has been carried out previously to identify misconceptions by Novak and Gowin (1984, pp. 123-124) and is described below:

> 'After identifying key concepts in a subject area of interest to us, we ask a sample of students to construct concept maps using all or some of these key concepts and encourage them to add other concepts they deem relevant. [Using many concept maps created] we can quite easily identify a large number of valid propositions, and many misconceptions, or invalid propositions as well.'

This suggests that concept maps can be used as a tool in interviews to evaluate the students' understanding of the concept or topic in question, as the maps that the students create will help to explain whether there have been any common misconceptions in the sample interviewed.

Section 4: Results

4.1 Results of the Chemistry Concept Inventory

When looking at the initial results from the questionnaire (Table 1), it is evident that there are particular questions that the majority of the cohort answered incorrectly. These fall into three main areas: Stoichiometry (Questions 1 and 2), Valence Shell Electron Pair Repulsion (VSEPR) Theory (Questions 5 and 6) and Polarity (Questions 8 & 10).

Table 1: Table of initial questionnaire answers from one school (1 teacher and 11 pupils) before analysis, with the correct answers shown in green, correct answers which have been guessed shown in orange, and incorrect answers in red. Where participants have indicated that they guessed, this is marked with '(G)', where participants found the question difficult, this is marked with a question mark '?', and if the student wrote in their own answer this was marked as 'OA' and was asked about during the interview if the student participated in the last stage of the research. Percentages calculated to one decimal place due to recurring decimal percentages.

Participant Code	Question Number										Total Marks
	1	2	3	4	5	6	7	8	9	10	
SCHW100	d	d	b	c	c	b	b	b	b	c	9
SCHW101	a (G)	c	b	c	a (G)	a	b	d (G)	b (G)	b ?	4
SCHW102	d	e	a	a (G)	b (G)	c (G)	b	d	b	b (G)	2
SCHW103	d	a	b	OA	b	OA	b	N/A	b	N/A	3
SCHW104	a	b	b	c	b	c	b	d	b	c	5
SCHW105	d	b	b	c	b	b	b	a	a	b	4
SCHW106	d	b (G)	b	c	b (G)	b	b	d	b	b	5
SCHW107	d	a	b	c	b	N/A	b	d	b	c	5
SCHW108	d	d	b	c	b	b	c	d	b	c	6
SCHW109	d	b	b	c	a	a	a	b	b	c	5
SCHW110	d	b (G)	b	c	b (G)	d	b	d	b	d	4
SCHW111	d	b	b	c	c	b	b	d	b	c	7
Total correct per question	0	2	11	10	2	5	10	2	11	6	
Percentage correct per question	0.0%	16.7%	91.7%	83.3%	16.7%	41.7%	83.3%	16.7%	91.7%	50.0%	

4.1.1 Evaluation of the Effectiveness of the Questionnaire as a Tool to Check for Conceptual Understanding

The results shown in Table 1 also suggest that the CCI did work as a valid evaluation of the students' ability to answer the questions, as the questionnaire appears to measure areas that the participants were able to answer, as well as areas that the participants were unable to answer as intended. This can be shown as although all questions were multiple choice, only one guessed answer turned out to be correct, showing that the results should not be skewed by the students' guessing. Furthermore, when the participants who volunteered to take part in the interviews were asked about their reasoning, almost all students who had not indicated a guess on the questionnaire had shown logical thinking and could explain their answers (see 4.3 Results of the Interviews with Student Participants). The notable exception to this was the student who could not remember their questionnaire number, though as they were working from a questionnaire which did not belong to them (as was shown later by another participant claiming responsibility for the same coded questionnaire) this is to be expected as no two participants have the exact same responses across the questionnaire. Therefore, it is highly unlikely that the students had been able to guess a correct answer without marking this down on the questionnaire as the participants were able to explain to the interviewer the reasoning behind their answers.

Additionally, as the majority of the incorrect answers (see Table 1) seemed to be common across a number of students (e.g. although all of the participants had indicated the incorrect answer for question 1, the only answers chosen were d) and a) with 10 and 2 students respectively), this suggests that the distractor options included in each question were suitable to illustrate the students having difficulties with the concepts tested in the CCI (Considine *et al.*, 2005, p. 20). This suggests that the CCI used in this research was able to show areas where there may potentially be misconceptions in the students' understanding as there were common incorrect answers across the class, suggesting these were areas which needed to be investigated further.

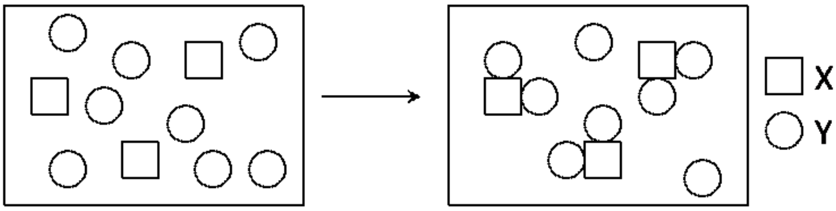
4.1.2 Potential Hypotheses to Explain the Issues with the Questions on Stoichiometry

By just looking at the questionnaire answers, and before conducting the interviews with some of the students, there were two hypotheses to explain potential issues that students may have based upon the incorrect answers the students gave on the stoichiometric questions in this questionnaire (included as Figure 2 for clarity):

Hypothesis 1: The students believe that an equation is an exact indication of all of the reactants and products in the reaction (as indicated if the student selected d) as their answer for Question 1, or b) for Question 2) rather than the overall rule of how the reactants react to form the products, and multiples of this are allowed if there are more atoms which can react.

For example, the incorrect answers indicated here suggest all elements shown in the reactants and products boxes must be included, regardless of whether there were unreacted reactants remaining in the products box (for Question 1) and no more than two sulphur trioxide compounds could form as that was the number stated in the equation given (for Question 2). This hypothesis suggests that the way equations are approached in teaching should be clarified to explain that unreacted reactants do not need to be included in the overall equation.

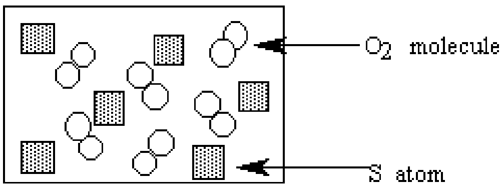
1. The reaction of element X with element Y is represented in the following diagram.



Which equation describes this reaction?

a. $3X + 8Y \rightarrow X_3Y_8$
b. $3X + 6Y \rightarrow X_3Y_8$
c. $X + 2Y \rightarrow XY_2$
d. $3X + 8Y \rightarrow 3XY_2 + 2Y$
e. $X + 4Y \rightarrow XY_2$

2. The diagram represents a mixture of S atoms and O_2 molecules in a closed container.



Which diagram shows the results after the mixture reacts as completely as possible according to the equation:

$$2S + 3O_2 \rightarrow 2SO_3$$

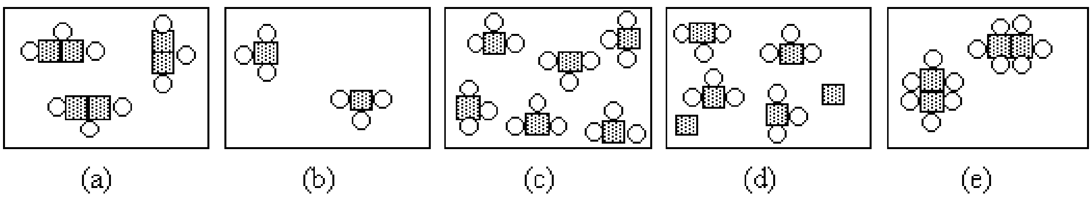


Figure 2: Questions 1 and 2 as shown on the CCI issued to the participants (questions from Taylor, 2013; adapted from Nurrenbern and Pickering, 1987 respectively)

Hypothesis 2: The students are not aware that there is a difference between subscript numbers in chemical formulae, and coefficients (numbers at the start of a chemical formula) (Siskin, 2018) e.g. the students may be unaware that there is a structural difference between X_2 and 2X (as indicated if the student selected a) as their answer for Question 1, or a) or e) for Question 2).

For example, the incorrect answers indicated here all suggest incorrect interpretations of the structure of the compounds formed in both questions. If the students are unaware that there is a difference in the meaning of the subscript numbers and normal text numbers, this is a major misconception as it would potentially lead the students to misidentify chemical compounds.

These two hypotheses were tested in the interview phase of the research project (see Section 4.3.1 Evaluation of the Original Hypotheses Formed by Looking at the Answers for Questions 1 and 2 from the Questionnaire) to evaluate whether either of these two hypotheses were able to explain the issues that the students had with the questions being asked, or whether an alternative explanation could be drawn from the interview data. However, the interview schedule was created before the CCI had even been issued, allowing for more objectivity in the interviews as the same questions were issued each time regardless of what the interviewer's opinions were. Therefore, these hypotheses have been analysed after the interviews have been completed rather than evaluating the hypotheses during the interview process itself.

4.1.3 Relation of the Chemistry Concept Inventory to the Research Questions

The questionnaire was mainly used to give context to and tackle Research Questions 4, 5 and 6. Although there are some limitations with the way this questionnaire has been used in this research project (in the fact that the questionnaire has only been issued once to the students to fill in rather than analysing pre/post filled in differences), the questionnaire still allowed for some conclusions to be drawn from the data as well as providing context for later stages of the research, and valuable conclusions can be drawn in relation to Research Question 5. The later conclusions will be discussed in Sections 4.2.1, 4.3.5 and 4.4.2 in terms of observations, interviews, and concept maps respectively.

4.1.3.1 Are students able to answer questions testing conceptual understanding in different circumstances (for example when asked questions not in the typical exam style)?

As stated in Section 1.3.2 Concept Inventories, the CCI was designed with questions in a different format to exam style questions. By using these questions in a different format to what the participants were used to (for the level they were studying at), conceptual understanding could potentially be analysed as the participants had to express their knowledge and understanding of a topic in a new format, which potentially allowed for the conceptual understanding to be tested rather than memory of specific answers to typical questions. Even if the format used was more similar to a previous style of questioning that the students would have seen prior to their AS year, the application of higher level conceptual knowledge into an older format is atypical for the participants at this level. However, despite exam style questions not being multiple choice (as seen in the CCI), there are some questions that are more similar to exam style questions than others. The similarities to exam style questions were assessed by looking at the formats of the question being asked and whether that style matched with what could potentially be seen for the exam style questions first; e.g. would the topic typically be addressed in a pictorial manner on an exam paper, or would this be typically asked in a text based, explanation format. Explanation style questions (such as Questions 4, 6, 8 and 10 as the *'What is the reason for your answer to the question above?* questions) are commonly used in exams, though students will typically be asked to answer questions in their own words rather than to select the answer as seen on this multiple choice questionnaire, and so were categorised as most similar to exam style questions as the students needed to select an answer closest to their explanation. Likewise, students could potentially be asked to draw a 3D structure of a compound (similarly to Question 5 but with the elements being indicated by the atomic symbol rather than spheres), identify the presence of a polar bond (similar to Question 9) or Lewis diagrams (similarly to Question 3) rather than selecting an answer. Therefore, these questions were classified as related to exam style questions, though as students would have to construct the diagrams themselves with the information presented in a different way, with access to a periodic table and other exam resources that the students may feel useful to answer the questions, these are less similar to exam style questions. The questions on the CCI which are most dissimilar to exam style questions are Questions 1 and 2, as these questions were pictorial on the CCI whereas exam style questions on balancing or stating reactions do not use this format, and instead tend to be purely text based.

The lowest scoring questions were Questions 1, 2, 5 and 8, and the highest scoring questions were Questions 3, 4, 7 and 9 (see Table 2). Question 7 has been identified as 'Not seen on AS Exam Papers' as the topic of polar molecules had not been covered by the cohort, though they had covered polar bonds, meaning that the format of this question does not have an exact equivalent at AS for the students tested as this was new information to them. Despite Question 8 being asked to explain the answer to Question 7, the format is similar to other explanation style questions on the AS (potential issues associated with having a more difficult level of question is discussed in Section 4.3.4 Alternative Explanations for Incorrect Answers).

Table 2: Table of initial questionnaire answers from one school (1 teacher and 11 pupils) before analysis, grouped by how similar the questions on the CCI issued to the participants are to AS Chemistry exam style questions. Percentages calculated to one decimal place due to recurring decimal percentages. Ranges have been included to show the variability in correct responses between the questions in the groups.

	Question Number	Percentage Correct	Average Percentage Correct per Grouping of Question	Range of Percentage Correct per Group of Question
Similar to Exam Style Questions	4	83.3%	47.9%	16.7% – 83.3%
	6	41.7%		
	8	16.7%		
	10	50.0%		
Related to Exam Style Questions Though Different Format	3	91.7%	66.7%	16.7% - 91.7%
	5	16.7%		
	9	91.7%		
Dissimilar to Exam Style Questions	1	0.0%	8.4%	0.0% - 16.7%
	2	16.7%		
Not seen on AS Exam Papers	7	83.3%	83.3%	83.3% - 83.3%

The results in Table 2 seem to suggest that the participants were less able to correctly answer questions which were dissimilar to a format they were used to, with only a mean of 8.4% across the two questions in this grouping. However, the participants appear to be able to answer questions related to the exam style questions more easily than those most similar to the exam style questions; even when removing the percentage correct for Question 8 due to this topic not being covered by the students tested, the correct percentage for the similar questions is lower than the related questions (58.3% to 66.7% respectively). Remarkably, the students scored highest on the group with material they had not covered yet, though the format of this question is most similar to the 'Related to Exam Style Questions Though Different Format' group which aligns with this group scoring the highest. The high percentage in this section could be due to the answers being already provided for the students; usually questions on the topics being asked here ask for diagrams or similar to be constructed by the students themselves rather than selecting the correct option. This could mean that the students are more easily able to apply their knowledge to select the correct option as the process required in the exam is similar, though they only have to select an option here rather than draw in the correct answer. The exception to this is Question 5 with a correct percentage of only 16.7% compared to Questions 3 and 9 which have correct percentages of 91.7% - the topic covered in Question 5, VSEPR, was identified as a problem area in the class, and was in fact the topic for the revision session (see Section 4.2 Results of the Classroom Observation). Therefore, this lower percentage shown in Question 5 could be due to the topic of the question rather than the question format, and so this was explored further in the interview portion of the research (see Section 4.3 Results of the Interviews with Student Participants, specifically 4.3.3 Terminological Understanding Problems or Wording of the Questions Problems which could be Incorrectly Classified as Misconceptions about Question 5).

As the participants appeared to struggle to answer questions which were not in the typical exam style, this suggests that the participants may not fully understand the concepts covered, and instead may only be able to apply these in the situation that they were taught i.e. seeing these as 'facts' rather than 'concepts'; see 2.5 Are students able to answer questions testing conceptual understanding in different circumstances (for example when asked questions not in the typical exam style)? This is further evidenced by the low percentage of correct responses in the group of 'Similar to Exam Style Questions' as these were all explanation style questions. As these questions were multiple choice, the participants had to select an explanation which was relevant to their choice of the answer to the previous question in the pair rather than stating their own answer which may have caused some difficulty with selecting the correct answer if the participants have only learnt set definitions or explanations rather than the science behind the concept. This is shown by one participant choosing to write in their own responses to two of the explanation questions (4 and 6) rather than selecting the most similar answer to their written explanation, and leaving the other two blank (8 and 10) as shown in Table 1. Therefore, the low mean percentage in this section could be due to the inability to reword the participants' own understanding to match one of the options, rather than due to the format of the question being most similar to the exam style questions causing the low percentage of correct answers.

Overall, the low percentages in both sections of questions grouped of 'Similar to Exam Style Questions' and 'Dissimilar to Exam Style Questions' seem to suggest that there are potential conceptual issues in the students' understanding as the initial results suggest issues with applying their understanding in different scenarios, which will be explored further in Section 4.3 Results of the Interviews with Student Participants.

4.2 Results of the Classroom Observation

For the case study, a revision session on Atomic Structure and Bonding (specifically shapes of molecules and VSEPR rules) was observed, and the completed observation schedule can be found in Appendix 5: The Completed Observation Schedule from SCHW1. However, the teacher taking the class for the revision session explained to the researcher that this topic was originally taught by the other chemistry teacher that the class had, so the teaching methods employed by the teacher being observed could have been implemented for the first time to the class in this revision session.

4.2.1 Relation of the Classroom Observations to the Research Questions

The classroom observation was mainly used to tackle Research Questions 1, 2 and 3, and also to help to provide some context to Research Question 4. Although there are some limitations with only using one lesson to answer these research questions, especially as the session observed was a revision session rather than a typical lesson, some conclusions could be drawn from observing this revision session. All students appeared to be familiar with the teaching approach and resources used by the teacher, suggesting this teaching style is used commonly by the observed teacher. Conversations with the teacher before the observed session took place allowed the researcher to be aware of the typical structure of most lessons from the teacher's perspective, especially if a resource was used in the revision session which had been utilised in a previous lesson (where the previous lesson was not observed).

4.2.1.1 Are teachers informing students of the concepts being covered in each lesson/are students aware of the concepts being covered in the class?

For the revision lesson being observed, the teacher did not directly or explicitly state the concepts being covered in the session. However, this does not mean that the teacher did not inform the students of the concepts being covered at another stage in the course, or that the students were unaware of the concepts. As the session being observed was not a typical lesson (as it was a revision session before the students had their summer exams), it may be the format of the lesson was not usual, especially as the questionnaire was completed at the beginning of the session, thus altering the format of the lesson. Even so, once the class began, a topic the students found challenging was chosen to cover (VSEPR theory and shapes of molecules), and as such the students were informed of what the overall topic was by the teacher. Following this, the first thing the teacher asked the students to do was to write down everything they knew about the topic of shapes of molecules, thus introducing a range of concepts to the whole class through what the students had written down and then shared with the class. This suggests that the students had an understanding of what concepts were covered in the class e.g. impact of lone pairs on bonding angles has been identified as a concept by Bojan (2017, p. 7), and was also suggested by students in the lesson.

Despite this initial activity creating opportunities for concepts to be identified by the teacher and the pupils, there were not many other occasions in the lesson where attention was focused on the concepts in atomic structure and bonding; although the students were initially able to identify a variety of concepts that they believed were important in atomic structure and bonding, focus soon moved onto the process of how to use VSEPR to calculate 3D shapes. Even though this could be potentially down to the revisionary nature of the lesson rather than teaching a new topic, it does suggest that the students are not always aware of the concepts being covered, especially as the teacher did not suggest new or additional concepts to those put forward by the students. This could mean that as the students looked at a narrow focus in the lesson (VSEPR) compared to a broader focus (Atomic Structure and Bonding), they may potentially generate the belief that these concepts fall under different headings, and they are viewed more as 'facts' by the students as the same process can be followed to get the correct answer if students are observing a worked example being carried out for a specific topic. However, the teacher illustrated how to use the concepts/the importance of the concepts in the lesson using many different resources and techniques, for example when going through exam questions (see 4.2.2.3 What techniques/resources do teachers use to illustrate and explain concepts?). Therefore, it can be inferred that the concepts have been mentioned at some stage in the past as the students were aware of potential concepts which related to the topic of VSEPR without the teacher stating any as prompts to start the students' discussion, and were present implicitly throughout this revision session by the teacher working through examples which used some of these concepts while answering the questions. However, whether the teacher explicitly informed the students of what was a concept and what was a fact cannot be commented on as only one lesson was observed, and the teacher did not correct or clarify any of the students' responses to state whether they were concepts or facts. Therefore, as the students were not given any clarification about what 'facts' and 'concepts' they needed to know to answer the questions, this meant that the students could potentially view the concepts used to work through the examples in class as facts.

Overall, the students were not directly informed of the concepts being covered in the lesson, though they did have some awareness of the concepts contained in the topic of atomic structure and bonding, as shown by the starter activity in the class as the students were able to identify some concepts that they believed were important for shapes of molecules without the teacher stating any or prompting the class to come up with their own concepts. Therefore, it can be presumed that students are aware of the concepts being covered in the class, though these concepts could be stated more clearly or reinforced so that the students have no doubts about what is meant by a concept.

4.2.2.2 DO TEACHERS AIM TO IDENTIFY AND RECTIFY MISCONCEPTIONS IN THE CLASSROOM?

For the cohort being observed, the teacher was very aware of the potential that the students may have misconceptions, and actively tried to rectify these misconceptions when any students appeared to state any (see Appendix 5: The Completed Observation Schedule from SCHW1 section 'Teacher Interactions'). In conversations with the teacher before the observed lesson, the observer was informed that the procedure for the lessons was not typical to many other schools or lessons, with the students doing a lot of their own reading around the subject before coming to the lessons, and the starter activity normally involving the students asking for help or clarification in the areas they felt weakest in which were covered in that session's reading; that way the lesson would start with an identification and correction of potential misconceptions. This technique can be shown in a number of different times in the lesson being observed despite the lesson being atypical, with the teacher both asking probing questions to the class to test the understanding of the students, and the teacher walking around the classroom correcting work and answering questions. As the teacher prompted a lot of class discussions within the class (e.g. after talking through a process of how to apply the VSEPR rules to calculate the shapes of molecules), the teacher was then free to move around the class, listening in to discussions that the students were having, and answering any questions that they may have at the same time. For example, the teacher would challenge any potential missteps in the students' thinking as they occurred, e.g. when a student had identified the bonding pairs' rather than looking at the central atom, the teacher had said: *"That's not the right group, how do you know what group* *it's in? Remember the periodic table"* which prompted the student into working out what they had done was in the wrong order, rather than just correcting the student without them understanding why they were wrong. This allowed for the identification of the misconceptions in the specific topic of atomic structure and bonding, and allowed the students to have their understanding tested and corrected without feeling embarrassed as it was done in small groups without everyone listening in.

Additionally, when the class was doing whole discussions (e.g. explaining how they had done the question step by step to the class), the teacher would often use phrases such as: *"What has [student] got this confused with?"* or *"Can anyone explain why that answer is not quite right?"* if the student had answered incorrectly, meaning that the whole class was involved with the learning process, and peer learning/teaching was being carried out to help explain any topics the class found difficult followed by a confirmation of the correct answer by the teacher. This allowed the whole class to benefit from the misconceptions of single students being pointed out, and thus help other students to be aware that they could ask for clarification on a concept without being singled out for not knowing it.

Finally, the teacher ended the lesson by asking the students to mark their own homework questions on the subject matter being tested (for this lesson, the students had previously completed a mock AS exam paper – 2016 AS Paper 1 (AQA, 2016a) - which had been used in all revision sessions) after giving a step by step answer to the class, modelling the answer for all students to work out what mark they had been able to achieve. After the class had marked their questions, the teacher asked the class to raise their hands for full marks, then one mark off etc. but also if the students had missed a mark or two, to explain what they had either got wrong or forgotten to include, so that it would both reinforce the process to the student, and emphasise what the class was weakest on to the teacher.

Overall, the teacher being observed seemed very aware of the potential that the students may have misconceptions in their understanding, and was making a conscious effort, both in the preparation of the lessons' structure as well as in the lesson observed to identify and rectify any misconceptions that the students may have. By including peer learning/teaching and assessments, worked examples from the class, and creating time to go around talking to students in the lesson, the teacher was able to quickly and easily turn a previous mistake or misconception into a learning point for the class, showing that for this particular case, the teacher was actively identifying and correcting misconceptions.

4.2.2.3 WHAT TECHNIQUES/RESOURCES DO TEACHERS USE TO ILLUSTRATE AND EXPLAIN CONCEPTS?

When observing the session carried out in the school used in this research, a number of different resources were used by the teacher (see Appendix 5: The Completed Observation Schedule from SCHW1 section 'Materials Used by the Teacher'). These resources and techniques were used to both open up the discussion from the class, and also to clarify or confirm the class' beliefs around certain topics. The resources used to open up the topics to the pupils were: individual whiteboards and pens, and past exam papers (which the students had been given by the teacher previously for homework). The first resource used was the individual whiteboards and pens, which opened up the discussion on concepts involved in atomic structure as the students were asked to put down everything they could think of involved in the determination of shapes of molecules, which allowed the teacher to then ask about the students' ideas and illustrate what these were to the rest of the class if the other students did not know about how these ideas related to the topic of shapes of molecules. Following on from the individual whiteboards, the teacher then collated the correct ideas from the class onto the main whiteboard, explaining to the class what these ideas were and how they could be used to answer questions on the shapes of molecules (e.g. a collation of all of the names of the shapes of the molecules next to a drawing of the shape and bond angles included was due to the first idea suggested by a student). Although the shapes of molecules, their names and the bond angles may not be considered a concept by itself, the underlying concept of electron pairs repelling each other to form various different shapes depending on the numbers of bonds that can be formed is suggested as a concept by Bojan (2017, p. 1). This concept was what the teacher was illustrating by giving example questions to the class and asking for the class to work through the questions first individually, and then to discuss the answers in groups, and finally asking the class to volunteer to state their working through as the teacher put the correct stages onto the board. This process allowed for the students to understand the underlying concept for the configuration of the 3D shapes, rather than just learning the shapes as fact without understanding how these shapes are formed.

Following on from these initial discussions and examples set by the teacher, it was evident that some students were still struggling with the way to apply the VSEPR rules. To help illustrate the rules, the teacher found a worksheet (Ali, 2017) which could potentially aid the students by showing a process of how the students could use the VSEPR method to determine the shapes of the molecules. This worksheet had step-by-step instructions on what to do, and so the teacher went through each step explaining why each step was important for the overall shape of the molecule being formed, which again helped the pupils understand the underlying concepts involved in atomic structure rather than just learning a table of shapes. As many of the students had forgotten about the potential presence of ions also being involved in VSEPR questions, having the worksheet showing a system to include positive and negative ions in questions allowed students to understand that VSEPR is not just applied to neutral molecules (which was a potential misconception by some of the students). This approach seemed to be in line with the Social Constructivist learning theory (see Section 1.2.3.5 Social Constructivism), as the teacher was attempting to get the students to discuss the answers to each of the questions using the step by step worksheet. However, this may have been implemented more as a 'structure' than a 'scaffold' as suggested by work done by Wass and Golding (2014, pp. 677-679) proposes (see Figure 3).

'Structures' and 'scaffolds' are commonly used to help pupils to overcome complex problems by providing a method of reducing the complexity e.g. breaking down the complex problem into more manageable steps, or monitoring the progress of the students to keep them on task and motivated to complete the tasks (Reiser, 2004, p. 284). If the teacher simplifies the complex problem, but leaves the important barriers that the pupils must overcome, then the teacher has left a 'scaffold' as the pupil still needs to work out a way of dealing with the remaining issues given the new parameters the teacher has implemented (Wass and Golding, 2014, p. 679). However, if the teacher removes all of the issues and leaves a list of instructions of what to do without the pupils having to work out why, then the teacher has implemented a 'structure' that the students can follow to get to the answer without facing having to think about why these steps are appropriate for the problem. Ritchhart (2002, p. 160) states the importance of scaffolding as if structures are used 'students tend to stop thinking and begin to operate mindlessly' as the students are following an instruction list rather than understanding how these steps can solve the issue. Therefore, scaffolds can help increase the pupil's understanding so they are able to attempt more tasks independently as they understand how to get to the answer in a similar problem (e.g. their understanding has expanded to include part of their previous Zone of Proximal Development), whereas structures do not promote independent thought, and so the student will still need support if they encounter a similar problem in the future. This could mean that the students may still struggle to answer questions on this topic in the future (see 4.3.3 Terminological Understanding Problems or Wording of the Questions Problems which could be Incorrectly Classified as Misconceptions about Question 5).

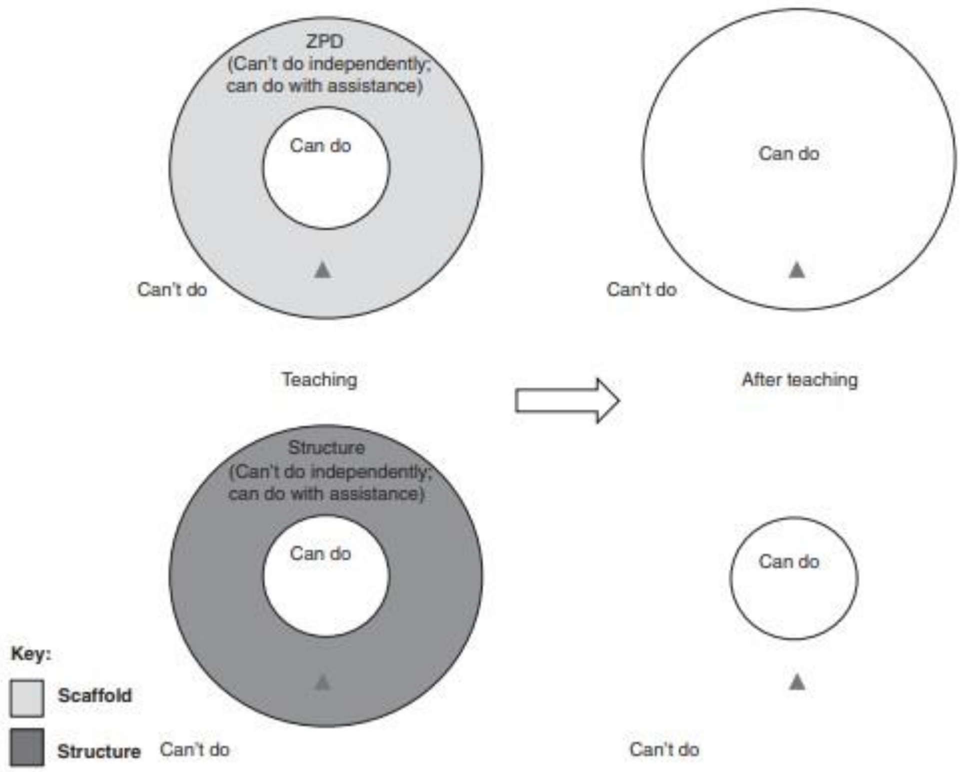


Figure 3: A figure created by Wass and Golding (2014) which shows the difference between constructing scaffolding for the students to use, and creating a structure for the students to follow.

The final resources used to illustrate concepts were past exam papers and mark schemes for the questions that the students were set as homework - again the teacher modelled the answer to the question, and then opened up the mark scheme to show the students how each mark had been obtained using the modelled answer. The link back to concepts was made both in modelling the answer and in the clarification of the mark scheme. The teacher would ask questions such as *"Why is this?"* when going through each section so that the students would continue to reinforce their ideas of the underlying reasoning behind each stage of their answers, and then when looking over the mark scheme, the teacher would emphasise the importance of the reasoning behind each mark, showcasing how important it was to truly understand the concepts behind the shapes of the molecules.

Overall, there were many different resources used in the lesson being observed (see Appendix 5: The Completed Observation Schedule from SCHW1 section 'Materials used by the Teacher'), though only a few were used to illustrate and explain concepts in the topic of shapes of molecules. By allowing the students to have time to express their understandings (or misunderstandings) about the concepts involved in shapes of molecules, the teacher was able to use a range of techniques and resources to identify and then explain concepts used in VSEPR rules and how they can be used to understand the reasoning behind the final shape formed.

4.2.2 Evaluation of the Effectiveness of the Classroom Observation

Overall, the classroom observation was effective in attempting to answer Research Questions 1, 2 and 3 being analysed using this technique, and also to provide further context for the interview portion of the research project. Despite the limitations of only being able to observe one session in one school (discussed further in 5.6 Limitations of this Research), the process of the classroom observation worked relatively well for the intended purpose in this research.

Assuming that the teacher being observed was being truthful when asked if the session observed was an accurate display of typical techniques used in other lessons taught by the same teacher, the techniques used by the teacher were commonly used when teaching the class. This is further reinforced by previous discussions that the researcher had with the teacher when first meeting the teacher to discuss the potential of research. In the first meeting, the teacher had stated how the focus of the lesson was more student focused onto any issues students had (as students were informed of what was being taught over the course of the term and were encouraged to read and work ahead in advance of lessons), and as such there was a more flexible structure to the lessons.

Additionally, due to the nature of the session being observed, it is even more unlikely that the teacher planned a session specifically for the observer as the teacher in fact used the questionnaire as an additional starting point to prompt the students to start suggesting areas they found difficult in order to identify a topic for the revision session. As the teacher had also completed the questionnaire alongside the students in the same conditions (they were not shown the questionnaire before the students), when the teacher's first request for suggestions of topics that the students wanted to revise was met with silence, the teacher was able to say what questions they had found more difficult than they expected, which then encouraged the students to do the same which is how the area of VSEPR was identified for the revision session.

As there was only one lesson observed, it was important that the observer was able to obtain as much useful data as they could. As there were many different aspects of the lesson to be recorded and analysed, the observation schedule had been created by the observer with clear sections allowing them to keep track (to the best of their ability) of all of the various aspects of the lesson in a clear manner for future reference (see Appendix 5: The Completed Observation Schedule from SCHW1). This structure allowed the observer to be able to note down things believed to be relevant to the project as and when it happened in a logical order, rather than attempting to remember everything which had occurred in the session when looking over the notes later. This aided in the answering of the three sub questions relevant to the classroom observations (see 4.2.1 Relation of the Classroom Observations to the Research Questions), suggesting that the classroom observations had been partially successful. However, the observations cannot be stated as being fully successful as the results are only seen for one revision session, so it is possible that the results shown in this observation are different to the lessons where new material was being taught.

4.3 Results of the Interviews with Student Participants

Table 3: Table of questionnaire answers from all participants who took part in the interview section of the research project for questions 1 and 2 on the questionnaire to illustrate the difficulties the participants had with these questions. The original answer given on the questionnaire is stated in the 'Original Answer' column, and all attempts during the interview are recorded in the 'Interview Answer' - the interviewer asked them to explain their original answer without interrupting, and the students were able to change their answer if they wanted. If their answer was wrong, the interviewer explained why, and asked them to try again given their new understanding. The answers given are colour coded with the correct answers shown in green, answers given to the students by the interviewer (due to the student being confused over the concept or time constraints) is shown in orange, and incorrect answers in red. Where participants have indicated that they guessed, this is marked with '(G)'. The 'Unknown' in the Participant Code column is due to a participant not being sure of their code during the interview portion of the project, though this participant could have been SCHW106 based on their explanations for their answers, and knowledge of what they had put down for questions 1 and 2.

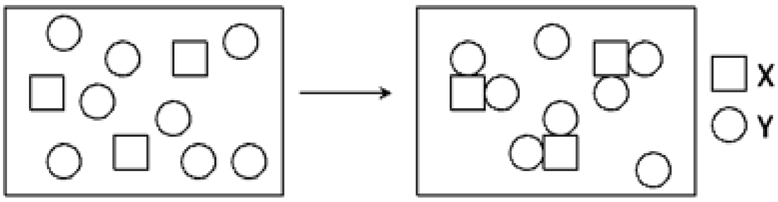
Participant Code	Question Number							
	1				2			
	Original Answer	Interview Answer 1	Interview Answer 2	Interview Answer 3	Original Answer	Interview Answer 1	Interview Answer 2	Interview Answer 3
SCHW101	a (G)	d	b	**c**	c	e	**d**	
SCHW102	d	a	None of them	**c**	e	b	**d**	
SCHW103	d	c			a	b	c	**d**
SCHW105	d	a	**c**		b	**d**		
SCHW108	d	a	**c**		**d**			
SCHW109	d	b	**c**		b	**d**		
SCHW110	d	c			b (G)	**d**		
SCHW111	d	**c**			b	c	**d**	
Unknown	d	**c**			b	c	**d**	

4.3.1 Evaluation of the Original Hypotheses Formed by Looking at the Answers for Questions 1 and 2 from the Questionnaire

In the interviews, it became clear that Hypothesis 1, the hypothesis that the participants believe that an equation is an exact indication of all of the reactants and products in the reaction rather than the overall rule of how the reactants react to form the products, was a good explanation of the difficulties that the students had with these questions as their explanations matched relatively well to this line of reasoning. Students gave very logical explanations to how they tackled the questions.

For Question 1 (included as Figure 4 below for clarity): first counting how many boxes and circles there were in the reactants and products boxes, looking for the structure which matched that shown in the products box, and then selecting the option that accounted for all of the boxes and circles shown in the correct structure.

1. The reaction of element X with element Y is represented in the following diagram.



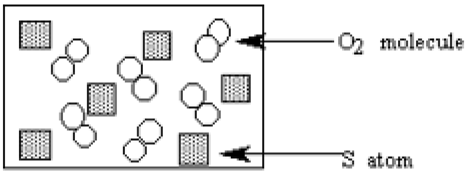
Which equation describes this reaction?

a. $3X + 8Y \rightarrow X_3Y_8$
b. $3X + 6Y \rightarrow X_3Y_8$
c. $X + 2Y \rightarrow XY_2$
d. $3X + 8Y \rightarrow 3XY_2 + 2Y$
e. $X + 4Y \rightarrow XY_2$

Figure 4: Question 1 as shown on the CCI issued to the participants (question from Taylor, 2013).

For Question 2 (included as Figure 5 below for clarity): looking for a box that contained two sulphur trioxide compounds as that was what was illustrated by the equation (many did not even consider the reactants box at all).

2. The diagram represents a mixture of S atoms and O_2 molecules in a closed container.



Which diagram shows the results after the mixture reacts as completely as possible according to the equation:

$$2S + 3O_2 \rightarrow 2SO_3$$

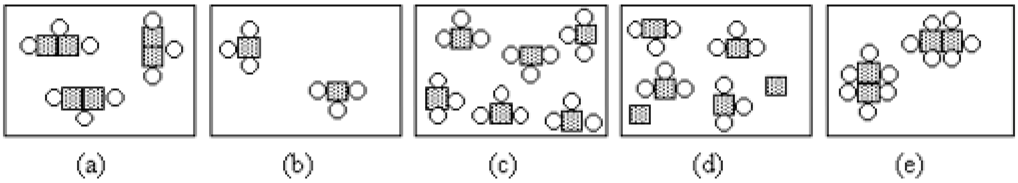


Figure 5: Question 2 as shown on the CCI issued to the participants (question adapted from Nurrenbern and Pickering, 1987).

In the current study, when the researcher asked the students who had got the incorrect structure to draw the structure given by the incorrect formulae (for Question 1), or what the formula was for the incorrect structures (for Question 2), most students were able to do this correctly, and became aware of how they had identified the wrong answer suggesting there was not a structural misconception. Furthermore, when the students who picked d) for Question 1 were asked if they knew of any overall equations which included unreacted reactants, some students replied that spectator ions existed, but when asked to explain what type of equations these were used in, their answers became less confident, and fewer could answer about ionic equations compared to overall equations. Additionally, most students who chose b) for Question 2 were able to get to the correct answer when the researcher simply pointed out the words 'after the mixture reacts as completely as possible' in the question, suggesting that the students did understand that the equations were not the limits of how many reactants could react to form products.

However, it also became evident in the interview that a few students seemed to fit into Hypothesis 2, the idea that the participants were not aware that there is a difference between subscript and coefficients in chemical formulae, e.g. they could believe that X_2 and 2X are the same compound, with one student explicitly asking what the difference was in the interview between a subscript number and one which was at the front. This issue was due to the fact that some of the students who got the wrong answers for Questions 1 or 2 (who understood that they had got the wrong answer by choosing options that were following exactly what was in the formulae or boxes as stated above) selected answers that had the incorrect structure as their second choice (most notably changing from d) - a correct structure - to a) - an incorrect structure still accounting for all atoms - for Question 1). Additionally, this was more evident when some students talked through their answers using the incorrect formulae in their speech (underlined for clarity): *"there's an X bonding to 2Ys for 3 of them, so there's 3<u>X2Y</u> because one X is bonded to 2Y"* and *"now I'm thinking it's this one because it's <u>S_2</u>"* (from two different participants in relation to Questions 1 and 2 respectively showing this to be an issue which is not unique to one student). This suggests that the students do not realise the difference between coefficients and subscript numbers when speaking, or initially writing out equations as shown in one of the questionnaires.

These observations taken together indicate that the students potentially thought that the number of atoms present in the reactants and product boxes was more important for the formula than the structure of the compound, which is a major misconception. On the other hand, if the students’ priorities were in the order of ‘finding an answer that accounts for all atoms and then checking to see if it matches up with the structure’, it is possible that the students chose a) as they simply went down the list in order, and as a) included all atoms, they selected this answer before moving on.

Despite these issues, all students were able to achieve the correct answer after being asked to draw the structure of the compound shown in a), suggesting that Hypothesis 1 is the better fit for this cohort. However, there were evident issues shown for some students appearing to not understand the difference between subscripts and coefficients when thinking out loud (or initially writing down their thoughts). The fact that these students had the ability to correct themselves when drawing out the structure suggests that this concept has not been reinforced strongly enough for this concept to be fully understood by the students, especially as other subjects (e.g. mathematics and physics) use numbers alongside letters to represent entirely different ideas to what is shown in chemistry.

A potential solution to these issues could be explicitly stating that equations are not an exact representation of the number of atoms which can react, but is instead an overall rule (or exercise sheets could be used so the students gain practice at applying this to real examples), as well as clarifying the difference between coefficients and subscript numbers in chemistry to reinforce this. Additionally, explaining the difference between equations which include spectator ions, and overall net ionic reactions may be needed to justify why unreacted reactants are not usually included in final equations.

4.3.2 Issues which could be Classified as Misconceptions

There were a number of occasions that the students' responses appeared to indicate an incorrect answer which could be classified as a misconception, though when evaluating these issues, these issues mainly seemed to fall in the Stoichiometry section of the questionnaire (Questions 1 and 2) with zero and two participants initially getting the questions correct. The reason that these issues have been classified as misconceptions is that the students interviewed struggled to get to the correct answer without a lot of prompting or explanation as to why their chosen answer was incorrect, taking multiple attempts to get to the correct answer in the interview stage of the project (see Table 3) despite the interviewer explaining the chemistry knowledge needed to why their original answers were wrong.

Questions 5 and 8 also had very low percentages of students who were able to obtain the correct answer (for both questions, only two participants were able to obtain the correct answer), but it became evident in the interviews that there were other reasons that the students had selected an incorrect answer rather than the students having misconceptions. During the interviews, the researcher became aware that some students had been confused over the pictorial representation shown in Question 5, suggesting an issue with the question itself (see Section 4.3.3 Terminological Understanding Problems or Wording of the Questions Problems which could be Incorrectly Classified as Misconceptions). Question 8 had been included on the test despite polar molecules not yet being covered in the syllabus – this was included to see whether the participants could extrapolate their understanding to novel situations that they would not have encountered (see 4.3.4 Alternative Explanations for Incorrect Answers).

4.3.3 TERMINOLOGICAL UNDERSTANDING PROBLEMS OR WORDING OF THE QUESTIONS PROBLEMS WHICH COULD BE INCORRECTLY CLASSIFIED AS MISCONCEPTIONS

When evaluating the initial responses to the questionnaires, there were many questions that the majority of students had answered incorrectly which may have suggested a potential misconception, though when asking the students clarifying questions during the interviews, many of these issues appeared to be issues more with terminology or the phrasing of the question than an issue with the students' understanding. This relates back to the idea of 'vernacular misconceptions' (see Section 1.2.2 Accepted Definitions for Misconceptions Used in this Research Project) as the explanations given by the students suggest a misunderstanding of a definition, rather than a misunderstanding of the concept itself.

The terminological issues that became apparent during the interviews appeared to be mainly centred around electronegativity as well as whether there was a difference with ions compared to delta charges. When looking at Questions 9 and 10 together (as they were paired as shown in Figure 6 below), many students had been able to get Question 9 correct (91.7%), however struggled to state the correct reason as to the science behind why (Question 10 had 50% correctly answering).

9. Oxygen is a group 6 element, while fluorine is a group 7 element. The polarity of the oxygen-fluorine bond would be best shown as:

a. $\overset{\delta-}{O} - \overset{\delta+}{F}$

b. $\overset{\delta+}{O} - \overset{\delta-}{F}$

10. What is the reason for your answer to the question above?

a. The non-bonding electron pairs present on each atom determine the polarity of the bond.
b. A polar covalent bond forms as oxygen has six outer shell electrons and fluorine seven outer shell electrons.
c. The shared electron pair is closer to fluorine.
d. The polarity of the bond is due to the oxygen atom forming an O^{2-} ion, whereas fluorine forms an F^- ion.

Figure 6: Questions 9 & 10 as shown on the CCI issued to the participants (questions from Warren (n.d.)).

The most common incorrect answer for Question 10 was b), which by itself did not indicate any terminological issues with the cohort, however when asked to explain their answers, some students indicated some terminological issues.

Firstly, the participant who had left Question 10 blank explained their personal understanding of electronegativity as the more electronegative elements would actually repel electrons as “negative repels negative”, suggesting that they were unable to obtain the correct answer as their definition of electronegativity was in fact the opposite way around; they had a vernacular misconception of believing that ‘electronegative’ meant the same as ‘negative’. This is a key example of a terminological issue as their conceptual understanding about charges was correct (e.g. that negative charges repel each other), however their terminological understanding was incorrect meaning that they were unable to obtain the correct answer. This student was able to obtain the correct answer when told the correct definition of electronegativity, suggesting the conceptual understanding was present in the student's mind as they were able to apply the correct conceptual understanding about charges and electronegativity (and explain how they arrived at the correct answer in their own words) after simply being informed of the correct terminology.

Secondly, some students indicated they had struggled with this question as 'oxygen and fluorine are both negative', and as such had chosen an option to explain why both of these elements typically form negative ions (based on the number of electrons in the outer shell). This issue of students thinking of ions rather than delta charges in a bond was not limited to Questions 9 and 10; Question 7 also had one student stating that "b) can't exist because oxygen and fluorine are both negative" (see Figure 7 below).

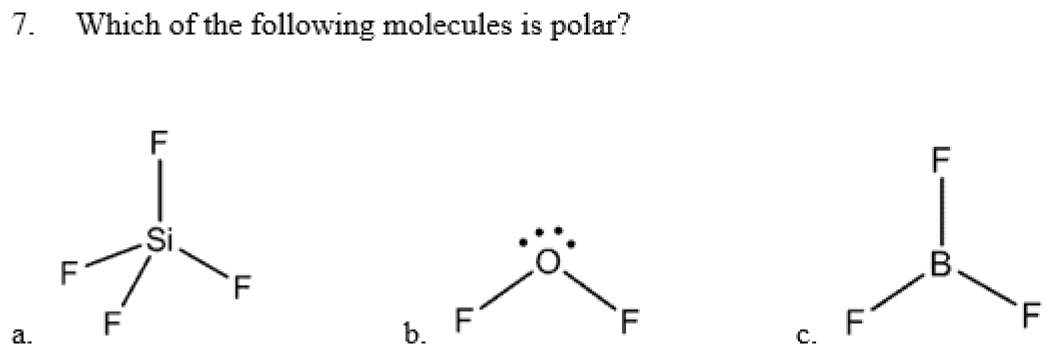


Figure 7: Question 7 as shown on the CCI issued to the participants (question from Taylor, 2013).

This could indicate some fundamental conceptual misunderstandings as the students were applying ionic bonding principles although the depiction is of a covalent molecule; the understanding being oxide and fluoride ions are both negative, so OF_2 could not form as an ionic compound. However, when the researcher asked follow up questions about what the 'δ' symbol meant (in Question 9) the students were able to discuss delta charges rather than ions, and many realised the question was depicting a covalent bond rather than an ionic bond.

Even though these examples may suggest some conceptual misunderstanding, almost all of the students were able to obtain the correct answer when prompted to think of the definition of electronegativity, or when reminding students to think of the difference between ionic bonds and covalent bonds. This suggests that the students had looked at the questions with delta charges present, and had started to think about ionic bonds rather than covalent bonds, however their conceptual understanding was correct when prompted to think about the correct scenario. These errors could also be due to exam stress or pressure, rather than misconceptions (see Section 4.3.4 Alternative Explanations for Incorrect Answers).

Additionally, the non-standard nature of the CCI questions could also have introduced some unexpected additional barriers to the students' understanding. By looking at the raw results of the questionnaire, many students had identified the incorrect answer b) for Question 5 (although three students had guessed) which suggested a problem area for the class. However, while conducting the interviews, one of the students explained that the layout of Question 5 itself had caused issues (included as Figure 8 below for clarity).

5. Nitrogen (a group 5 element) combines with bromine (a group 7 element) to form a molecule. This molecule is likely to have the following shape:

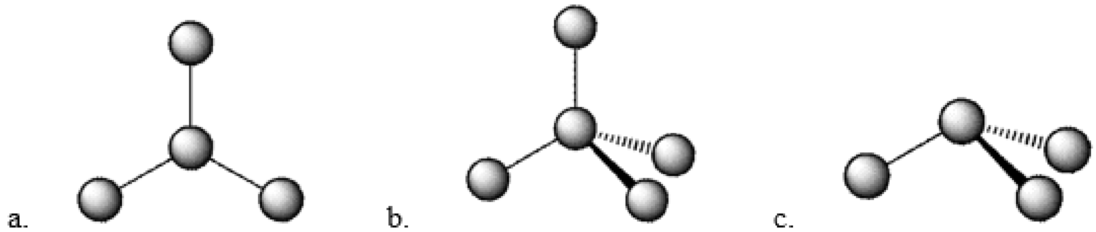


Figure 8: Question 5 as shown on the CCI issued to the participants (question from Taylor, 2013).

Despite the correct answer for Question 5 being c), some students had discounted this as an option due to the representation of the overall shape. The students appeared to have some issues visualising the 3D shape drawn as c) as pyramidal, even though the dash and wedge notation had been used to show the overall shape of the molecule. Firstly, as there were no lone pairs of electrons shown on c), one student stated "this shape just doesn't occur so I discounted it", identifying that without the lone pair of electrons being present, the 3D shape shown in c) would not be formed, and selecting a) as the answer as 3 bonds are being formed with the most distance between the bonds due to repulsion. This does suggest an understanding of the VSEPR rules in the students' minds, however this seems to be more of a factual understanding rather than conceptual due to the context of the question (with the groups that the elements were in being stated in the question).

This lack of conceptual understanding of VSEPR is further reinforced by other students' responses in the interviews. If the students had stated that they had not thought of c) as a potential option when first looking at the question, the researcher asked a follow up question before stating whether the student was correct or incorrect: "if a lone pair of electrons was shown to be present in c) like [Figure 9], would you have considered this shape as a potential option?”

5. Nitrogen (a group 5 element) combines with bromine (a group 7 element) to form a molecule. This molecule is likely to have the following shape:

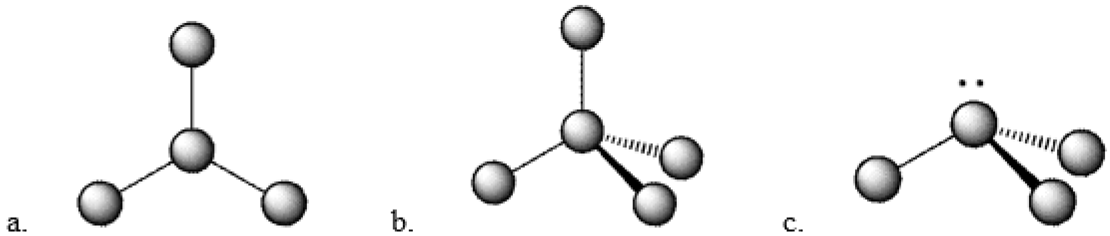


Figure 9: A potential edit to Question 5 to rectify the issue of students discounting c) due to the lack of a lone pair of electrons being shown on the diagram. The lone pair of electrons was drawn on with pencil by the researcher during the interviews to illustrate the point further, though no permanent changes were made to the CCI.

Many students stated that they still would not have changed their original answer to c) even with the lone pairs being present on the diagram. In fact, more students mentioned their struggles with this question was due to the representation of both nitrogen and bromine as ‘blobs’ rather than having the letters; one student stated they struggled with the depiction as they were unsure as to which was the central atom out of nitrogen and bromine. However, one student suggested that the most useful addition for them would have been the inclusion of bond angles (still with the inclusion of the ‘blobs’) so that the 3D shape would have been evident even without the lone pair of electrons being included. All of these suggestions from the students potentially indicate that the students struggled when applying their knowledge to questions not in the exam style, however they also struggled a lot with the topic of VSEPR (see Section 4.3.5.1 Are students able to answer questions testing conceptual understanding in different circumstances (for example when asked questions not in the typical exam style)? for more information).

4.3.4 Alternative Explanations for Incorrect Answers

As briefly mentioned above, many students were able to correctly explain the science behind the correct answers despite obtaining incorrect answers when answering the questionnaire, even if this process required the participants being asked the same question multiple times. Therefore, if the students were able to answer correctly in the interview, it is possible that there are other explanations for obtaining the incorrect answer.

Firstly, there is the possibility that the scenario of exam stress or the time pressure had caused the students to have increased nerves about the questionnaire, and as such could have struggled with pressure of the situation they were placed in rather than the content of the questionnaire itself. This is reinforced slightly by the students' words and attitude in the interviews; some participants stated they were unsure how they were able to select the answer they had originally chosen, and while explaining their answer elected to choose an alternative option. Although the interviews took place almost three weeks after the questionnaire was issued, and so the participants may have forgotten their reasoning for their original answer as time had passed, participants were able to remember both their participant number (with the exception of one student) as well as recognise their questionnaire. This indicates that the students would be likely to remember the answers they gave, even if this required prompting by looking back over their questionnaire, and so further reinforces the idea that the participants were under pressure while sitting the questionnaire as although they could remember their answer, they were sometimes unable to remember their reasoning.

Additionally, some participants struggled (particularly with Question 2) to either read all of the question rather than answer the last section of the question, or if the questions were asked in pairs, to relate the two answers together, with the reasoning behind the answer of the first question in the pair not being explained by the answer given in the second. This could be due to the layout or wording of the questions, with Question 2 being split with both a diagram and an equation as part of the question (see Figure 10 below for clarity), and the second question in the pair simply asking *'What is the reason for your answer to the question above'* rather than stating specific questions e.g. for the pair of questions 3 and 4, Question 4 could have been worded *'What is the reason for your answer to Question 3?'*.

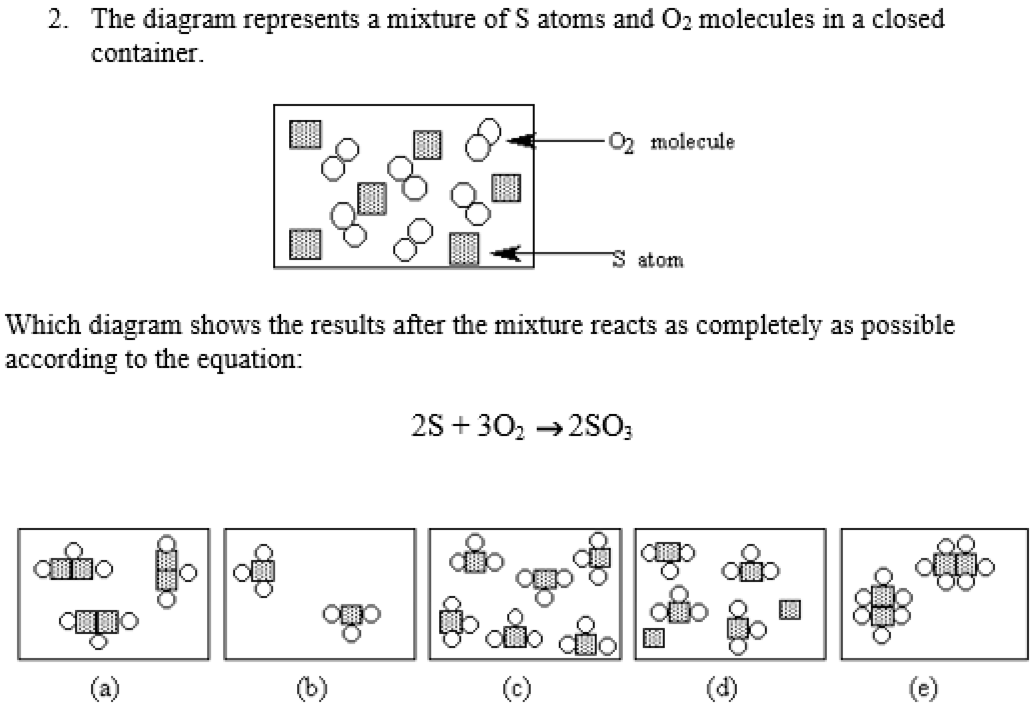
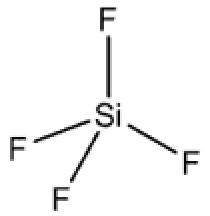


Figure 10: Question 2 as shown on the CCI issued to the participants (question adapted from Mulford, 1996; Nurrenbern and Pickering, 1987).

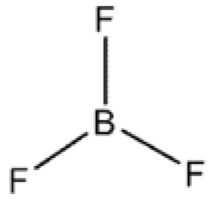
However, only one participant struggled with understanding what was meant by the phrasing of *'What is the reason for your answer to the question above?'*, choosing to write in their own responses rather than select an option, suggesting that this was not a common design flaw of the questionnaire, but was potentially another indicator of the participants being nervous or under stress while answering the questions. During the interviews, many of the participants were able to calmly explain their answers, suggesting the nerves had subsided slightly, potentially due to the interviewer explaining multiple times the answers had no bearing on the participants' marks, and that the questions had been found difficult at multiple different educational levels.

Finally, there is the possibility that the students were unable to answer questions which had been set at a higher standard that they had studied. Questions 7 and 8 (see Figure 11 below for clarity) asks about polar molecules, a topic that the cohort who participated in the research project had not covered.

7. Which of the following molecules is polar?

a. 

b. 

c. 

8. What is the reason for your answer to the question above?

a. The polarity of the molecule is due to the high electronegativity of fluorine.
b. Non-symmetrical molecules containing different atoms are polar.
c. Non-bonding electrons on an atom in the molecule produce a dipole and hence a polar molecule.
d. A large difference in the electronegativities of the atoms in bonding results in a polar molecule.

Figure 11: Questions 7 and 8 as shown on the CCI issued to the participants (question from Taylor, 2013).

However, these questions had been selected to see if the students were able to apply their existing knowledge to a different situation that the students would not have already encountered. The students would have been taught about polarity and polar bonds, and so this pair of questions is included to test whether the students could apply the fundamental principles of this concept to a new scenario; most students were able to talk through their understanding of polar bonds when answering interview questions about this pair. Although most participants were able to identify the correct polar molecule (10 correct out of 12 for Question 7), very few participants were able to follow this up in Question 8 (only 2 out of 12 correct). The most common incorrect answer chosen was d), which indicates a response the students would potentially be familiar with in polar bonds (i.e. a difference in the electronegativities of the two atoms results in a polar bond forming), and many participants simply explained this orally to the interviewer as well when asked to talk through their reasoning to Questions 7 and 8. This suggests that the students may not have been able to fully extrapolate their conceptual understanding to a new situation as they restated a similar response to what they had been taught in class rather than think about the new scenario and how it differed to what the situations that had been taught previously.

4.3.5 Relation of the Interviews to the Research Questions

The interviews were mainly used to tackle Research Questions 4, 5 and 6. Although there are some limitations due to the time constraints of the interviews and the small sample of interviewees (as this is a case study), there were some interesting conclusions which could be drawn about the data set. As the interview included the construction of the concept maps by each student, the full conclusions drawn about Research Questions 4 and 6 will be discussed in 4.4.2 Relation of the Concept Maps to the Research Questions, and only Research Question 5 will be discussed here in detail.

4.3.5.1 Are students able to answer questions testing conceptual understanding in different circumstances (for example when asked questions not in the typical exam style)?

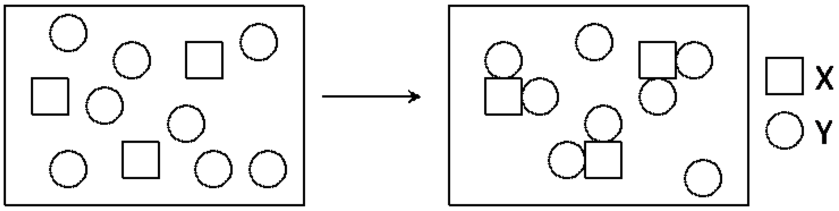
Although the responses on the CCI seemed to indicate several problem areas for the participants (see Section 4.1 Results of the Chemistry Concept Inventory), the majority of the interviewees were able to explain their thought process and arrive at the correct answer with minimal prompts by the researcher regardless of whether they had obtained the correct answer to begin with.

This seems to correlate with the participants' own evaluation of what was easy and difficult within the topic of Atomic Structure and Bonding; some students cited the exam papers' inconsistency with marks/terminology to be an issue as they felt under pressure to remember key words rather than explanations e.g. *"it's too vague in what does matter [in the student's mind] and too precise in what doesn't"*. This opinion was reinforced slightly as the students often described a term or concept rather than using the exact terminology during their explanations. When participants were asked to explain to the researcher why the correct answer was correct in their own words (after a series of incorrect answers had been given to make sure the participants understood the science behind the answer rather than going through a process of elimination), many used colloquial language through their oral explanation. This suggests that the students actually were able to implement the conceptual understanding required, though struggled to apply this to the questions being asked as they were unable to identify how their answer related to the options given on the CCI. Therefore, the students may have a conceptual understanding of the topics covered in some of the questions, but have terminological issues preventing them from obtaining the correct answer on the CCI.

However, despite the majority of participants' responses seeming to demonstrate conceptual understanding (even when obtaining the incorrect answer initially), there were clear gaps in the participants' knowledge. This was most noticeable when considering Question 5 on VSEPR, as almost all participants struggled to even consider the correct answer initially, although this could have been due to the format of the question (see Section 4.3.3 Terminological Understanding Problems or Wording of the Questions Problems which could be Incorrectly Classified as Misconceptions). Although initially the CCI was issued before the revision session on VSEPR which could account for the low marks, the responses given in the interviews about how the participants had tackled Question 5 seemed to indicate very few, if any, had remembered the content taught in the observed session (which took place almost three weeks prior to the interviews). Despite the researcher attempting to remove any misunderstandings of the answers to Question 5 by clarifying the options and even drawing in the presence of the lone pair of electrons, many students still discounted that option, or struggled to apply (or in some cases even recall) the principles taught in the revision session. This suggests that the teacher may have implemented a structure rather than a scaffold when teaching this topic to the students (Wass and Golding, 2014, pp. 667-679), as some interviewees struggled and contradicted themselves without realising until it was pointed out by the researcher when the participants were trying to explain their reasoning. Therefore, the topic of VSEPR remains an area which requires further assistance/guidance in the lessons, as although the revision session observed was also on VSEPR, most participants still struggled to apply what was taught in the revision session to the relevant questions on the CCI.

Additionally, the repeated issues that some participants had with Questions 1 and 2 (the most varied from the typical exam style) suggested the presence of misconceptions which could potentially go unnoticed by only using exam style questions (again included as Figure 12 below for clarity).

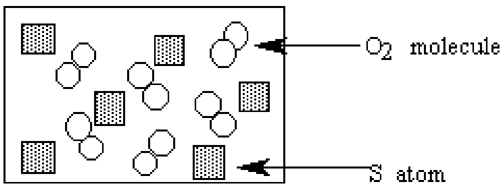
1. The reaction of element X with element Y is represented in the following diagram.



Which equation describes this reaction?

a. $3X + 8Y \rightarrow X_3Y_8$
b. $3X + 6Y \rightarrow X_3Y_8$
c. $X + 2Y \rightarrow XY_2$
d. $3X + 8Y \rightarrow 3XY_2 + 2Y$
e. $X + 4Y \rightarrow XY_2$

2. The diagram represents a mixture of S atoms and O_2 molecules in a closed container.



Which diagram shows the results after the mixture reacts as completely as possible according to the equation:

$$2S + 3O_2 \rightarrow 2SO_3$$

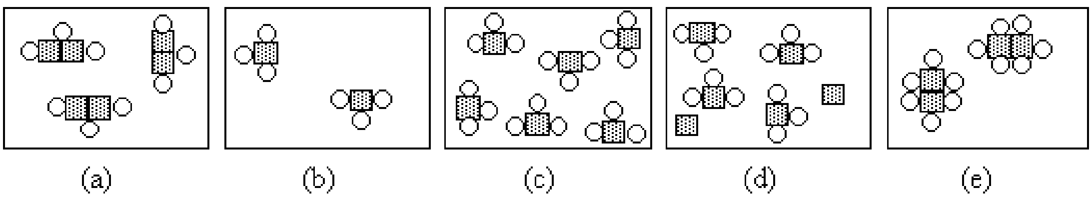


Figure 12: Questions 1 and 2 as shown on the CCI issued to the participants (questions from Taylor, 2013; adapted from Mulford, 1996; Nurrenbern and Pickering, 1987 respectively).

By asking the participants to explain their process, most participants showed a very logical process to come to their answer; accounting for all Xs and Ys present (Question 1), or looking for an option which matched the equation shown (Question 2) (see 4.3.1 Evaluation of the Original Hypotheses Formed by Looking at the Answers from the Questionnaire for more information). Even though these are logical processes, the processes only appear to work for the particular scenario being shown, and are less generalisable to be able to answer a similar problem if asked, though the majority of the students' issues with Question 2 was failing to read all of the question rather than implementing a flawed methodology.

It could be argued that a method for Question 1 which shows conceptual understanding of an equation could be seeing what changes occur between the reactant and product boxes; one X is shown to react with 2Ys, so the equation for the reaction is $\mathrm{X} + 2\mathrm{Y} \rightarrow \mathrm{XY_2}$. This method can be applied to all situations to give an equation for a reaction rather than being specific to this question – one of the properties which shows conceptual understanding rather than factual understanding. None of the students interviewed used this method, instead all of them accounted for all of the boxes and circles shown in both the reactants and products boxes for Question 1. Although this method was not required to be used to demonstrate conceptual understanding, the students seemed to prioritise the inclusion of all atoms in the equation for Question 1 over the changes occurring between the two boxes, whereas this was the opposite for Question 2 as the most common incorrect answer only accounts for the presence of two product compounds being formed, potentially ignoring the atoms in the reactants box (though this can be explained by the incorrect reading of the question).

By asking the questions in this format, it does show a potential misconception over what is meant by the term 'equation'; the students' responses appeared to suggest that if there was a greater number of moles reacting in the same way, the equations between these two scenarios would change although there was no difference in the reaction taking place. For example, this opinion can be explained by the belief that $X + 2Y \rightarrow XY_2$ is different to $2X + 4Y \rightarrow 2XY_2$ and the first equation could not explain the reaction occurring in the second, whereas the first equation can be used in both cases as it is one mole of X reacting with two moles of Y to form a mole of XY_2 in both cases; the molar ratio is the same. As exam style questions typically ask for students to balance equations rather than write the whole reaction (e.g. the equations are listed without any coefficients and the students have to identify what coefficients are needed to complete the equation), it could be possible that the students mistakenly believe that the reactions can only take place exactly as dictated in the equations (e.g. in the exact amount shown by the equation rather than in the ratio dictated by the equation if there is a greater number of moles present).

These results suggest that the participants struggled to answer questions which were not in the typical exam style, however this could be due to terminological issues (where the participants were unable to identify which of the options was closest to their own understanding despite being able to demonstrate conceptual understanding orally to the researcher), not being familiar with the content needed to answer the questions (Questions 5, 6, 7 and 8) or potential misconceptions being present (Questions 1 and 2) preventing them from choosing the right answer. This means that further research needs to be completed in order to evaluate which one of these options is most likely. However, as there are problems specific to certain questions whereas the terminological issue appears to be common across multiple questions, it could be beneficial to reinforce the terminology used in chemistry (and science in general) while both identifying and combatting misconceptions as well as teaching new material.

4.4 Results of the Concept Maps

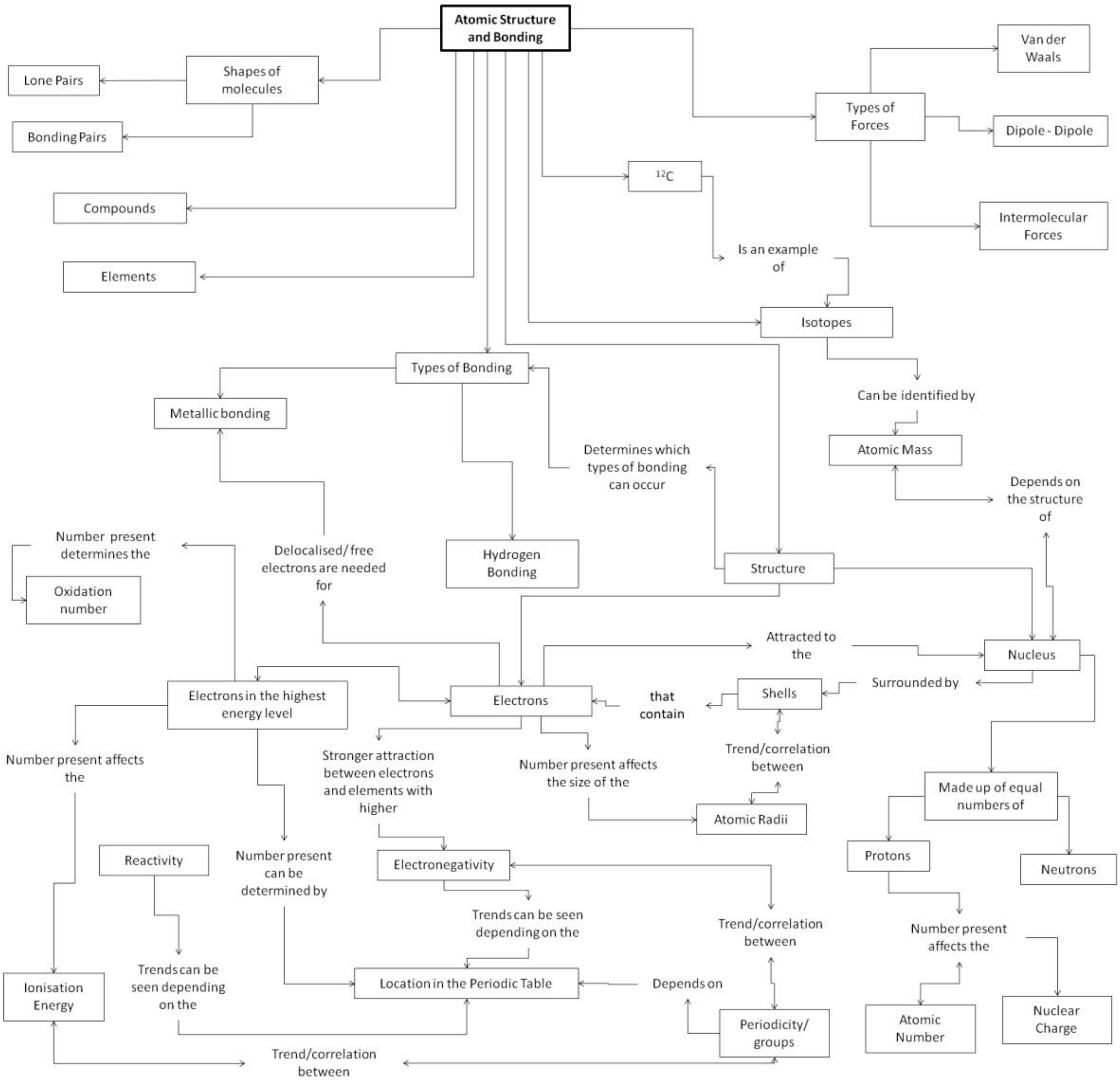


Figure 13: An amalgamated concept map created by the researcher to show all concepts students analysed the topic of Atomic Structure and Bonding in one concept map (five participants). This has been amalgamated by the researcher as many students orally stated the links rather than drawing them in, or wrote lists of concepts rather than creating a map. Therefore, the placement of the concepts does not reflect what the students ranked as the most important, but instead is an amalgamation of the thoughts of the students. All concepts and links are as stated verbatim by the participants; all of the information contained on this concept map was generated by the students rather than the researcher.

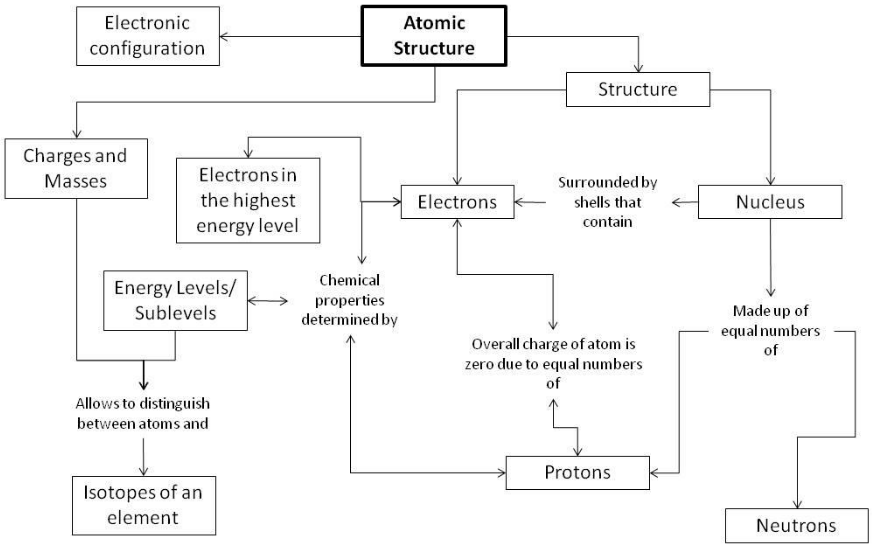


Figure 14: An amalgamated concept map created by the researcher to show all concepts the four students who had divided the concept map into Atomic Structure as one map and Bonding as another had created (the concept map for Bonding created by the same students is shown in Figure 15). This has been amalgamated by the researcher as many students orally stated the links rather than drawing them in, or wrote lists of concepts rather than creating a map. Therefore, the placement of the concepts does not reflect what the students ranked as the most important, but instead is an amalgamation of the thoughts of the students. All concepts and links are as stated verbatim by the participants; all of the information contained on this concept map was generated by the students rather than the researcher.

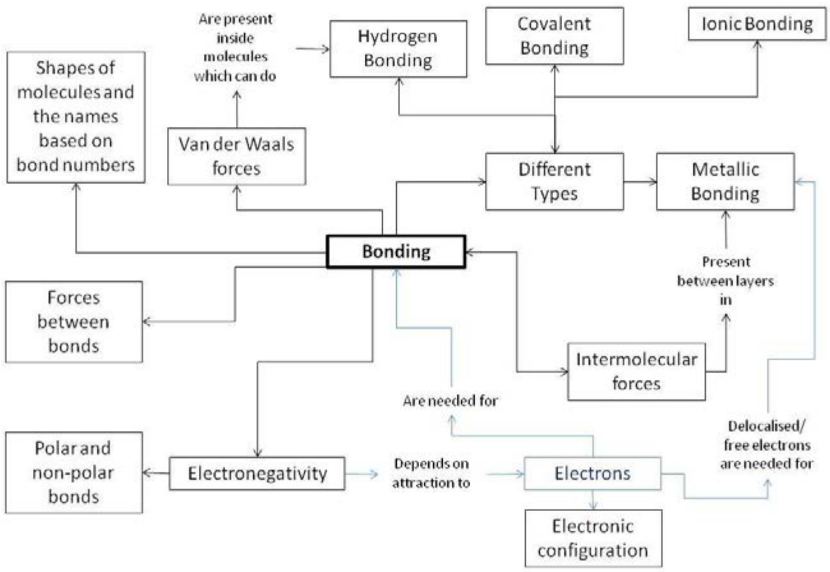


Figure 15: An amalgamated concept map created by the researcher to show all concepts the four students who had divided the concept map into Atomic Structure as one map and Bonding as another had created (the concept map for Atomic Structure created by the same students is shown in Figure 14). This has been amalgamated by the researcher as many students orally stated the links rather than drawing them in, or wrote lists of concepts rather than creating a map. Therefore, the placement of the concepts does not reflect what the students ranked as the most important, but instead is an amalgamation of the thoughts of the students. All concepts and links are as stated verbatim by the participants; all of the information contained on this concept map was generated by the students with the exception of 'Electrons'. 'Electrons' is shown in blue as although it was not listed as a concept on the initial bonding maps created, many students used electrons when orally stating the links they had created, so was added in by the researcher to show the importance of this concept.

4.4.1 EVALUATION OF THE CONCEPT MAPS

The three concept maps shown above (Figures 13 - 15) were created by the researcher by amalgamating all of the participants' individual 'maps' due to the fact that each participant was interviewed individually (see below). No primary data of the participants' individual work has been included as many participants expressed a desire that their individual written work was not to be included (e.g. did not give consent for a picture of their work to be included), though they did consent to the data being analysed alongside the rest of the cohort interviewed. All concepts and links stated on the amalgamated concept maps are as stated verbatim by the participants with the exception of 'Electrons' on the Bonding concept map (see below).

There was an almost even split between the numbers of participants who made one map in the overall topic of Atomic Structure and Bonding (Figure 13, converted into a concept map by the researcher using an amalgamation of the ideas of five students) and in those participants who made two maps; one for Atomic Structure (Figure 14, converted into a concept map by the researcher using an amalgamation of the ideas of four students) and one for Bonding (Figure 15, converted into a concept map by the researcher using an amalgamation of the ideas of the same four students). Despite the majority of students writing lists of concepts that they thought were important rather than attempting to make a 'map', the concept maps shown above suggest that students are able to identify concepts that they believe are important to a central topic, and also to create some links between the concepts they had listed.

There were some commonalities across many participants' initial thoughts. Electrons, energy levels/shells, protons and neutrons were identified by almost all participants as important concepts on their lists for atomic structure, and intermolecular forces, and different types of bonding (e.g. metallic, covalent and ionic) were common for bonding. However, although the students who had created two separate lists did not list electrons as being important to the Bonding map, when orally explaining links between different concepts they had listed within the Bonding map, almost all discussed the importance of electrons (e.g. for metallic bonding). Therefore, when creating the amalgamated map, electrons was added as an important concept on the Bonding map as it was clear to the researcher that all participants who had mentioned electrons in their oral discussion had required this concept to be added (though the boxes and arrows going from this concept have a different colour outline for clarity). This lack of including electrons on both maps could indicate that the students had compartmentalised their concepts in their minds, and held the belief that one concept could not be used in different topics, no matter how closely linked the topics were. Additionally, very few participants were able to see links between concepts on their map(s) without prompting from the researcher. This could indicate the concepts were again kept separate in the mind, however as some participants were able to create multiple links after the original prompt by the researcher, this may indicate nerves from the participant, and could explain the initial hesitation to create links (see 4.4.2.2 Are students able to see links between different chemical concepts and use a combination of concepts to tackle difficult questions, or are the concepts kept separate in their minds? for further discussion). On the other hand, as participants had not created a concept map on the paper as they included oral links rather than writing their links, the fourth stage of creating a map put forward by Trochim (1989, pp. 2-14) was not carried out by the participants independently as most required prompting for the links. Although this does create some limitations in evaluating the concept maps such as they have been created by the amalgamation of ideas from the participants, all concepts and links included are as stated verbatim by the participants (with the exception of 'Electrons' on the bonding map as stated earlier). This means that when these maps have been analysed, commonalities between the different maps have been identified and looked at rather than the prioritisation of concepts' importance (as this was not given by the students).

The mean number of concepts individually identified by the participants was 8.6 concepts for the students who created one map (maximum concepts = 17, minimum concepts = 5), and 9.5 concepts for the students who created two separate maps (maximum concepts = 12, minimum concepts = 6). This suggests that there was not a large advantage to creating one or two maps in the topic, however there was a large difference between individuals in their ability to identify links. Despite the fact that the students who created two maps were able to identify more concepts, the students who had created one map were able to develop more links between the concepts, and would often come up with multiple links from the same concept, whereas this was less common from the students who had created two maps as shown on the difference between the number of links in Figure 13 compared to Figures 14 and 15.

However, despite the students being able to create links between the concepts identified, no students were able to create a full concept map during the interview, although one participant was able to orally identify at least one link per concept identified on their map; many still only had a list at the end of the interview with no links written down. This could be due to a combination of multiple factors.

Firstly, the time constraints of the interviews being fitted around the students' timetables meant the interviews were only 30 minutes long for the creation of the concept map and the questioning on the questionnaire. This meant that typically a maximum of 10 minutes was spent on the concept map, and although the participants were reminded that at any stage during the interview they could add to their map, very few decided to do this. This suggests that more time, or prompting to the participants to add to their map may have been helpful to allow time for the participants to create the concept map layout without the time pressure. However, the researcher asked all students “Are there any other links?” to all participants after each link had been stated if there had been a pause by the student, and moved on only if the participant gave a response to indicate they were unable to identify any more links, which could limit the impact the time constraint had on the ability to complete the concept map.

Secondly, in order to reduce the potential stress to the participants, the researcher gave the option to the participants to orally state the links if the participants felt more comfortable explaining their answers orally rather than in writing, though they did ask the participants to draw an arrow or line between the concepts being linked. This option was taken by all of the participants, though a few did also write down some of the links stated. This is highly likely to be the reason that no links were originally written down, as a few participants also did not draw the arrows or indicate what the links were on the paper, and this was not picked up during the interview as the researcher was taking notes from the oral responses.

Finally, the most significant limitation to the use of concept maps was that none of the participants had created a concept map before the interview, and as such the procedure was not followed strictly by the participants. Although the participants had been issued with an information sheet with a brief explanation of how to create a concept map (see Appendix 4: The Interview Information Sheet Issued to All Students section ‘How is a concept map made?’, and had oral prompts in the interview from the researcher (see Appendix 3: An Example of an Interview Schedule used in this Research Questions 1-3), there was no example of a completed map shown to the students in the interview, so the students were unlikely to know what the final map should look like. Therefore, an example concept map (using a different topic to prevent any bias of participants using the concepts on the example map) could be shown to participants in the future in order to increase the chance that the participants would be able to create a full concept map in the interview despite any time constraints.

Overall, the use of the concept maps is limited in this research project as the researcher has amalgamated the participants' responses into three concept maps rather than having individual concept maps to evaluate. However, these concept maps still show common themes of what the participants thought was important to the overall topic of Atomic Structure and Bonding, and consequently can be evaluated within the context of this research to come to some limited conclusions.

4.4.2 Relation of the Concept Maps to the Research Questions

The concept maps were used to address Research Questions 4 and 6, however the conclusions drawn are limited for two main reasons. Firstly, as only one lesson was observed on a specific section within Atomic Structure and Bonding (VSEPR), it is unlikely that the conclusions drawn in Research Question 4 will be representative of the whole topic of Atomic Structure and Bonding due to the limited data. Secondly, as the researcher has amalgamated the lists created and oral explanations given by the participants to form the three concept maps (Figures 13 - 15), the conclusions drawn may be slightly impacted by the lack of a student created concept map. However, there are still some conclusions which can be drawn from the results, though these will mainly be indicative and will not be generalisable.

4.4.2.1 DO THE CONCEPTS THAT STUDENTS FIND IMPORTANT OR ESSENTIAL FOR ANSWERING QUESTIONS CORRELATE WITH WHAT IS COVERED IN THE LESSONS?

As stated in Section 4.2 Results of the Classroom Observation, only one lesson was observed in this research project; a revision session on VSEPR. As the topic of the concept maps was Atomic Structure and Bonding on the whole, and not specific to the topic of VSEPR, the concepts listed by the students were not expected to be limited to the concepts covered in the lesson by the teacher. However, there is an overlap between some of the concepts covered in the lesson and the concepts that the students had included on the concept map.

In the revision session, many ideas of concepts that were needed for VSEPR were suggested by students including: lone pairs, bonding pairs, and the importance of using the periodic table to identify which groups the atoms in the molecule were in to identify how many electrons were in the outer shell (electron configuration). By looking at the students' initial thoughts on their concept lists, the researcher found that some students had included a selection of the concepts covered in the lesson, though these concepts were not common to all students (see Table 4 below).

Table 4: A table to show the number of participants (out of the nine interviewed) who included the concepts covered in the VSEPR revision session on their concept map initially, or in oral explanations when talking through potential links or the importance of the concepts listed on the concept map. Some participants included the concepts in both their concept map and their oral explanations, however other participants only discussed the concept orally, and others only wrote the concepts down on their initial concept map, but did not discuss the concept orally when explaining potential links or importance of concepts to the interviewer.

Concept	Number of Participants who Included the Concept on their Concept Map	Number of Participants who Included the Concept in Oral Explanations	Was the Same Participant Mentioning the Concept on the Concept Map and in Oral Explanations?
Shape of Molecule	2	2	- Both participants mentioned this at both stages
Lone Pairs	1	2	- One participant mentioned this at both stages - One participant mentioned this orally only
Bonding Pairs	1	2	- One participant mentioned this at both stages - One participant mentioned this orally only
Periodic Table	2	2	- One participant mentioned this at both stages - One participant mentioned this on concept map only - One participant mentioned this orally only
Groups	1	2	- One participant mentioned this at both stages - One participant mentioned this orally only
Electronic Configuration	3	3	- One participant mentioned this at both stages - Two participants mentioned this on concept map only - Two participants mentioned this orally only
Outer Shell Electrons	2	2	- One participant mentioned this at both stages - One participant mentioned this on concept map only - One participant mentioned this orally only
Energy Levels/Shells	5	5	- All five participants mentioned this at both stages

As shown in Table 4, the most commonly included concept on the students' concept maps was energy level/shells, though there was at least one mention of all the other concepts covered in the revision session observed. Only two students specifically mentioned the shapes of molecules as important on the concept map, and only one included the lone and bonding pairs as well, however both students orally discussed the lone and bonding pairs when either mentioning links between the concepts or the importance of the concepts on their concept maps. This limited number of participants mentioning the shapes of molecules, lone pairs and bonding pairs could be due to the broad topic posed to the students in the interviews, rather than the specific topic of VSEPR to match the revision session. Additionally, the students who mentioned the periodic table talked about how the electron configuration and number of electrons in the outer shell could be discovered from the location of the element in the periodic table, which was similar to what the teacher had said when going through the methodology of calculating the 3D shape of a molecule (to both identify the central atom, and work out how many bonding and non-bonding pairs would be present). A potential explanation for these results could be that even without the students specifically stating the shape of the molecule as concepts on their map, it was considered at some level in regards to bonding (one student discussed how the periodic table and electronic configuration could be used to work out the type of bonding that would be likely to take place). Therefore, even though only a small percentage of students included the concepts covered in the revision session on their concept maps, it is possible that the students were thinking more generally than just on the topic of VSEPR, so gave responses which would be useful concepts to consider across different forms of bonding (e.g. metallic bonding, ionic bonding, covalent bonding) rather than in one form (as VSEPR applies in covalent bonding).

Overall, some of the concepts that the participants found important did correlate with what was taught in the revision session. None of the participants put down all of the concepts mentioned in the revision session on their map, and as such each concept is only mentioned by a few participants. However, it is possible that the difference in concepts mentioned on the map is because the students were given a specific topic in the lesson whereas the concept maps have been developed for a general topic, rather than the students missing the concepts off their map as they viewed the concepts as unimportant.

4.4.2.2 Are students able to see links between different chemical concepts and use a combination of concepts to tackle difficult questions, or are the concepts kept separate in their minds?

When constructing the concept maps, very few participants were able to create links between the concepts they had put down on their map without initial prompting by the researcher. However, as mentioned in Section 4.4.1 Evaluation of the Concept Maps, once the participants had been able to identify one link between some concepts, the majority of the students were able to come up with multiple links between different concepts, suggesting that the hesitation in their response may have been for a different reason. For example, as the concept maps were only introduced to the participants by the researcher, the hesitation in the responses could potentially suggest that the students were unsure of what was expected of them, rather than them being unable to identify any links. Additionally, the participants could have felt under pressure, and nervous to offer a response initially, however were able to have a confidence boost from their first answer to be able to continue to find more responses as the interview and creation of the concept map continued. Therefore, although there were hesitations in the responses of the students to create links in the concept map, this does not necessarily mean that the students were unable to create links, especially as the cohort had common concepts and links present across a number of concept maps.

However, the cohort did not seem as certain when applying the concepts they had identified on their concept map to the questionnaire. When asked to explain which concepts were useful to answer a specific question on the questionnaire (the question chosen depended on the participant), many students only mentioned one or two concepts, even if they had identified more links on the concept map with those same concepts. For example, if the students were asked about a question which included electronegativity as one of the concepts required, many were able to state that electronegativity was needed, but very few would relate that to other concepts which may be useful to consider e.g. electrons, polarity, covalent bonding. There was a very slight difference in the ability for the students tested to identify concepts which may help answer questions based on whether the students had made one or two concept maps. Although most students could identify two concepts per question (5 out of 9 total interview participants), those who had created two separate concept maps could only identify one or two concepts relevant to answer a question, whereas those who had created one concept map were able to find two or three concepts relevant to the questions in their minds, again suggesting a combined concept map between Atomic Structure and Bonding allowed for more links to be identified. Additionally, many students purely stated the concepts being applied, and occasionally a definition of the concept, rather than explaining why the concepts they had selected would work to answer the questions. However, the number of links that the students had created on their concept map(s) did not appear to impact on how many concepts the students identified to help answer the questions. The participants with the most and least links identified on their combined concept maps both identified three concepts to help answer the questions; likewise the same was shown for the separate Atomic Structure and Bonding maps, with two concepts identified from their concept maps to help answer the questions. This potentially suggests that the students may either struggle to identify multiple concepts to apply to a problem, or that once the students have identified a concept they believe may be useful to tackle the question, they do not look for other concepts that they could use alongside this unless they identify that the concept chosen is not able to solve the question by itself.

Overall, the results shown by the responses of the participants to both the creation of the concept map and the interview questions on concepts suggest that there may be some compartmentalisation in the students' minds between different concepts, but that when encouraged to think of links between concepts, the students are able to identify how the concepts can be linked. As the students were able to create and explain some links between concepts outside of the context of answering questions (on the concept map), it is likely that the concepts are not fully separated in the students' minds, however the students are not as able to identify a variety of concepts in the context of answering tricky questions, often choosing to only select one or two concepts to apply while answering the question. This suggests that the students may be seeing the 'concepts' as 'facts' and as such only apply the concepts to situations that they are familiar with, rather than attempting to apply them to the trickier questions which they had not seen before (see Section 2.1 Are teachers informing students of the concepts being covered in each lesson/are students aware of the concepts being covered in the class?). Therefore, the results suggest that although the students are able to create links between various chemistry concepts, they may elect not to do so when answering questions if they have already a method of tackling the question based on previous experience in that topic with limited concepts.

SECTION 5: DISCUSSION

5.1 ANSWERING AND EVALUATING THE RESEARCH QUESTIONS

5.1.1 SUMMARISING THE SIX RESEARCH QUESTIONS

To evaluate the main aim of this research, six research questions were asked (see Section 2: Research Questions and Aims):

1) Are teachers informing students of the concepts being covered in each lesson/are students aware of the concepts being covered in the class?
2) Do teachers aim to identify and rectify misconceptions in the classroom?
3) What techniques/resources do teachers use to illustrate and explain concepts?
4) Do the concepts that students find important or essential for answering questions correlate with what is covered in the lessons?
5) Are students able to answer questions testing conceptual understanding in different circumstances (for example when asked questions not in the typical exam style?)
6) Are students able to see links between different chemical concepts and use a combination of concepts to tackle difficult questions, or are the concepts kept separate in their mind?

These sub questions have been evaluated in the context of the case study, and as such the results indicated in the previous section (see Section 4: Results for detailed analysis, specifically Sections 4.1.3, 4.2.1, 4.3.5 and 4.4.2) suggest limited conclusions can be drawn in these areas based on the research conducted.

For Questions 1) to 3), it was found that the teacher observed implicitly mentioned concepts which were relevant to the topic through collecting and presenting students' ideas of what they knew was important about the topic (suggesting these concepts have potentially been stated more explicitly in the past), made a conscious effort in the classroom to identify any misconceptions present in the students' minds, as well as rectify them with a variety of resources with some evidence of success in the lesson itself. However, when addressing Questions 4) to 6), it appears that the students only showed limited ability to correlate and apply their knowledge to novel situations, and required a lot of prompting from the researcher to arrive at the correct answer (on the CCI) or to create links between their own ideas (on the concept maps); however, this could be due to the way the research project was presented to the students (see Section 5.6 Limitations of this Research).

5.1.2 Answering the Main Aim of this Research

When evaluating all of the six research questions above, there are many different areas to consider when evaluating the main aim of this research: to ascertain the extent and cause of conceptual chemical misconceptions in the classroom and whether they can be rectified within the curriculum.

Based on the research conducted in the study, it can be concluded that for the cohort tested, there are a couple of potential causes for the introduction of misconceptions. Firstly, the terminology in the chemistry classroom (and in the education setting in general) is different to the colloquial language used in their everyday lives. This has caused issues in the understanding with some of the students (see Section 4.3.3 Terminological Understanding Problems or

Wording of the Questions Problems which could be Incorrectly Classified as Misconceptions). However, the larger issue appears to be the ambiguity in what is meant when orally stating or explaining new concepts to students, as well as the time constraint in the lessons preventing teachers and students from effectively being able to analyse whether the students have fully understood what is being taught. Despite the teacher’s efforts to identify any misconceptions present in the class during the observed lesson, there was still evidence of misconceptions present when interviewing the students, particularly in their understanding of equations. It appeared to be due to students being unclear in oral explanations whether the number stated is a coefficient or a subscript number, and why this is important (see Issue of Terminology in the School Environment below). This could also suggest that the students appear to be exhibiting some signs of rote learning despite efforts made by the teacher to prevent this; further evidenced by the reasons given in the interview stage for the answers the students gave. Some answers given suggested that occasionally the students had selected an answer without understanding why this answer was correct, as they restated a known definition or principle, but struggled to explain in their own words what this meant, or how this related to why they had chosen their answer. This could mean that teachers are unable to identify these issues in the lessons, as correct answers given are unlikely to be explored further within the constraints of the timetable, especially if these restating of facts can lead to students gaining correct marks in exam questions as this can potentially suggest they understand the topic.

Therefore, the causes of the misconceptions shown in this project could be due to time restrictions on teachers being able to effectively explore whether the class does have misconceptions as the students could correctly answer questions on these topics in the lessons first being taught, and potentially later (if the student is rote learning) as well as a miscommunication between the students and teachers as oral dialogue could allow both parties to be misunderstanding what the other is saying despite using the same words.

The extent of the misconceptions shown in this cohort fortunately does not appear to be too detrimental to the students' understandings at this time (as students were able to correct themselves with limited prompting by the researcher in most cases), however this suggests that, if left unchallenged, these misconceptions could become ingrained in the students' minds leading to further problems later on if the students decided to study chemistry at a higher level. The issues present in this study (in terms of atomic structure and bonding) have been found at higher education levels (Smith, 2016), suggesting that this finding is not unique to the participants who took part to this project (see 5.3 Comparisons of Results with Other Results from Similar Projects below) which potentially means that if these misconceptions can be addressed in the earlier stages of education, then this can help to limit the extent of the misconceptions found at these higher levels.

As these misconceptions appear to be surface level rather than deeper level for this cohort as the students were mainly able to correct their own mistakes, these should be able to be rectified to a certain extent within the curriculum without having to make any major changes to the curriculum structure itself. The importance of terminology in science is stated clearly in the Key Stages 3 and 4 Framework Document for the English National Curriculum with a brief section specifically targeting the ‘spoken language’ component in science, mentioning the importance of using spoken language to ‘[develop] their scientific vocabulary and [articulate] scientific concepts clearly and precisely (Gov.uk, 2014, p. 57). When this is coupled with the assertion that teachers should use ‘discussion to probe and remedy [the pupils’] misconceptions', it can be assumed that the framework document was developed with an awareness of the importance of using the correct scientific terminology. Additionally, the guidance from Key Stages 1-4 in science states 'pupils should be able to describe associated processes and key characteristics in common language, but they should also be familiar with, and use, technical terminology accurately and precisely' (Gov.uk, 2015). This shows that the English National Curriculum was developed with a consideration of the importance to establish the pupils' understanding of the scientific terminology, though there may be more an issue with the emphasis towards spoken terminology/specific terminology on topics rather than an understanding of the terminology itself. As some exam mark schemes still occasionally request the specific words (see Section 2.5), rather than allowing for an explanation of the key word in its place, this potentially means that the terminological issues are identified as conceptual issues as the student is unable to articulate the concept in the desired way when writing down their thinking even though conceptual understanding is present in oral discussions. Therefore, the teacher should take steps to make sure that the students are aware of how to communicate both orally and through writing to mitigate the chances of terminological issues arising when students are answering exam questions, or other written tests.

One way of potentially rectifying the terminological issues based on oral explanations is to clearly state the oral explanations alongside having the equations written down so that the students can see the difference between any coefficients and subscripts as written in the equation (e.g. the differences between the two twos in $2XY_2$). Additionally, asking the students to explain what the difference is in their own words or to draw out the various different structures shown by the different formulas may aid with embedding the idea that there is a difference between coefficients, subscripts and superscripts in chemistry, as this was the technique used by the researcher with some success in the interview portion of this project. Furthermore, new terminology should be explained to the students clearly if there is a chance of students associating the new vocabulary with an incorrect principle (e.g. thinking incorrectly that elements with high electronegativities would repel electrons due to their understanding of negative charges).

As the teacher observed in this research appeared to be attempting to tackle the misconceptions in the classroom, another approach could be that the students could be asked to interact between themselves to explain the concepts/topics to each other as an exercise, or have to attempt a written explanation as part of a homework exercise alongside the answers to show their understanding outside of what the teacher is saying. This could attempt to combat students accidentally falling into rote learning as the students are not only repeating what the teacher says as an explanation, but having to understand what that means to a suitably high level to be able to rephrase and explain in their own words what the teacher means.

As these issues are not unique to this report, more detail on these areas are discussed below in the context of education on the whole, and what can potentially be done in education as a whole if applying the findings of this study to a larger population.

In this discussion, various aspects of the research project are considered:

- Issue of terminology in the education environment
- Use of the CCI as a diagnostic tool for misconceptions vs a diagnostic tool for identifying areas the cohort has difficulties with

- Comparisons of results on the areas which the participants seemed to find difficult with results from similar projects
- Reflections on the research methods used compared to other methods used by the author previously

5.2 Issue of Terminology in the School Environment

Many of the participants in this study appeared to have some level of difficulty with terminology (either in the CCI itself, or when expressing themselves in the interviews – see Section 4.3.3 Terminological Understanding Problems or Wording of the Questions Problems which could be Incorrectly Classified as Misconceptions), an issue which has been shown in chemistry education before (Yager, 1983; Song and Carheden, 2014).

As stated in Section 1.2.2 Accepted Definitions for Misconceptions Used in this Research Project, vernacular misconceptions have been identified when there is an issue with terminology which has a different meaning in different scenarios. The research conducted here does not identify specific 'dual meaning vocabulary (DMV) words' – words that 'can be used in both scientific and everyday contexts' (Song and Carheden, 2014, p. 129) – however, it does help to illustrate the vernacular misconceptions or conceptual misunderstandings that can arise when students are not fully aware of the scientific meanings or expected format/convention of equations/formulas. Previous researchers have emphasised the potential issues students could have when carrying out 'multilevel thought' when learning new topics in science; the idea that 'students are commonly presented with explanations that involve being asked to think about very different types of things at once' (Taber, 2013, p. 157). In fact, Johnstone posed the idea of three levels of knowledge in the 1980s - the ‘macroscopic’, ‘submicroscopic’ and ‘symbolic’ levels (Johnstone, 1991) – now commonly referred to as ‘Johnstone’s Triangle’ or ‘The Chemistry Triplet’ (see Figure 16 created by Roché (2013) below) though explained later: ‘it is psychological folly to introduce learners to ideas at all three levels simultaneously. Herein lies the origins of many misconceptions.’ (Johnstone, 2000).

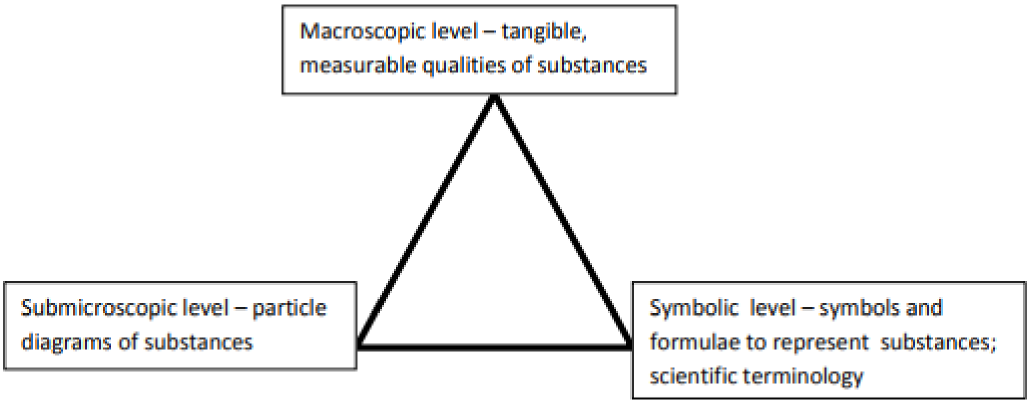


Figure 16: A diagram created by Roché (2013, p. 8) depicting ‘The Chemistry 'Triplet'’.

The emerging issue found in this research was that the participants often struggled to express their thoughts using the expected terminology, and some seemed to have some issues fully understanding the questions; the students seemed to have issues with the ‘symbolic level’ described in Johnstone’s Triangle. This could be due to the ambiguity when orally explaining certain aspects in the lesson; unless the students understand the common format when orally stating a formula, equation etc., it is unlikely they will be able to correctly write down the equation being orally stated. For example, chemistry convention for formulas can include a combination of subscript numbers, coefficients, and superscript numbers. If students are unaware or not certain of the format, and only hear an oral description of the formula, mistakes could be introduced when the students write down what they understand the formula to be.

As stated in Sections 4.3.1 Evaluation of the Original Hypotheses Formed by Looking at the Answers for Questions 1 and 2 from the Questionnaire and 4.3.2 Issues which could be Classified as Misconceptions, some participants orally explained what would be classified as a different formula from the one written on the questions being asked (orally stating "X two Y" to describe the compound XY_2), and another participant (who opted out of interview) rewrote all equations with coefficients rather than a combination of coefficients and subscripts. This shows the importance of understanding the writing convention used in chemistry (or any other subject) lessons when orally explaining equations or topics which contain DMV words to students when first approaching these topics; the oral explanation could be considered ambiguous in meaning as the students are not as used to the context of the lesson when compared to the teacher.

5.2.1 Potential Issues Arising from Utilising Peer Learning in the Classroom

As mentioned earlier, a key feature of the lesson observed was peer learning and group discussions in the classroom as Social Constructivism seemed to be one of the main learning theories adopted in the classroom. Most of the lesson revolved around students discussing in groups and collating their thoughts, both in terms of broad ideas and methods to answer the problems posed (see Sections 4.2.2.2 and 4.2.2.3) with the teacher collating the ideas onto the main whiteboard where relevant. Also, the majority of the teaching was done through peer learning as the students were working in groups and only one student would pose an answer if the teacher asked for a method of how to answer the questions posed; even if the student had given an incorrect answer or methodology, the teacher would ask a peer to correct this, showing how the lesson was focused around students helping each other learn. Although this worked well in order to get the students' initial thoughts on the topic being taught in the session so that the teacher had an idea of the students' level of understanding, and then asking students to provide their answers to the questions posed in the class (e.g. sharing their thought process) and correct each other if needed, there are potential problems with using this technique in relation to terminology.

In the interview portion of this project, the participants who agreed to be interviewed all showed they had taken a logical approach to answering the questions being asked on the CCI, though some had struggled to effectively communicate this in a way which used scientific language, preferring to default to using colloquial language. This is not by itself a problem; it showed the students had been able to interpret what they had been taught by their teacher into a way which they understood rather than repeating what the teacher stated. However, it introduces a question of whether by always talking in colloquialisms to peers, the students will be able to be as comfortable with the scientific language in the classroom.

For example, the main issue with terminology found in this research project was the potential for accidental misunderstandings occurring with oral communication (e.g. stating "X two Y" when meaning XY_2). If the students are discussing with each other, and all are able to understand what is meant by the speaker, or think that they do – even if it is not scientifically accurate – it is less likely to be raised as something to be corrected in the future. This means that there is a chance that a misunderstanding can go undetected by the peer group as the participants think that they understand what is meant by the other members in the group, but there is a slight difference in what is said and what is meant, leading to issues later on for the student (Topping and Ehly, 1998, p. 54). Therefore, although this could be a small issue in a failure for the student to be able to explain a correct line of reasoning, it could also be a much larger issue where the student has misunderstood a concept being taught and has never been corrected due to the teaching methods used. This restates the importance of teachers needing to be aware of any pitfalls that may occur depending on the method of teaching being used, and any workarounds that can be used to try and combat these; if an individual assessment is used alongside peer learning, this may help to identify whether misconceptions are present in the individuals' minds.

5.3 Use of the CCI as a Diagnostic Tool for Misconceptions Compared to a Diagnostic Tool for Identifying Areas the Cohort has Difficulties With

A CCI was used in this research as a method of identifying whether the students had misconceptions as the CCI has been established as a method of analysing conceptual understanding (Mulford and Robinson, 2002; Pavelich *et al.*, 2004; Barbera, 2013). However, although CCIs can be used to discover misconceptions that the class could have through the use of the distractor answers (Mulford and Robinson, 2002, p. 739), the interview portion of this research suggested that the students chose the distractor answers for different reasons which were not necessarily misconceptions. Therefore, without having the interview portion of this project, it is likely that an incorrect assumption would have been made about why the students chose the distractor answers, as can be seen by the different hypotheses which were theorised to explain the students' responses to the stoichiometry questions based purely from the CCI results in this case study.

This correlates with the research carried out by Krause *et al.* (2004, p. 3) when creating a CCI as they discovered ‘a distractor might be written to test for a particular misconception, but students might be selecting that distractor for a different reason’. Thus CCIs can be used as a standalone resource to identify areas that the cohort struggles with by identifying questions where there is a higher percentage of students selecting the distractor answers (e.g. those questions with high discrimination scores), but cannot be used to say why the students have selected their chosen answer (Krause *et al.*, 2004, p. 2).

Additionally, the nature of multiple choice questionnaires prevents the CCI from being able to be used as a method of understanding the reasoning behind the answers chosen. The CCIs are designed to have one correct answer, and the other alternative options are distractor options, however the distractor answers are only attempting to identify known misconceptions. For example, distractors are often created by using ‘conceptual student errors’ or, if it is a calculation question, by deliberately missing a step so that the distractor answers can seem plausible (Towns, 2014, pp. 1426, 1428-1430). Due to this process of creating the CCI, the CCI used in this project and in other studies will not be able to effectively identify or tackle all misconceptions held by the students.

This means that CCIs and other multiple choice tests should not be used as the full extent of identifying any misconceptions held by the cohort being tested. However, these will help any teachers and educators to identify areas which their students struggle with that may hold misconceptions, and further in depth exploration can aid teachers to work out exactly what needs to be improved upon.

5.4 Comparisons of Results on the Areas which Indicate Conceptual Difficulties with Results from Similar Projects

Although this project was only a case study, there are many parallels that can be drawn with previous studies, both other case studies as well as large scale studies. Many other projects have applied similar methodologies when developing their CCIs in the first place; setting the questionnaire and then interviewing the students to find out why the questions posed did not necessarily obtain the expected results (Mulford and Robinson, 2002, p. 740; Krause *et al.*, 2004, p. 4; Towns, 2014). As a similar process has been carried out in these other projects using the same or very similar questions as the questions used in this research have been collated from existing CCIs (Nurrenbern and Pickering, 1987; Peterson and Treagust, 1989; Williamson and Abraham, 1995; Mulford, 1996; Mulford and Robinson, 2002; Taylor, 2013; Smith, 2016), some comparisons can be drawn despite the limited data sample in this project.

By looking over the areas in this project which the participants seemed to find difficult, specifically Questions 1, 2, 5 and 6 as these all had a percentage score of less than 50% correct despite these subject areas being covered in the syllabus, the results shown here seem to align with results shown in other projects.

Previous data gathered by using Question 1 shows that this question has been challenging for a number of different students across the years. As different interventions were used in these projects, only the pre-test or initial data gathered when participants first saw these questions will be compared to allow for a more accurate comparison across the data sets. In this project, none of the participants were able to answer this question correctly (0% of 12 participants);

Nurrenbern and Pickering (1987, p. 509) obtained a correct result from 17.5% out of 200 participants, Sawrey (1990, p. 253) obtained a correct result from 11.46% out of 323 participants, Arasasingham *et al.* (2004, p. 1521) obtained an average of 21% correct from a total of 731 participants across three groups of participants, and Taylor (2013, p. 17) obtained ~25% correct from 52 participants. Although the cohort tested in this project has the lowest percentage correct score, the most commonly chosen incorrect answer by the participants in the studies conducted by Sawrey (1990) and Arasasingham *et al.* (2004) was also $3X + 8Y \rightarrow 3XY_2 + 2Y$. The difficulties that the students had with Question 1 seems to correlate to the results shown by previous studies using this question, summarised by Taskin and Bernholt (2014, p. 168) with an excerpt from Arasasingham *et al.* (2004, p. 1521) referring to previous work done by Yarroch (1985, pp. 454-457) stating 'the arrow in the balanced chemical equation was nothing more than an equal sign where the number of atoms on each side of the equation had to equal each other, rather than the chemical process expressed in the equation'. This seems to suggest that the observation that the students appeared to prioritise including all atoms of the reactants and products in the final equation, rather than a molar ratio for the reaction, is not unique to the cohort tested. Therefore, although the participants in this study seemed to exhibit some confusion over the chemical conventions used in chemistry, a potentially larger issue is that students do not realise what an equation is representing in chemistry. Again, this is perhaps essentially a terminological issue; students may have the understanding that ‘Reactant A and Reactant B make Product AB’, and mistakenly infer that ‘Reactant A + Reactant B = Product AB’ rather than having the understanding of the difference between an ‘=’ and ‘→’ in equations. This is especially relevant when talking about reversible reactions ‘⇋’ as the reaction can occur in either direction, meaning that an ‘=’ would be inaccurate to explain the reaction taking place.

Additionally, the difficulties with Question 2 are not unique to the cohort tested in this research. By looking at only the initial responses from when the questionnaire was first completed by the students i.e. the raw data from the CCI before any interviews were completed, this can be compared to other projects pre-test result. In this study, only 16.7% of 12 participants were able to answer this question correctly; Mulford and Robinson (2002, p. 79) obtained a correct response from 11% of 1418 participants, whereas Nurrenbern and Pickering (1987, p. 509) were able to obtain a correct result from 29% of 200 participants, and Taylor (2013, p. 17) was able to obtain a correct result from 30% from 52 participants, and Arasasingham *et al.* (2004, p. 1521) obtained an average of 26% correct from a total of 731 participants across three groups of participants when asking the participants to draw the products in a blank box rather than selecting an answer. Again, the cohort studied in this report has a low percentage correct score compared to the other studies, however the issues faced by the participants in the other studies shows some signs of correlation. The most common reason that the students failed to obtain the correct answer was due to the students choosing an answer that did not have the same number of S atoms and O atoms in the products box compared to the reactants box. Similarly to Question 1, this could suggest a lack of understanding about an equation; Mulford and Robinson (2002, p. 741) found that initial responses 65% 'chose responses that do not conserve atoms'. However, there is little to no discussion in the other papers with multiple choice answers as to the incorrect answers chosen. The open-ended question set by Arasasingham *et al.* (2004, pp. 1521, 1523) suggested that the cohort tested there had an issue with drawing the structure using the boxes and circles. They found many 'representing $2SO_3$ as S_2O_6' (option e) on the questionnaire issued in this report) or 'S-O-O linkage; these students believed that O_2 directly added to S' although the same equation for the reaction had been stated and the reactants box provided similarly to Question 2 in the CCI used here: 'The equation for a reaction is: $2S + 3O_2 \rightarrow 2SO_3$.' Again, this suggests students struggling with the difference between coefficients and subscripts in the first incorrect response, and a potential lack of understanding that O_2 molecules can disassociate into 2O atoms during reactions; the initial structure of the reactants does not need to be maintained in the products. Therefore, it can be suggested that the students who participated in this study showed a greater level of conceptual understanding of atomic structure compared to the cohort tested by Arasasingham *et al.* (2004). This is due to the fact the majority of students tested in this project selected an answer that was structurally correct although it did not conserve the atoms from reactants to products, though many students in interviews stated they had not considered the reactants box and relied solely on the equation provided.

There is limited research carried out using the same questions on VSEPR as used in this research project. In this study, Questions 5 and 6 were only answered correctly by 16.7% and 41.7% respectively from 12 participants. Taylor (2013, p. 17) was the only paper authored by another researcher which used this exact question as this question was taken from the report written by Taylor (2013), and obtained a correct result from 40% and 45% respectively from 52 participants. However, as Taylor (2013, pp. 1, 34) was investigating the 'effects of visualization tools on the conceptual understanding of basic chemical processes and changes' and found that 'the averages of correct answers on the Chemical Concept Inventory did not change from the beginning of the semester to the end' as the test was administered twice, there is no discussion on potential reasons for these results.

This question set on VSEPR was first posed by Peterson *et al.* (1989) when developing a 'written diagnostic instrument to identify grade-11 and -12 students' misconceptions and misunderstandings of the chemistry topic covalent bonding and structure', though the original question set is slightly different to the one used in this research project. The original question set did not include pictorial answers, and references to the specific 3D shapes of the molecule formed as seen in the original question have been removed from the follow up question to prevent a bias towards any option for the second half of the question based on the answer to the first half; the original question set can be found in Figure 17 below:

Item Testing the Shape of Molecules

Nitrogen (a group 5 element) combines with bromine (a group 7 element) to form a molecule. This molecule is likely to have a shape which is best described as

(1) trigonal planar
(2) trigonal pyramidal
(3) tetrahedral

Reason

(A) Nitrogen forms three bonds which equally repel each other to form a trigonal planar shape.

(B) The tetrahedral arrangement of the bonding and non-bonding electron pairs around nitrogen results in the shape of the molecule.

(C) The polarity of the nitrogen-bromine bonds determines the shape of the molecule.

(D) The difference in electronegativity values for bromine and nitrogen determine the shape of the molecule.

Figure 17: The original question pair as first presented by Peterson *et al.* (1989, p. 305).

Peterson *et al.* (1989, pp. 309, 311) do report the results of using this question pairing, stating 35% of 159 grade-11 students and 63% of 84 grade-12 students managed to obtain the correct shape of the molecule, though 'only 13% of the grade-11 and 38% of grade-12 students could correctly predict and explain the shape of the NBr_3 molecule'. It is of note that Peterson *et al.*

(1989, p. 311) did state the answers provided by the participants and found all questions asked 'relating to the shape of molecules illustrated weaknesses in student understanding of the valence shell electron pair repulsion theory', although the CCI used in this research study only had one question set on VSEPR. The multiple questions used in the original questionnaire suggested 'although students in the sample generally appeared to understand the principle of [VSEPR], its application to problem situations led to the identification of three common misconceptions: bond polarity, repulsion between bonds only, and repulsion between nonbonding electron pairs only were three factors commonly identified by students as being responsible for molecular shape' (Peterson *et al.*, 1989, p. 311). These results are relatively similar to the results found in this study, though present in the opposite manner to those discussed by Peterson *et al.* (1989). Although very few participants were able to predict the correct shape of the NBr_3 molecule formed, the students interviewed seemed to show an understanding of the principle behind VSEPR rules. More students in this study stated the correct reasoning behind their answer than had selected the correct 3D shape (e.g. were able to suggest factors contributing to the 3D shape than could tell the correct shape), though this opposite result to Peterson *et al.* (1989) could have been due to the slight differences in the questions from the original.

The question set created by Peterson *et al.* (1989) was also used by Birk and Kurtz (1999, p. 124) to analyse the retention of misconceptions over time with the test being administered twice across the year; this was a study across a number of different age groups from high school up to graduate students, as well as community college and university chemistry faculty staff. The numerical results are only given for a statement which relates to the concept or misconception being addressed, and are stated as 'Percent Selecting Pairs Supporting the Statement >75% of the time'. Therefore, it can be inferred that there is a high chance the results stated for the support of the statement 'Repulsions between all electron pairs (bonding and nonbonding) result in the shape (according to VSEPR theory)' obtained the correct structure of the NBr_3 molecule as well as the correct reasoning. The results suggest a trend of conceptual understanding improving with the level of education the participants held: 2% of General Chemistry 1 (n = 244), 4.8% of General Chemistry 2 (n = 271), 31% of advanced undergraduates (n = 62), 34% of new graduate students (n = 34), 56% of advanced graduate students (n = 55) and 81% of faculty members (n = 21) selected pairs supporting the statement (Birk and Kurtz, 1999, p. 127). However, the researchers have excluded the results given by the 139 high school students who would compare more to the cohort tested in this project stating 'high-school subjects were not included because their results were at the level of statistical guessing. Analysis of specific answer-reason pairs for the high school students confirmed this result' (Birk and Kurtz, 1999, pp. 124-125). Again, this result by Birk and Kurtz (1999) correlates slightly to the results in this study as one student indicated they guessed on Question 5, and one participant indicated a guess on Question 6 as well. However, all of the interviewees who had not indicated a guess were able to explain their thought process for the question set, suggesting that the four students who had indicated a guess were the only four who had guessed on these questions, and it was potentially dismissive to exclude the results from the high school students as the results may have indicated a lack of concept understanding as has been shown in previous studies.

Overall, by looking at the four questions which indicate areas for student misunderstanding on this study, the results shown in this project are able to be correlated to previous work into misconceptions. However, the in depth research obtained from the interviews suggests that the reasoning behind the answers given by the participants in this study may be different to the assumed reasoning from the participants in other studies.

5.5 Reflections on the Research Methods Used

As stated earlier, this research was proposed as a follow on from previous research carried out by the author. As previous work carried out by Smith (2016) suggested that at undergraduate level there were chemical misconceptions present, this research was posed to evaluate whether similar results were shown at a younger age, but using a much more in depth approach.

The initial research design carried out by Smith (2016) was issued in a different format to the research design used in this project, with a 20 question CCI being generated looking at five areas in chemistry while working with four other researchers. This CCI was issued three times to participants, with CCI 2 being adapted from CCI 1 to focus on the problem areas of the participants, and two resources being generated (on Stoichiometry and Shapes of Molecules/VSEPR Theory) to attempt to aid students' understanding before CCI 3 was issued. Therefore, the CCI in the original study was primarily used as a way of identifying misconceptions in the participants, and to evaluate the effectiveness of the resources generated when CCI 2 and CCI 3 were issued in a pre/post design to see if the issues were still as prevalent in CCI 3 (Smith, 2016).

However, the in depth research design utilised in this study allows for methods triangulation between the various research stages, as this study was investigating the reasons behind why the questionnaire answers were chosen. Due to this mixed methods approach, the results collected suggest that it could have been inaccurate to assume that an incorrect answer chosen by the participants in the Smith (2016) study showed conceptual misunderstandings were present.

The methods used in this project and the links between these stages are depicted in Figure 18 below; there are multiple links between the four stages of the project which allow for multiple correlations of the results to take place rather than each stage being separate.

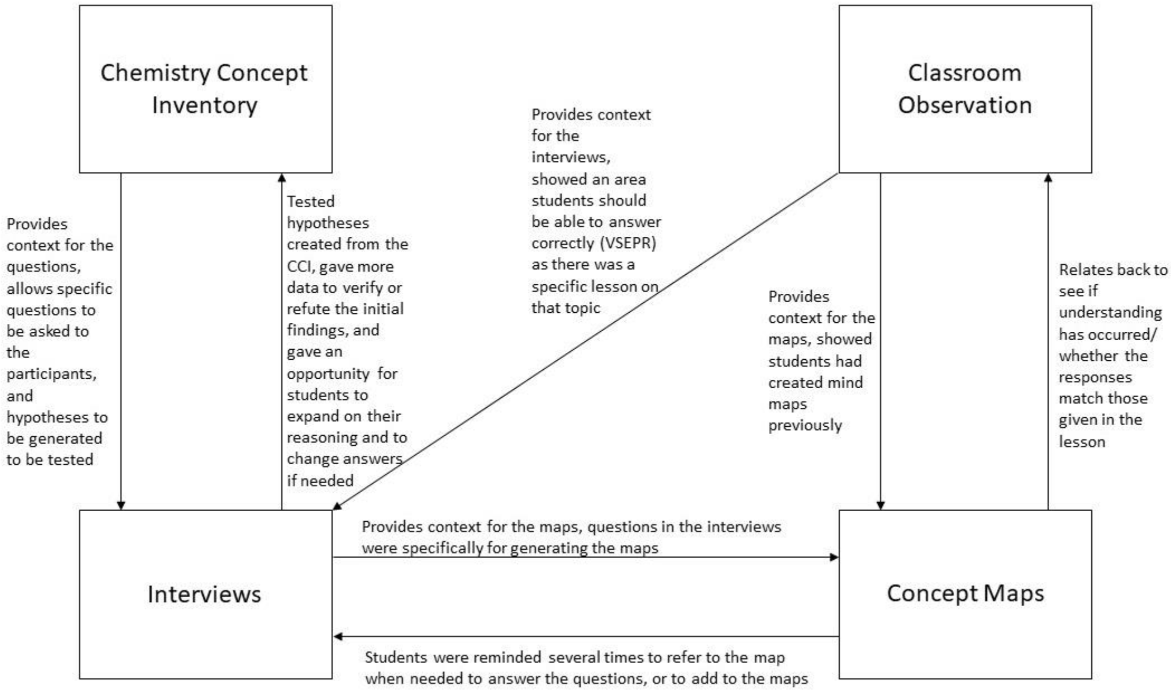


Figure 18: A diagram to show the various links between the sections of the research project, and how methods triangulation has occurred.

By using the research design depicted in Figure 18 in this study, the data collected was able to be analysed in depth a number of times, with potential hypotheses generated at the various stages to be tested throughout the project. This is an improvement upon the original design used in the study at the undergraduate level as although the data collected from both studies indicates a weakness in the areas of Stoichiometry and Shapes of Molecules/VSEPR, the original study carried out by Smith (2016) assumed the reason for the incorrect answers was due to chemical misconceptions, whereas this study suggests that this assumption could be incorrect as the answers given in the interviews suggest vernacular misconceptions for this cohort, or a lack of conceptual knowledge rather than chemical misconceptions.

These findings suggest that this research design can be applied in many other studies to allow for an explanation of why the questionnaire responses were chosen, rather than jumping to a potentially incorrect conclusion to explain the results. Likewise, the CCI can be used in a school setting rather than as part of a research project. For example, a CCI may be issued to students as part of a lesson as a learning tool to aid the teacher to identify areas that the students may need more work on rather than to suggest that the students have misconceptions in this area (see Section 5.3); it can be used to prompt discussions so that the teacher can more effectively identify why the students have struggled to choose the correct answer rather than assuming they understand why the class is struggling.

5.6 Limitations of this Research

There are a number of limitations with this study. Firstly, and most importantly, only one school participated in this research project, with only 12 participants for the questionnaire, and nine of these agreeing to interview.

The limited number of participants in this study alongside the fact that only one school participated in this research means that this is a case study, rather than representative of the opinions and abilities of all AS Level Chemistry students across England. As such, the results here cannot be used to generalise these results unless ‘other readers/researchers see their applications’ (Cohen *et al.*, 2018, p. 379 adapted from Nisbet and Watt (1984)). However, as has been previously stated in 5.4 Comparisons of Results on the Areas which Indicate Conceptual Difficulties with Results from Similar Projects, the results shown by this study do line up with other authors’ conclusions from both different schools and different countries.

Another limitation with this study was due to the anonymity of the participants from the researcher. Although this helped to make sure that the researcher had no way of introducing bias into the project by not having the identities of the participants recorded next to their participant code, this caused an issue in the later stages of the research project when a participant was unsure of their code and it could not be effectively discovered. However, as the participant was able to provide a series of answers and reasoning which was similar to a completed questionnaire, it can be inferred that this participant was able to answer the questions honestly and that the data could still be used without being skewed by this unknown identity; for clarity, this student was now coded as ‘Unknown’ rather than presuming the similarly coded questionnaire (SCHW106) did belong to the participant.

Furthermore, the concept maps were not implemented as successfully as intended; the students seemed unsure of the process, and rarely were able to complete the task set forth to create a concept map without being prompted by the researcher at any stage in the process. If this study was to be repeated again, an example concept map would be provided by the researcher on a different topic to illustrate what a finished concept map could look like, and help the students to visualise what the task was. Alternatively, the researcher would choose a narrower topic (e.g.

Stoichiometry) for the students to create the concept map, as many of the participants overlooked some links which were present, potentially as the topic given (Atomic Structure and Bonding) was very broad.

Finally, there were limitations with only using one researcher; the researcher did not always identify mistakes being made by the students as they were taking notes alongside conducting the interview; some mistakes were only identified when reviewing audio recordings of the interview. This means that there is a chance that the students will have some unchallenged misconceptions which could have been identified earlier, though as many other mistakes were identified during the interviews and each student was questioned until they were able to state the correct answer to the CCI questions with their own explanations, this process may have indirectly helped to combat any misconceptions not identified at the time of interview.

5.7 Areas for Further Study

There are many different potential areas for further study to follow on from this project, including replicating this project over a larger number of schools in the country, improving on the methodology used, or investigating areas of interest that have arisen from this research.

Firstly, as this research is a case study, there is an opportunity to carry out the same research project with multiple different schools and cohorts in order to verify whether these results are also applicable to a wider range of students. By comparing the results from the cohort analysed in this project to others, and so obtaining a much larger sample would help to check whether the findings and suggestions put forward as part of this study are applicable to the wider population. Furthermore, the concept maps were not utilised as effectively as intended, and so if this project was to be repeated, an example concept map would be provided to the participants so the process of creating the concept map would be clearer.

Additionally, there were two interesting findings shown from this research which could be investigated to follow up from this research. When interviewing the students, the interviewees seemed to struggle with the terminology used, and further research into whether this is a common issue at different ages in education (both specifically in chemistry and broader in the school education on the whole) could aid teachers and students in the future. The findings in this report suggest that the issues with terminology come from oral communications not always being corrected as the listener can understand what is meant by the incorrect speech, though the extent to which this is true or not should be researched further. This would allow the ability to check whether students who exhibit this issue do understand the difference, and may help the students to more easily recognise, or be able to work out, common compounds even when the formula is stated orally and not written down. Also, carrying out this research at younger ages than observed in this research would potentially allow for the identification of when this terminological issue was first introduced to the students. Additionally, further research could provide insight into the impacts of these vernacular misconceptions being left unchallenged; whether they stay as vernacular misconceptions, or whether they develop into conceptual misunderstandings in the future as the students are unable to apply their understanding to a new scenario.

Similarly, the students seemed to struggle with the questions on VSEPR, which suggests that further research should be carried out in this area to identify why the students were struggling in this area. This is especially relevant due to the lack of similar projects carried out on the subtopic of VSEPR found when comparing the results in this project to other studies. Although the research here does not suggest that the students held misconceptions about VSEPR, it does suggest that the students do not know how to apply their knowledge to different questions on this topic, and as such this is an area which the students interviewed found difficult. One potential explanation as to why the students struggled with the VSEPR question on the CCI although they were able to answer the question in the revision session was due to the way that the students were taught how to answer the VSEPR questions; they were given steps to follow rather than applying principles. However, as only one lesson was observed it is unclear as to whether the students had originally been taught differently, though as this topic was chosen by the students to be covered in their revision session, it is likely that the students had struggled with this topic for a while. Therefore, it is an area which should be followed up in the future, as VSEPR was the only section on the questionnaire and in the interviews where the students did not seem to show conceptual understanding, and by being able to evaluate why this was the case would help educators and students in the future.

SECTION 6: CONCLUSION

In short, this study has been successful in what it set out to achieve for the cohort tested. CCI results are broadly in line with previous work which reported chemical misconceptions, and therefore the fact that the participants had chemical misconceptions could have been assumed. However, by using a mixed methods approach to allow methods triangulation to occur in the study, it was found in the interview stage of the study that many of the misconceptions present in the cohort were vernacular misconceptions rather than conceptual misunderstandings. It is possible that simply clarifying the notation used in chemistry and why it is different from that used in the other sciences continually at early ages would solve the stoichiometric problems, though time constraints in the classroom suggest that teachers occasionally do not have enough time to reinforce a scaffold for the students' learning rather than a structure to work from.

The results from this research project seem to suggest that what could potentially be first indicated as a misconception could be a terminological misunderstanding, or a lack of knowledge rather than a conceptual misconception. This suggests that these misunderstandings can be rectified within the curriculum without needing the introduction of external resources or a restructure of the existing curriculum, as the students interviewed were normally able to correct their own incorrect answers with only a few prompts by the researcher. Due to the extensive amount of previous research carried out to indicate misconceptions on the topic of Atomic Structure and Bonding, the results in this report are reassuring as the conclusions drawn indicate that students have potentially been mistakenly assumed to have deep rooted misconceptions in this area. Results indicate two key areas which may need further support, stoichiometry and VSEPR, though for different reasons.

Stoichiometric issues in the cohort tested seemed to be due to an ambiguity in the students' minds about what the terminological convention was in chemistry, as well as an incorrect priority of what was important in an equation. Terminological misunderstandings can cause various issues for the students in a number of different topics and are not only limited to stoichiometry, though can potentially be tackled more easily than challenging deep rooted misconceptions. Oral explanations using chemical conventions may seem clear to the educator, though can potentially be seen as another language to learn in the classroom as there has to be a level of understanding to correctly interpret any ambiguity in the speech, e.g. the difference between coefficients, subscript and superscript numbers when orally stated. Additionally, if the student assumes they are aware of what is meant, the students are likely to continue to hold this misunderstanding for a much longer time. Although this may eventually grow into a misconception if it is not addressed, the students were evaluated as not having a misconception in stoichiometry as the students were able to correct themselves with little external input, showing a conceptual understanding as the students could explain the concepts correctly to the researcher. However, the students seemed to prioritise the need for the equation to depict the exact scenario shown in the question rather than being applicable as a rule for the reaction, indicating a misunderstanding about what an equation represents. Again, this could be a terminological mistake; if a student has misinterpreted what is meant by the arrow in reactions and views this as synonymous with an equals sign, this could be the cause of the confusion. Both of these terminological issues can potentially be addressed in the classroom through a number of ways: the educator being aware of the chance of ambiguity in their speech and reinforcing the true meaning behind what they are saying, individual students being corrected/informed if they make terminological mistakes orally as well as written whether the teacher understands what is meant or not, and allowing chances for students to explain in their own words what they mean so that the educator can be made aware of whether there is a deeper misunderstanding present.

VSEPR issues in the cohort seem to be a lack of subject knowledge rather than a misconception. Although the students interviewed seemed to show some understanding about the rules of VSEPR and when to apply them to a question, very few were able to do this correctly to predict a 3D molecular shape. This was further evidenced by the students' lack of clear explanations in their reasoning during the interview stage of the research; while explaining the process of how the participants had arrived at the correct answer, very few were able to explain their process without contradicting themselves, though none of the participants who had contradicted themselves noticed the contradictions. This indicates the students may not have held conceptual understanding to be able to apply it to the questions asked, instead holding factual knowledge and going through a process of steps to arrive at the correct answer. If this was the case, as the questions being asked in the CCI administered to the participants were not in the typical form that the participants would be used to, their factual knowledge may not have been able to be applied to this question. This indicates that the topic of VSEPR needs to be introduced in a way that explains the process of why the VSEPR rules work to predict the shapes of the molecules. However, time constraints in both individual lessons and the school year on the whole may mean that teachers have to fall back on teaching the VSEPR rules as a step-by-step guide; in the short term this appears to be working, though this structure is not an effective long term strategy for subject knowledge retention based on the interview data collected. This is a harder issue to address than the terminological issue due to time constraints, although the change back to a two year assessment for the complete A Level at the end of Year 13 rather than preparing for separate AS exams at the end of Year 12 may aid in allowing for more time for teachers to address any issues which have arisen during Year 12.

Overall, there were clear indications of areas in Atomic Structure and Bonding which may need further support in the classroom, though the participants' explanations in the interviews suggested that these issues in the cohort tested are not due to chemical misconceptions. Therefore, there is a high chance that these mistakes can be rectified with minor changes in the classroom, for example: by the educator being aware that the terminology in the classroom may be misinterpreted, students being able and confident enough to both give and take corrections or ask for clarity when needed, by more opportunities for students to give explanations in their own words so teachers can evaluate whether a deeper issue is present, and if time allows, to be able to teach theory rather than processes to tackle questions.

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SECTION 8: APPENDICES

APPENDIX 1: THE CHEMISTRY CONCEPT INVENTORY ISSUED TO ALL STUDENTS

UNIVERSITY OF BIRMINGHAM

CCI 1	
No. of Pages	4
No of Questions	10

Participant No.: SCH001 (this code will be unique for each student so that pre and post questionnaires can be matched to the same student)

Title of questionnaire **CHEMISTRY CONCEPT INVENTORY**[1]

Time allowed **10 mins**

Instructions:

Answer all questions

Circle the appropriate answer

If you are stuck on a question, please mark it with a question mark (?) before moving on

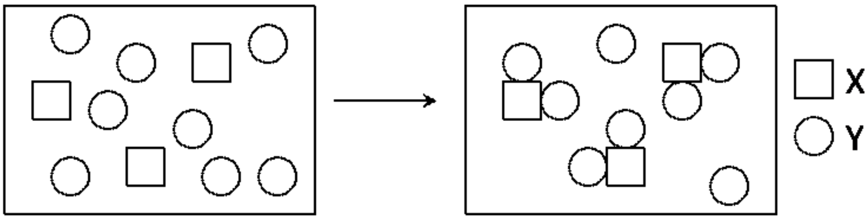
---

Disclaimer: This test is not used as a school test examination, but is for the purposes of a MA by Research educational project. This test is carried out confidentially, and your privacy is treated very seriously. In the event of you wishing to withdraw from the questionnaire, please inform Katherine Smith within 2 weeks either in person or via email at kes727@student.bham.ac.uk and your data will be destroyed.

[1] Questions selected from a range of sources (Mulford and Robinson, 2002; Nurrenbern and Pickering, 1987; Peterson et al., 1989; Williamson and Abraham, 1995; Yezierski and Birk, 2006)

Section 1:

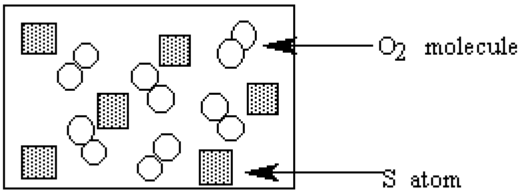
1. The reaction of element X with element Y is represented in the following diagram.



Which equation describes this reaction?

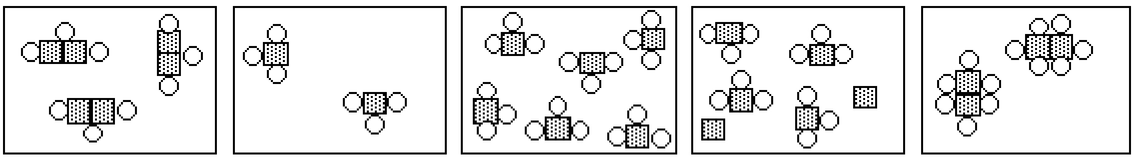
a. $3X + 8Y \rightarrow X_3Y_8$
b. $3X + 6Y \rightarrow X_3Y_8$
c. $X + 2Y \rightarrow XY_2$
d. $3X + 8Y \rightarrow 3XY_2 + 2Y$
e. $X + 4Y \rightarrow XY_2$

2. The diagram represents a mixture of S atoms and O_2 molecules in a closed container.



Which diagram shows the results after the mixture reacts as completely as possible according to the equation:

$$2S + 3O_2 \rightarrow 2SO_3$$



(a) (b) (c) (d) (e)

Section 2

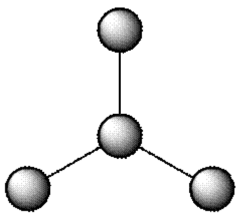
3. Hydrogen is a group 1 element, while fluorine is a group 7 element. Which of the following best represents the position of the shared electron pair in the HF molecule?

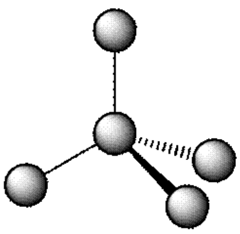
H : F	H : F	H : F	H · · F
a)	b)	c)	d)

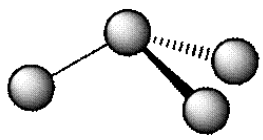
4. What is the reason for your answer to the question above?

a. Non-bonding electrons influence the position of the bonding or shared electron pair.
b. As hydrogen and fluorine form a covalent bond the electron pair must be centrally located.
c. Fluorine has a stronger attraction for the shared electron pair.
d. Fluorine is the larger of the two atoms and hence exerts greater control over the shared electron pair.

5. Nitrogen (a group 5 element) combines with bromine (a group 7 element) to form a molecule. This molecule is likely to have the following shape:

a. 

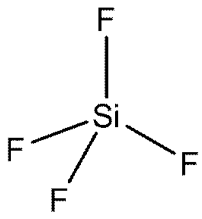
b. 

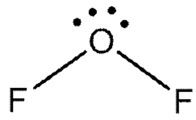
c. 

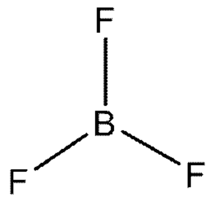
6. What is the reason for your answer to the question above?

a. Nitrogen forms three bonds which equally repel each other.
b. The arrangement of the bonding and non-bonding electron pairs around nitrogen results in the shape of the molecule.
c. The polarity of the nitrogen-bromine bonds determines the shape of the molecule.
d. The difference in electronegativity values for bromine and nitrogen determine the shape of the molecule.

7. Which of the following molecules is polar?

a. 

b. 

c. 

8. What is the reason for your answer to the question above?

a. The polarity of the molecule is due to the high electronegativity of fluorine.
b. Non-symmetrical molecules containing different atoms are polar.
c. Non-bonding electrons on an atom in the molecule produce a dipole and hence a polar molecule.
d. A large difference in the electronegativities of the atoms in bonding results in a polar molecule.

9. Oxygen is a group 6 element, while fluorine is a group 7 element. The polarity of the oxygen-fluorine bond would be best shown as:

a. $\overset{\delta-}{\mathbf{O}} - \overset{\delta+}{\mathbf{F}}$

b. $\overset{\delta+}{\mathbf{O}} - \overset{\delta-}{\mathbf{F}}$

10. What is the reason for your answer to the question above?

a. The non-bonding electron pairs present on each atom determine the polarity of the bond.
b. A polar covalent bond forms as oxygen has six outer shell electrons and fluorine seven outer shell electrons.
c. The shared electron pair is closer to fluorine.
d. The polarity of the bond is due to the oxygen atom forming an O^{2-} ion, whereas fluorine forms an F^{-} ion.

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UNIVERSITY OF BIRMINGHAM

Observation Schedule

Background:	
School/Class: This will be coded to keep the anonymity of the students and teachers	**Lesson Number:** This is to check whether the topic is part of a series of lessons, or a one off class
Proposed Learning Outcomes: To give an idea of what specifically the teacher is intending the students to know by the end of the session	
Concepts covered by the teacher: What concepts are covered; whether these are stated explicitly or not; whether this is a new or revised concept; how it is introduced/taught.	
Planned resources:	
Materials used by the teacher: For example: PowerPoint slides, drawing on the whiteboard, textbook usage etc.	
Relation of the topic to other contexts: Noting whether the topic is taught as a standalone topic, or related to other situations. Links to other subjects/topics and anecdotes would go in here	
Teacher interactions:	
How the teacher interacts with the class: This is made up of conversations led by the teacher: questioning; modelling etc; how well student thinking is extended; how much time the teacher is talking.	
How the teacher deals with individual questions: This is made up with how the teacher reacts to questions rather than posing them: do they use examples, references to external materials, restate what has been said etc.?	
Other notes:	
Anything noteworthy that does not specifically fit into one of the topics above	

Adapted from Debra Myhill (2016) *Example of a Structured Observation Schedule Qualitative*
February 2018, Version 3

UNIVERSITY OF BIRMINGHAM

Example Interview Schedule for Chemical Concepts Study

My name is Katherine Smith, and I am carrying out a research project at the University of Birmingham in partnership with your school to identify challenging chemistry concepts and how students are approaching questions in these topics. Thank you for volunteering to take part in this interview session, and for participating in the previous stages of this project. You have already seen the interview information sheet and consent form, but can you just check that you understand what this interview is about.

Before I commence the interview, do you have any questions about the study?

What you write down for the concept maps or say in this session will only be seen by the members of the research team, comprised of myself and my two supervisors, and any quotes that I may use will be untraceable back to you as they will be anonymised. All of the records will be stored securely.

If you decide that you do not want your interview responses to be included in my final report, please let me know within two weeks of this interview taking place by emailing me. This discussion will be informal - there are no expected answers as I'd just like to hear your own opinion. At the end of this session, I'll ask whether you would like feedback on your answers to the questionnaire.

If you are comfortable with what is being covered here, please can you sign the consent form, and say if you're happy for the interview to be recorded. [If they do not wish to sign the consent form, then the interview is stopped.]

Potential questions:

Please note, you are free to amend what you write down at any point during this interview.

1. *Beginning to create the concept map.* To start with, could you please write down what concepts or topics that you believe are important to be able to answer questions on atomic structure and bonding.
if prompting is needed: for example, do you think the location of electrons is important?

2. Thank you very much; please note that at any time during this interview you are free to add anything to this piece of paper. Now, could you please draw arrows between topics that you think are linked and explain these links?
If prompting is needed, one potential link may be pointed out: for example, can you think of a link between electrons and orbitals?

3. Wonderful, could you now please explain why you think that (concept listed e.g. polarity) is important?
This process is repeated for up to 5 concepts - depending on how many concepts the student puts down on the paper

4. If I could, I would like to focus on specific examples from the questionnaire. When looking at questions 5 and 6 here (the questionnaire is shown to the student for reference), could you tell me which concepts you think you needed to answer this question? Feel free to add more to the concept map you made at the start of this interview if needed.

5. *Specific to any questions not answered by the student.* E.g. Could you explain to me what you found difficult about this question?
Following student response, the student will be told the correct answer to the question as well as the reasons.

6. *Specific to the student's incorrect answers, asking a maximum of three questions here.* E.g. Could you talk me through your reasoning behind your answer to question 4? If you can't remember what you put, could you please talk me through how you would tackle this question now?
If the student is showing misunderstandings and repeatedly getting the questions wrong, then they will be corrected here after answering the interview question.

7. *Specific to the student's correct answers, asking a maximum of three questions here.* E.g. Could you do the same again for questions 1 and 2? Please talk me through how you tackled these questions.
Following student's response: That was correctly answered, well done!

8. Do you have any comments on difficulty of atomic structure and bonding? For example, are there any aspects of what has been covered in the questionnaire or in the lesson that you found particularly easy or challenging?

9. I hope to give feedback to the whole class; but do you have any questions that you would like answered now about your questionnaire or any other aspect of this study?

As a final reminder, you can contact me with any questions via email: kes727@student.bham.ac.uk. Thank you very much for your participation in this study.

APPENDIX 4: THE INTERVIEW INFORMATION SHEET ISSUED TO ALL STUDENTS

UNIVERSITY OF BIRMINGHAM

Chemistry Concepts Research Project – Interview Information Sheet

Dear Student,

Thank you for your previous participation in the research project looking at Chemistry Conceptual Understanding at A Level. This information covered in this sheet relates to the interview portion of the project, so please read through this information carefully, and ask if you have any questions about the research.

What is being researched by the interview?

The interview will consist of three broad sections. Firstly, you will be asked to make a concept map (which you can add to at any stage of the interview). Secondly, you will be asked questions relating to the questionnaire specifically (talking through what concepts and methodology you used to answer the questions). Finally, you will be asked about the level of difficulty of the central topic of atomic structure and bonding.

How is a concept map made?

For this research, firstly, you will be asked to write down all the concepts that you think relate to structure and bonding. Secondly, you should make connections between the concepts; some concepts may have multiple links, and others may have fewer. This process creates a 'concept map' which shows how different ideas relate to each other and can potentially be used together when tackling difficult questions.

How does this affect me?

The results from this research will aim to identify areas which are typically more difficult for students, and to try and combat these issues. Therefore, by taking part you will help to improve the teaching of these difficult concepts in the future, as well as receiving personalised feedback on the questionnaire if you wish.

Is there a right or wrong answer?

Each interview is looking at your individual responses – there is no correct or incorrect way to answer the questions as they are investigating your own opinions and approaches.

However, when asking questions about examples on the questionnaire, if you previously chose an incorrect answer on the questionnaire, you will be told the correct answer after you have explained your reasoning. Errors are not a problem as the questionnaire was designed to be purposely difficult; indeed many university Chemistry students choose the wrong answers!

What will happen to the information I share?

All information collected will be kept completely confidential – including from your class teachers! This means that no matter your responses to the questionnaires and interviews, your teacher will not be told what your put. Information will be kept on a secured password protected university server, and paper copies will be kept in a locked cabinet in a locked office. Ethical and legal practices will be followed throughout, and all data will be coded so that in the final report nobody will be able to identify you as the person who said the statements. This project has been reviewed and approved by the University of Birmingham ethics committee, and given the reference number ERN_18-0072.

Is participation compulsory?

The hope is that you would want to participate as the results will help both you and the class understand these challenging concepts. If you wish to participate, please complete the interview consent form. Interviews are to take place on school grounds during normal school hours, though they may occur during study periods or your lunch break – these can be organised at a time to suit you, and will last around 30 minutes.

Where can I go for more information?

If you would like to know anything else about the study, I would be happy to talk to you. Likewise, if you are unsure about anything covered in the study, please let me know and I will do my best to answer your questions. Feel free to email me at a time that suits you, and I will reply as soon as possible.

Katherine Smith, University of Birmingham kes727@student.bham.ac.uk

Supervisors: Dr Ian Davison i.w.davison@bham.ac.uk and Dr Sandy Wilkinson

APPENDIX 5: THE COMPLETED OBSERVATION SCHEDULE FROM SCHW1

UNIVERSITY OF BIRMINGHAM

Observation Schedule for SCHW1

Background:	
School/Class: SCHW1	**Lesson Number:** Revision session in May
Proposed Learning Outcomes: To give an idea of what specifically the teacher is intending the students to know by the end of the session - Go over problem areas, tackle difficult areas that the students think they struggled with (revision session). - VSEPR rules were to be covered to help students with the shapes of molecules.	
Student Engagement: Describe here how motivated and engaged students (generally and individually) are with the task and learning. - Quite engaged - Seemed like interactions between the class and teacher and between students and other students were common in the classroom. - - Nobody was silent; all answered questions at various stages (either as volunteering answers or being asked to participate.	
Planned resources:	
Materials used by the teacher: For example, PowerPoint slides, drawing on the whiteboard, textbook usage etc. • Individual whiteboards and pens • Main whiteboard used to collate the information/suggestions from students (as long as they were correct) • Past exam papers to look at questions posed similar to the questions students worried about not being able to answer • Past exam mark schemes as well: also includes notes of what the teacher thinks is important to note on the mark scheme (importance of being specific) as well as what she thinks should be clarified (wedge and dashes in 3D shapes) • Online worksheet of VSEPR rules with the steps of the procedure to use • Periodic tables	
Relation of the topic to other contexts: Noting whether the topic is taught as a standalone topic, or related to other situations. Links to other subjects/topics and anecdotes would go in here - Revision session; only talked about VSEPR rules and electron configurations	
Teacher interactions:	
How the teacher interacts with the class: This is made up of conversations led by the teacher: questioning; modelling etc; how well student thinking is extended; how much time the teacher is talking. - Teacher posed questions to students so it was more student led: 'write down everything you know about…' then asks class for participation - not leading lecture style at all - Mostly using probing questions (why is this…? What has [student] got this angle confused with?) - Teacher asks student to explain all steps when putting forward a suggested answer - Teacher very interactive with the class o Asking often if the class understands what she has taught o Gives example, but asks the class to answer rather than just explaining the answer ▪ Sort of models after the fact (for the first 30 mins) o Clarifying terminology often o Walks around the classroom circulating to all students rather than just teaching from the front	

- Checking students' understanding as a class after examples (again students go through it)
- Has no problem saying 'I'll look that up' if not fully sure of an answer before clarifying and getting back to the student
- Gives a range of examples to the class so the method being taught is clear on how it can be used for most molecular shapes
- Asks questions to the students as she walks around the classroom, no student is left for a long time without being asked something
- Poses questions at a higher level for students who finish early
  - Challenges missteps when they happen (potential misconception identification) e.g. identifying the bonding pairs first than the looking at the central atom or 'That's not the right group, how do you know what group it's in? Remember the periodic table'
  - How does this work or change with lone pairs
- Constantly asking students for explanations
  - Testing understandings rather than pure memory (attempts)
  - Explaining processes so students can have a go
  - Explains her own steps and thought process as well

- Goes over the exam question (AS Paper 1 inorganic and physical chemistry 27th May 2016) which people had been given in advance and could answer at home before the lesson (used for all revision questions)
  - Step by step answers to the question (shapes and bond angles of NH_3 and $AlCl_3$) modelling the question for the class
  - Asks everyone to mark their own answers, and explain how they had gone wrong (if they had any mistakes)

How the students interact between themselves:

This is made up of conversations led by the students (if any): discussions, questions to their peers about the topic, how much time is given to individual/group work

- 2 minutes for initial brainstorming, 2 mins for each example (10 mins between themselves for VSEPR shapes initially with 5 shapes including charged molecules)
- Students sitting in groups, discussing all the answers; never in complete silence
- Able to discuss between themselves at any time

Other notes:

Anything noteworthy that does not specifically fit into one of the topics above

- Teacher being observed has clearly taught a 'method' for VSEPR rules before, though explains to the researcher at the end of the lesson that she was not the teacher of the topic to the class being taught
- Resources are all over the classroom on the boards around the wall as well as on the windows
- Any question that the teacher is asked one on one, the teacher remembers to state to the whole class during discussions e.g. 'what does valence mean?' is answered one on one, and then during class discussion teacher states 'remember that valence means outer shell'.

APPENDIX 6: THE ETHICAL APPROVAL FORM FOR THIS RESEARCH PROJECT

UNIVERSITY OF BIRMINGHAM APPLICATION FOR ETHICAL REVIEW

Who should use this form:

This form is to be completed by PIs or supervisors (for PGR student research) who have completed the University of Birmingham's Ethical Review of Research Self Assessment Form (SAF) and have decided that further ethical review and approval is required before the commencement of a given Research Project.

Please be aware that all new research projects undertaken by postgraduate research (PGR) students first registered as from 1st September 2008 will be subject to the University's Ethical Review Process. PGR students first registered before 1st September 2008 should refer to their Department/School/College for further advice.

Researchers in the following categories are to use this form:

1. The project is to be conducted by:
   - staff of the University of Birmingham; or
   - postgraduate research (PGR) students enrolled at the University of Birmingham (to be completed by the student's supervisor);

2. The project is to be conducted at the University of Birmingham by visiting researchers.

Students undertaking undergraduate projects and taught postgraduate (PGT) students should refer to their Department/School for advice.

NOTES:

- An electronic version of the completed form should be submitted to the Research Ethics Officer, at the following email address: aer-ethics@contacts.bham.ac.uk. Please **do not** submit paper copies.
- If, in any section, you find that you have insufficient space, or you wish to supply additional material not specifically requested by the form, please it in a separate file, clearly marked and attached to the submission email.
- If you have any queries about the form, please address them to the Research Ethics Team.

☒ **Before submitting, please tick this box to confirm that you have consulted and understood the following information and guidance and that you have taken it into account when completing your application:**

- **The information and guidance provided on the University's ethics webpages (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-of-Research.aspx)**

- **The University's Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf)**

UNIVERSITY OF BIRMINGHAM APPLICATION FOR ETHICAL REVIEW	*OFFICE USE ONLY:* Application No: Date Received:

1. TITLE OF PROJECT

Investigating Conceptual Chemical Misconceptions in Year 12 Chemistry Students

2. THIS PROJECT IS:

University of Birmingham Staff Research project ☐
University of Birmingham Postgraduate Research (PGR) Student project ☒
Other ☐ (Please specify):

3. INVESTIGATORS

a) PLEASE GIVE DETAILS OF THE PRINCIPAL INVESTIGATORS OR SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Dr Ian Davison
Highest qualification & position held:	PhD Lecturer
School/Department	Education/Teacher Education
Telephone:	0121 414 4808
Email address:	i.w.davison@bham.ac.uk

Name: Title / first name / family name	
Highest qualification & position held:	
School/Department	
Telephone:	
Email address:	

b) PLEASE GIVE DETAILS OF ANY CO-INVESTIGATORS OR CO-SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Dr Sandy Wilkinson
Highest qualification & position held:	Lecturer in Science Education (Chemistry)
School/Department	School of Education
Telephone:	0121 414 4825
Email address:	s.wilkinson@bham.ac.uk

c) In the case of PGR student projects, please give details of the student

Name of student:	Katherine E Smith	Student No:	[redacted]
Course of study:	MA by Research Education	Email address:	kes727@bham.ac.uk
Principal supervisor:	Dr Ian Davison		

Name of student:		Student No:	
Course of study:		Email address:	
Principal supervisor:			

4. ESTIMATED START OF PROJECT Date: 1st March 2018

ESTIMATED END OF PROJECT Date: 21st December 2018

5. FUNDING

List the funding sources (including internal sources) and give the status of each source.

Funding Body	*Approved/Pending /To be submitted*
None	

If you are requesting a quick turnaround on your application, please explain the reasons below (including funding-related deadlines). You should be aware that whilst effort will be made in cases of genuine urgency, it will not always be possible for the Ethics Committees to meet such requests.

6. SUMMARY OF PROJECT

Describe the purpose, background rationale for the proposed project, as well as the hypotheses/research questions to be examined and expected outcomes. This description should be in everyday language that is free from jargon. Please explain any technical terms or discipline-specific phrases.

Purpose of research:
To aim to identify potential causes of students' misunderstandings on key chemistry topics. This should help teachers to identify problem areas which require more guidance, and potentially offer reasons that these issues are introduced.

Background Rationale:
Research into misconceptions has been carried out at a number of different educational levels in the past, though many studies focus on how to improve the teaching methodology rather than attempting to identify how/why these misconceptions are introduced. As science GCSEs are now commonly compulsory and there are a high proportion of students who choose to take Chemistry A Levels, it is important to identify areas which require more assistance to allow students to have a good foundation if they choose to take this subject on to higher levels in the future.

Hypotheses/research questions to be examined:
This research is investigating conceptual challenges in A Level students in atomic structure and bonding, and looks at both staff and students in different areas in the project. As the study will include a mixture between pre and post questionnaires and interviews/concept mapping, it is envisaged that there will be an exploration of the students' understanding will show further insight into why typically 'difficult' areas to teach effectively (e.g. stoichiometry or atomic structure and bonding) are commonly misunderstood. There is also a particular focus on the teacher in the lessons to identify whether anything the teacher does inadvertently leads to misunderstandings.

For example, this could be due to the nature of school chemistry teaching in the past as typically constructivist, meaning that misunderstandings could be introduced if the student does not possess the existing knowledge to build the more complex ideas upon.

Expected outcomes:
The intended outcomes are to be able to identify typical problem areas in the Chemistry A Level syllabus which require further attention (either through additional time being spent on these topics, or through teaching strategies), and to suggest reasons that different students have varying experiences from the same lesson.

7. CONDUCT OF PROJECT

Please give a description of the research methodology that will be used

A mixture of methods will be used in this classroom study.

Firstly, a questionnaire will be issued to attempt to identify the students' conceptual understanding on a topic before that topic has been taught.

Secondly, lesson observations will be used to understand how these chemistry concepts are conveyed to the student; after which the original questionnaire will be reissued to look for any changes in the students' understandings. This observation of the study will be focusing on the teacher rather than the students (see Observational Schedule).

Finally, a random sample of students will be interviewed. During the interviews, they will be asked to create concept maps (the process to create this is explained on the Interview Information Form and is orally stated in steps during the interview as well). Differences in the maps that the students create will help us to infer differences in conceptual understanding. The questions used in the 'interview' will ask the students to explain what they mean by the ideas they put on the concept map, and as such the interview will be reflective of the students' participation (see example interview schedule).

8. DOES THE PROJECT INVOLVE PARTICIPATION OF PEOPLE OTHER THAN THE RESEARCHERS AND SUPERVISORS?

Yes ☒ No ☐

Note: 'Participation' includes both active participation (such as when participants take part in an interview) and cases where participants take part in the study without their knowledge and consent at the time (for example, in crowd behaviour research).

If you have answered NO please go to Section 18. If you have answered YES to this question please complete all the following sections.

9. PARTICIPANTS AS THE SUBJECTS OF THE RESEARCH

Describe the number of participants and important characteristics (such as age, gender, location, affiliation, level of fitness, intellectual ability etc.). Specify any inclusion/exclusion criteria to be used.

This research is to be conducted with between three to five Year 12 Chemistry classes in Birmingham schools, with a typical class size of 25 (75-125 participants). As the study is carried out on Year 12, the students will be 16 or 17 years old.

Teachers will be approached about the prospect of taking part in the research, and both the teachers and students will be asked if they wish to participate - there are no exclusion criteria. All teachers and students will be given consent forms with participant information to allow them to make an informed decision of whether they would like to take part in the study.

10. RECRUITMENT

Please state clearly how the participants will be identified, approached and recruited. Include any relationship between the investigator(s) and participant(s) (e.g. instructor-student).

Note: Attach a copy of any poster(s), advertisement(s) or letter(s) to be used for recruitment.

Teachers will be contacted through Sandy Wilkinson (in charge of initial teacher education in Chemistry) asking about whether they are interested in participating in the study. This will include a brief description of the project, along with an information sheet and consent form to be completed. Students will be invited to participate once the teachers are recruited. If a teacher wishes to take part, then all of their Year 12 Chemistry students will be given the questionnaire/observation consent form and information so that they may choose whether they wish to opt out of their questionnaire being used for research purposes and/ or anonymous notes being taken about their class participation. The research student will be in the classroom in the lesson after the forms are distributed to answer any questions and to explain the process. After the questionnaires have been completed for the second time, an interview information sheet and consent form will be distributed inviting students to be interviewed - again the research student will be around to answer any of the questions the students have.

11. CONSENT

a) Describe the process that the investigator(s) will be using to obtain valid consent. If consent is not to be obtained explain why**.** If the participants are minors or for other reasons are not competent to consent, describe the proposed alternate source of consent, including any permission / information letter to be provided to the person(s) providing the consent.

All participants (both teachers and students) will be given information sheets and consent forms to inform them of the study and so that they can give informed consent. Initially teachers will be given the Teacher Information Sheet and the Teacher Consent Form so that they may give initial consent. Next, in the classes with teacher consent, all students will be given the Student CCI & Obs Information Sheet and Student CCI & Obs Consent Form. These forms are allowed to be taken home so that the students can discuss the form with their parents. In the next lesson, the research student will be present so that all participants will be given the opportunity to ask any questions they may have about the study, and give full, informed consent if they wish to participate. If any student in a class wishes to opt out of being observed in the classroom, the researcher will ignore all participation from that student, and will continue to focus on the teacher and the resources used in the lesson (please see the Observation Schedule for notes on what will be recorded). The researcher would give the teacher the list of names of those who haven't agreed to be included; the teacher would mark them on a plan of the classroom. This plan would be used to give the questionnaires out as well as for lesson observations, so that only data from those participating in the study would be included. There is a separate information sheet and consent form for the student interviews, which will be issued to the participants after the questionnaire has been issued for a second time, so that they can give informed consent about the final stage of the project.

Note: Attach a copy of the Participant Information Sheet (if applicable), the Consent Form (if applicable), the content of any telephone script (if applicable) and any other material that will be used in the consent process.

b) Will the participants be deceived in any way about the purpose of the study? **Yes** ☐ **No** ☒

If yes, please describe the nature and extent of the deception involved. Include how and when the deception will be revealed, and who will administer this feedback.

Not applicable

12. PARTICIPANT FEEDBACK

Explain what feedback/ information will be provided to the participants after participation in the research. (For example, a more complete description of the purpose of the research, or access to the results of the research).

The research student will be offering class specific feedback to both the teachers and students (including the answers to the questionnaires) after the interviews have taken place in each class being studied so that all participants are aware of the strongest and weakest areas in the class (this can either be in the form of a presentation or a written summary).

Also, any students who took part in an interview are given personalised feedback when conducting the interview as it focuses on examples from their questionnaires.

13. PARTICIPANT WITHDRAWAL

a) Describe how the participants will be informed of their right to withdraw from the project.

On the information sheets/consent forms, participants are informed that they are free to withdraw from the study at any time up until two weeks after their last involvement in the research.

b) Explain any consequences for the participant of withdrawing from the study and indicate what will be done with the participant's data if they withdraw.

There will be no consequences if a participant chooses to withdraw from the study.

If a student participant withdraws from the study, any data collected from them within the previous 2 weeks will be destroyed.

If a teacher withdraws from the study, any data recorded from lesson observations in the two weeks prior to the withdrawal date will be destroyed; any data recorded before this will be kept; all student questionnaires and interviews already completed will also be kept.

14. COMPENSATION

Will participants receive compensation for participation?

i) Financial **Yes** ☐ **No** ☒

ii) Non-financial **Yes** ☐ **No** ☒

If **Yes** to **either** i) or ii) above, please provide details.

Not applicable

If participants choose to withdraw, how will you deal with compensation?

Not applicable

15. CONFIDENTIALITY

a) Will all participants be anonymous? **Yes** ☐ **No** ☒

b) Will all data be treated as confidential? **Yes** ☒ **No** ☐

Note: Participants' identity/data will be confidential if an assigned ID code or number is used, but it will not be anonymous. Anonymous data cannot be traced back to an individual participant.

Describe the procedures to be used to ensure anonymity of participants and/or confidentiality of data both during the conduct of the research and in the release of its findings.

As the study uses a pre- and post- topic questionnaire, all the questionnaires must be coded so that any differences in students' understanding can be identified (with the participants making a note of the code for reference for the interview portion). The questionnaires are coded before the questionnaires are given out, and are issued in a set order around the classroom so that the questionnaires will be given to the same students when issued both times. However, no identifying codes will be used to identify individuals in the report, these will be renamed or numbered (e.g. student 1, student 2, etc.) so that non-researchers will not be able to identify anyone in the final report. All data will be collected by the student researcher so that the school teachers being observed will not know the students' responses (for questionnaires and interviews).

When carrying out the data analysis, the data will be transferred to an electronic programme without personal identifiers (e.g. only be labelled by the code rather than their names).

If participant anonymity or confidentiality is not appropriate to this research project, explain, providing details of how all participants will be advised of the fact that data will not be anonymous or confidential.

16. STORAGE, ACCESS AND DISPOSAL OF DATA

Describe what research data will be stored, where, for what period of time, the measures that will be put in place to ensure security of the data, who will have access to the data, and the method and timing of disposal of the data.

All completed questionnaires will be stored subject to the University of Birmingham's policy of 10 years, and it will only be accessible by the researchers on the project. The raw physical data (the paper questionnaires, observation sheets and concept maps) will be stored in a locked cupboard in the supervisor's office (both the room and cupboard are locked unless in use. Electronic data will be stored on the password protected university secure servers (network drive).

17. OTHER APPROVALS REQUIRED? e.g. Criminal Records Bureau (CRB) checks or NHS R&D approvals.

☒ YES ☐ NO ☐ NOT APPLICABLE

If yes, please specify.

A DBS Check would be needed to allow the student researcher to carry out the interviews without a school teacher present (as this may influence the results).

18. SIGNIFICANCE/BENEFITS
Outline the potential significance and/or benefits of the research

The main benefit of this research is to allow teachers to identify areas that students typically find more difficult to understand. Additionally, it is hoped that by looking at the responses to the interviews, this will identify potential reasons that some students find these topics more difficult, and to investigate the nature of these difficulties. Again, this aims to benefit both teachers and students by allowing teachers to be able to make their teachings more accessible to their students and prevent or correct misunderstandings in their future teachings.

19. RISKS

a) Outline any potential risks to **INDIVIDUALS**, including research staff, research participants, other individuals not involved in the research and the measures that will be taken to minimise any risks and the procedures to be adopted in the event of mishap

Physical risks are unlikely as the research is being carried out in a school classroom environment. As the research is being carried out by the research student (rather than the school students' teachers), there is also a low chance that there would be any negative effect/assumptions made towards the students by their class teachers based on the questionnaire responses. Due to the nature of school research, there is a small risk that the students may make allegations. The student researcher will follow all of the rules of the school that she is in, and all school procedures and safeguarding regulations will be followed.

b) Outline any potential risks to **THE ENVIRONMENT and/or SOCIETY** and the measures that will be taken to minimise any risks and the procedures to be adopted in the event of mishap.

Not applicable

20. ARE THERE ANY OTHER ETHICAL ISSUES RAISED BY THE RESEARCH?

Yes ☐ **No** ☒

If yes, please specify

21. EXPERT REVIEWER/OPINION

You may be asked to nominate an expert reviewer for certain types of project, including those of an interventional nature or those involving significant risks. If you anticipate that this may apply to your work and you would like to nominate an expert reviewer at this stage, please provide details below.

Name
Contact details (including email address)
Brief explanation of reasons for nominating and/or nominee's suitability

22. CHECKLIST

Please mark if the study involves any of the following:

- Vulnerable groups, such as children and young people aged under 18 years, those with learning disability, or cognitive impairments ☒
- Research that induces or results in or causes anxiety, stress, pain or physical discomfort, or poses a risk of harm to participants (which is more than is expected from everyday life) ☐
- Risk to the personal safety of the researcher ☐
- Deception or research that is conducted without full and informed consent of the participants at time study is carried out ☐
- Administration of a chemical agent or vaccines or other substances (including vitamins or food substances) to human participants. ☐
- Production and/or use of genetically modified plants or microbes ☐
- Results that may have an adverse impact on the environment or food safety ☐
- Results that may be used to develop chemical or biological weapons ☐

Please check that the following documents are attached to your application.

	ATTACHED	NOT APPLICABLE
Recruitment advertisement	☐	☒
Participant information sheet	☒	☐
Consent form	☒	☐
Questionnaire	☒	☐
Interview Schedule	☒	☐

23. DECLARATION BY APPLICANTS

I submit this application on the basis that the information it contains is confidential and will be used by the University of Birmingham for the purposes of ethical review and monitoring of the research project described herein, and to satisfy reporting requirements to regulatory bodies. The information will not be used for any other purpose without my prior consent.

I declare that:

- The information in this form together with any accompanying information is complete and correct to the best of my knowledge and belief and I take full responsibility for it.
- I undertake to abide by University Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf) alongside any other relevant professional bodies' codes of conduct and/or ethical guidelines.
- I will report any changes affecting the ethical aspects of the project to the University of Birmingham Research Ethics Officer.
- I will report any adverse or unforeseen events which occur to the relevant Ethics Committee via the University of Birmingham Research Ethics Officer.

Name of principal investigator/project supervisor:	Ian Davison
Date:	20th February 2018

Please now save your completed form, print a copy for your records, and then email a copy to the Research Ethics Officer, at aer-ethics@contacts.bham.ac.uk. As noted above, please do not submit a paper copy.