TOWARDS THE DEVELOPMENT OF A PEDAGOGICAL HISTORY FOR A KEY CHEMICAL IDEA:

CHEMICAL BONDING

Presented in partial fulfilment of the requirements of:

Master of Education (Honours)

to the

Faculty of Education

AVONDALE COLLEGE

September 2010

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Student declaration

I, Michael Croft hereby declare that:

(i) this thesis is my own work,

(ii) all persons consulted, and all assistance rendered are fully acknowledged,

(iii) all references used are indicated in the text and accurately reported in the list of references,

(iv) the substance of this thesis has not been presented, in whole, or part by me, to any university for a degree.

Date: September, 2010 Signature: 

Acknowledgements

I would sincerely like to thank Dr Kevin de Berg for his invaluable and generous assistance over the entire time spent on this thesis. Without him this research project would not have been possible. His positive guidance and his skill as an expert researcher have been very much appreciated.

I would like to express gratitude to the students who willingly participated in this research.

I would really like to thank my family for their patience and understanding. Without the support of my wife, Kate, and my two daughters, Eden and Bethany, this research would have been very difficult.

I am grateful for the generous sponsorship of this study by the Education Department of the Seventh-day Adventist Church. Thank you for supporting your employees and enabling them to improve their knowledge and understanding.

Abstract

This study provides background research for the subsequent construction of a pedagogical history of chemical bonding. This includes original research to confirm and extend the literature on students' alternative conceptions of chemical bonding. The study additionally surveys the history of the development of chemical bonding ideas. A pedagogical history provides a new way to help students gain a comprehensive understanding of chemical bonding. It takes the form of an interesting narrative, using attention-grabbing historical episodes and original scientific data to help students understand the topic in a deeper way and to counteract known student alternative conceptions.

Students have many alternative conceptions of chemical bonding. Alternative conceptions reported by other researchers have been described in this thesis. In addition, a short history of the development of chemical bonding has been compiled. It was observed that many present alternative conceptions are rooted in historical ideas.

A diagnostic test was constructed to confirm and extend the research on students' alternative conceptions of chemical bonding. The diagnostic test employed sub-microscopic representations to probe students' understanding of chemical bonding. 172 students from two Melbourne high schools participated in the diagnostic testing. Furthermore, seven senior students were interviewed to further probe their thinking about chemical bonding. A number of alternative conceptions previously reported were reproduced. In addition, some new alternative student conceptions were found that have not been reported in the literature on chemical bonding.

In order to remediate the alternative conceptions described by this study, a future pedagogical history will include discussions on sub-microscopic representations of chemical bonding, describing particles undergoing bonding, understanding the range of bond types that exist, avoiding oversimplified chemical bonding descriptions, and significant historical episodes that have a high human interest and educational value. Recommendations for further research were made.

Contents

Introduction 1

Research Aim 2

Important Terms Defined 3

What is a Pedagogical History? 3

What is a Chemical Bond? 4

Need for the Study 5

Human Interest 6

Learning in Context 7

Nature of Science 8

Active Learning 10

Alternative Conceptions 11

Arrangement of the Report 12

Review of Literature 13

Students' Alternative Conceptions of Chemical Bonding Literature 13

Constructivism and Alternative Conceptions 14

The Persistent Nature of Alternative Conceptions 15

Changing Student Conceptions 17

Examples of Chemical Bonding Alternative Conceptions 26

The Literature on the History of the Development of Chemical Bonding 40

A Short History of the Development of Some Chemical Bonding Ideas 40

The Ionic Bond 41

G. N. Lewis and the Covalent Bond 42

The Metallic Bond 49

Other Bonding Models 51

The Link Between the History of Chemical Bonding Theory and Students' Alternative Conceptions of Chemical Bonding 52

Bonds are Physical Objects 52

Bonds and Forces are Different 53

Electron Transfer is Bonding 53

The Number of Bond Types 54

Atoms Bond to Follow the Octet Rule 55

The Laws of Physics are Suspended in Bonding 56

Summary 56

Research Design 58

Theoretical Framework 58

Constructivist approach 58

Sub-microscopic Representations of Bonding 59

Historical Approach 62

Diagnostic Assessments 63

Two Phase Approach 64

Instruments 65

The Diagnostic Multiple-choice Test 65

The Interview 68

Data Collection 71

Population 72

Sample 73

Student Profile 73

Data Analysis 77

The Multiple-choice Test 77

The Interview 78

Results: Analysis of Data and Discussion of Results 80

Introduction 80

Response Rates 80

Student Diagnostic Test: Analysis of Data and Discussion of Results 81

Results from Part A of the Chemical Bonding Test 86

Results from Part B of the Chemical Bonding Test 88

Results from Part C of the Chemical Bonding Test 91

Performance of Senior (Yr 11/12) Students 107

Performance of Junior (Yr 9/10) Students 110

Performance of Males and Females 115

Performance of Students at Different Schools 118

Interviews: Analysis of Data and Discussion of Results 119

Year 12 Student – Jack 119

Year 12 Student – James 125

Year 12 Student – Chloe 126

Year 11 Student – Thomas 129

Year 11 Student – Grace 130

Year 12 Student – Emily 133

Year 11 Student – Sophie 134

Interview Item Analysis 136

Description and Purpose of a Chemical Bond 136

Describing the Bonding in Potassium Iodide, Aluminium and Hexane 137

Sub-microscopic Representations of Metallic, Ionic and Covalent Bonding 138

Properties of ionic, Metallic and Covalent Substances 141

Summary of Chapter 142

Conclusion 152

Appendices 167

Appendix #1 – A List of Student Chemical Bonding Alternative Conceptions Found in the Literature 167

Appendix #2 – Diagnostic Chemical Bonding Test 185

Appendix #3 – Interview Questions 194

List of References 199

List of Tables

Table 1	Summary List of the Themes Uncovered in the Literature Regarding Students' Alternative Conceptions about Chemical Bonding	27
Table 2	Summary of Students' Alternative Conceptions within the Themes of the Concept of Chemical Bonding	28
Table 3	Overview of the Year Level and Gender of Interviewees	77
Table 4	Average Test Scores for Each Age Level	84
Table 5	Descriptive Statistics Associated with Chart 7	86
Table 6	Senior Student Responses to Chemical Bonding Test	107
Table 7	Junior Student Responses to Chemical Bonding Test	111
Table 8	Average Tests Results for Each Year Level for Males and Females	115
Table 9	Mean Test Score and Standard Deviation for Males and Females	115
Table 10	Common Alternative Conceptions Featured During the Test and Interview	143

List of Figures

Figure 1	Core Science Education Needs Addressed by Pedagogical Histories	6
Figure 2	Conceptual Profile Change in Students	22
Figure 3	A Sketch of the Cubic Atom by Lewis	43
Figure 4	A Diagram of the Cubical Atom Published in Lewis's 1916 Treatise	43
Figure 5	Lewis's Models of Covalent Bonds	44
Figure 6	Lewis Dot Formulae for HCN	47
Figure 7	The First Attempt to Visualise All Three Types of Bonding Situations	50
Figure 8	Bonding-type Triangle	50
Figure 9	Information Processing Model	60
Figure 10	The Three Conceptual Levels of Chemistry	61
Figure 11	The Important Elements of a Pedagogical History	164

List of Charts

Chart 1	Number of Students from Each School	74
Chart 2	Number of Students at Each Age Level	75
Chart 3	Number of Students at Each Year Level	75
Chart 4	Gender of Students	76
Chart 5	Average Test Results for Each Year Level	82
Chart 6	Distribution of Scores For Each Year Level Sitting the Test	82
Chart 7	Frequency Distribution of Scores From the Chemical Bonding Test	86
Chart 8	Percentage of Students Who Correctly Identified Each Bonding Model	87
Chart 9	Average Test Result for Each Year Level (Part A)	88
Chart 10	Percentage of Students Who Correctly Identified Macroscopic Representations Compared to Sub-microscopic Representations	89
Chart 11	Average Test Result for Each Year Level (Part B)	91
Chart 12	The Identity of the Negative Charges in a Model of Copper	92
Chart 13	The Identity of the Positive Charges in a Model of Copper	93
Chart 14	The Forces Holding Together the Copper Lattice	94
Chart 15	The Identity of the Negative Charges in Salt	95
Chart 16	The Identity of the Positive Charges in Salt	96
Chart 17	The Forces Holding Together the Ionic Lattice	97
Chart 18	Number of Sub-atomic Particles in a Sodium Cation	98
Chart 19	Number of Sub-atomic Particles in a Chloride Anion	99
Chart 20	The Sphere(s) that Represent a Hydrogen Atom	100

Chart 21	The Sphere(s) that Represent an Oxygen Atom	101
Chart 22	The Forces Holding Together Small Molecules	102
Chart 23	Students Who Could Describe a Covalent Bond Correctly	104
Chart 24	Percentage of Students Who Could Correctly Describe the Forces Holding Together Different Types of Substances	105
Chart 25	Average Test Results for Each Year Level for Each Section of Test	106
Chart 26	Grade Distributions for the 2008 End of Year VCE Exam for Males and Females	117
Chart 27	Grade Distributions for the 2009 End of Year VCE Exam for Males and Females	118

Chapter 1 - Introduction

Gilbert N. Lewis may have been the most brilliant chemist (LeMaster & McGann, 1992) to never receive a Nobel Prize. He probably should have. Lewis was nominated for the Prize over 30 times. In all likelihood only one man prevented him from winning the Prize. Twenty students that he mentored went on to receive the Prize (Estabrooks, 1998). He received numerous other honorary degrees and awards. He published more than 150 papers. But he never received a Nobel Prize, a disappointment that may well have sent him to an early grave.

G. N. Lewis developed the concept of the covalent bond, coined the term photon, championed the then unpopular theory of relativity, was the first to produce heavy water, produced tables of thermodynamic data that are still used today, invented Lewis structures, developed the idea of Lewis acids, and made numerous other discoveries (LeMaster & McGann, 1992; Hildebrand, 1958). And yet one man may be responsible for blocking this great chemist from receiving an award most thought he richly deserved.

Lewis was a brilliant conversationalist who was addicted to limericks, puns and imported cigars. He squirmed under personal praise, but still greatly desired the Prize. At age 70 he was found dead in his laboratory. The doctors said he died of coronary heart disease, but that diagnosis ignored the deadly poisonous hydrogen cyanide fumes present in the laboratory. Colleagues speculated that he committed suicide after slipping into depression (Coffey, 2008), but this was kept quiet. Lewis had only hours earlier lunched with a rival who had gained considerable success by using some of Lewis's best ideas. If Lewis had lived

a little longer he may have shared the Nobel Prize with Pauling (Jensen, 2010). Pauling received the prize for his work on the nature of the chemical bond. Much can be learned from looking at the life and work of a man like Lewis.

Every student loves a good story! Anecdotes from the life of an individual such as G. N. Lewis serve a valuable educational purpose as we teach students about chemical bonding. This research project will make it possible to craft a special type of story - a pedagogical history - to help students understand chemical bonding concepts. This introductory chapter will introduce the research aim and define the nature of a *pedagogical history* and a *chemical bond*. It will also explain the importance of developing a pedagogical history for chemical bonding and outline the structure of this report.

Research Aim

The aim of this project is to perform the research needed to develop a pedagogical history for chemical bonding. This will include:

1. Using primary and secondary sources to survey the range of alternative conceptions students hold on the topic of chemical bonding, and to ask the question "do students in two Victorian high schools also communicate these alternative conceptions about chemical bonding?"
2. Using primary and secondary sources to determine the way chemists' understanding of bonding has developed, and to ask the question "can student conceptions be linked to historical conceptions of chemical bonding in a way that might inform student conceptions?"

3. Developing and applying a diagnostic test and interview protocol to determine students' alternative conceptions in the area of chemical bonding, and to ask the question "can a diagnostic test which makes use of sub-microscopic representations of chemical bonding reveal new student conceptions not reported in the literature?"

Important Terms Defined

What is a Pedagogical History?

A pedagogical history is like an interesting story. It is a story that is told for the purpose of facilitating student learning. As the story unfolds the reader learns about the history of the development of a scientific idea. The student may read about the triumphs and tribulations of a scientist, attempt to interpret the scientist's data, or study how alternate conclusions generated from the data competed for attention. The story is presented in a way that helps the student understand the topic in a deeper way and to counteract students' alternative conceptions about the idea.

Student learning is the core motivation for every pedagogical history. A pedagogical history combines important historical and philosophical information about the development of a concept with information about common student misconceptions about a concept (de Berg, 2004). Pedagogical histories are important because the original historical material about chemical concepts is not easily read or understood by students. However, a pedagogical history takes into account the students' language levels and alternative conceptions, as well as the background history of the topic, learning theory, discipline knowledge and the

teaching and learning context (de Berg, 2003a). An excellent example of a pedagogical history written by de Berg (2003b) is freely available on the internet.

What is a Chemical Bond?

Students at all levels struggle to understand the nature of the chemical bond. Some scientists suggest that a chemical bond "is a figment of our own imagination" and "not a real thing", "it does not exist", "no-one has ever seen it", "no-one ever can" (Ritter, 2007, p. 37, quoting Charles A. Coulson, a prominent theoretical chemist at the University of Oxford). According to Gillespie & Robinson (2007, p. 97) the chemical bond is "not a real measurable object and it cannot be clearly defined". No wonder students have difficulties in understanding the nature of chemical bonds! Nonetheless, it is necessary that our students understand chemical bonding theories. The concept of a chemical bond is one of the most useful ideas in chemistry. Furthermore, students will be examined on their knowledge of the concept.

Unfortunately, definitions of even the most fundamental concepts in science are problematic and not as straightforward as one might expect (Taber, 2001c). There are a number of ways to define a chemical bond. Each chemical bonding model has its own strengths and weaknesses. Different chemical bonding models will be employed by chemists in various circumstances. Nonetheless, the various chemical bonding theories are incredibly useful ideas that can explain much of the world around us.

For the purposes of this study a chemical bond is defined as what holds matter together at the atomic level. Bonds result from the electrostatic attraction between positive and negative particles. Chemical bonds enable atoms to join together to create an enormous variety of larger compounds. There are a number of different types of chemical bonds. Australian high school students study three primary (intramolecular) forms of bonding:

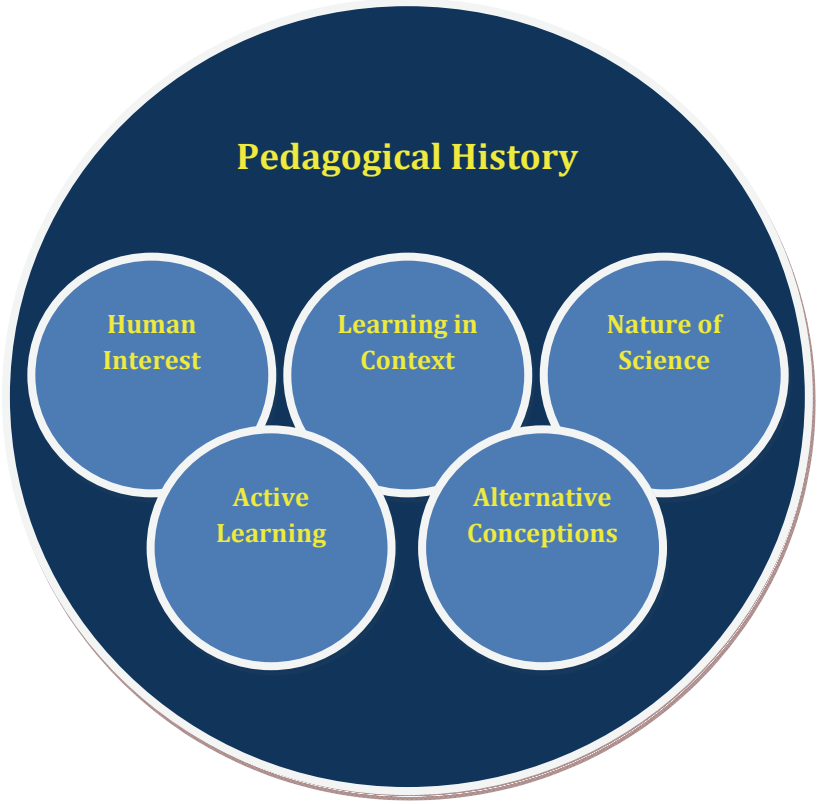
1. Metallic bonding – the electrostatic attraction between positively charged cations and the negatively charged 'sea of electrons'.
2. Ionic bonding – the electrostatic attraction between positively charged cations and negatively charged anions.
3. Covalent bonding – the electrostatic attraction between negatively charged shared electrons and the positively charged nuclei of the atoms involved in the bond.

Furthermore, students learn about a range of secondary (intermolecular) chemical bond types. They typically study hydrogen bonding, dipole-dipole bonding, ion-dipole bonding and dispersion forces.

Need for the Study

Recent scholarly work in science education suggests there is a real need for curriculum materials to address issues of human interest, learning in context, nature of science, active learning and alternative conceptions. A pedagogical history is designed with these core needs in mind.

Figure 1 – Core Science Education Needs Addressed by Pedagogical Histories



Human Interest

A well-told pedagogical history captures the imagination as the story introduces real conflict and emotion. It depicts scientists as human beings and portrays science realistically. The student unravels the mystery as the story unfolds. They tread along a similar road to that of the original scientists (albeit a little more quickly)! A pedagogical history adds creativity and variety into the classroom and helps make the concepts more interesting and memorable. It breathes feeling and "life" (de Berg, 2004, p. 16) into the topic and helps instil in students a deeper conceptual understanding of the subject (Niaz, 2009). A story exposes our students to the wonders of science (de Berg, 2008b).

The formal use of story-telling is used to engage students, mimic critical thinking, help students remember information and increase students' enjoyment of the subject matter (Herreid, 2005a). "Who doesn't like a good story?" asks Herreid (p. 1). While it requires careful preparation to craft a well-told story, teachers who trialled a particular case study technique overwhelmingly (92% of respondents) reported that their students were more engaged as a result (Herreid, 2005b).

There is a "critical" (de Berg, 2003a, p. 417) need for pedagogical histories written specifically for different groups of students in fundamental concepts such as chemical bonding. There is a curriculum demand that teachers use stories from history to enhance their teaching of chemical concepts (de Berg, 2006). For example, the Board of Studies NSW (2007) states that teaching the history and philosophy of science is important in developing students' understanding of chemistry. However, there is a real lack of material to help teachers in this task (de Berg, 2006). This research project would help alleviate a small part of this need by providing data to assist the development of teaching materials which could be used by high school chemistry teachers in the area of chemical bonding.

Learning in Context

Teaching the history of a concept can facilitate students' conceptual understanding. Students can greatly benefit from historical reconstructions where they see how an idea is a product of conflicting or rival theories. It helps put the theory into context. It shows science with all of its "speculation, theory, discussion, and controversy" (de Berg, 2008b, p. 1, discussing Arrhenius). As students grapple with rival theories their understanding grows

(Niaz, 2001). In a similar manner to the way that arguments and counter-arguments have stimulated the development of scientific knowledge in professionals (de Berg, 2003a), so it will promote active learning in students (de Berg, 2006).

A pedagogical history improves upon "normal science education" – an education which is described by Dietrich & Klassen (2008, p. 1) as lacking in "context, imagination, and engagement" due to its "oversimplification and dependency on textbooks". The story slows down our "rush to abstraction" as we consider how long it took for scientists to develop chemical concepts (Wandersee & Griffard, 2002, p. 33). For a moment students can pursue their investigation using a written pedagogical history at their own pace, rather than at the usual frenetic pace of a chemistry course with an attempted level of content coverage that is "so grand" (de Berg, 2003a, p. 387). Niaz and Rodriguez (2001, p. 162) are convinced that a presentation of the history of our understanding of the covalent bond "based on its rivalry with the ionic bond can facilitate conceptual understanding."

Nature of Science

Using historical examples helps students understand the nature of science (de Berg, 2008a; Yip, 2006) with its multiplicity of approaches. As students look at past controversies they gain an understanding of the dynamic process of scientific knowledge development (de Berg, 2006). Studying the history of science helps students appreciate that scientific ideas are not absolute truth but are subject to continual modification. It demonstrates the role of creativity, bias and preconceptions in the decisions made by scientists. Beasley (2007) argues that we should design curriculum documents with more emphasis on understanding

scientific concepts in their context, including the history and nature of science, personal and social perspectives, and with an emphasis on student enquiry.

One of the stated objectives of the NSW HSC Chemistry Syllabus (Board of Studies NSW, 2007) is for students to obtain knowledge and understanding of "the history of chemistry" (p. 8). Other curriculum documents around Australia and beyond (e.g. Victorian Curriculum and Assessment Authority, 2005) require students to have an understanding of the historical development of some chemical ideas. Understanding the history and philosophy of chemistry is considered necessary in "developing current understanding in chemistry and its applications" (Board of Studies NSW, 2007, p. 6).

The new Australian Science Curriculum (Australian Curriculum Assessment and Reporting Authority, 2010) requires all Australian students to study the nature and history of science. One of the aims of the curriculum document is to ensure that students develop an understanding of the historical and cultural aspects of science. All students will be expected to study the contribution of scientists, to analyse the influence of science, to see the way scientists collaborate, to think about how science and culture interact, and appreciate the way that science can be used in many career pathways. All of these focus areas come under the 'Science as a Human Endeavour' strand of the new curriculum. A pedagogical history of chemical bonding can help achieve the aims of this strand, in addition to helping to achieve outcomes in the two other science strands: 'Science Understanding' and "Science Inquiry Skills'.

Active Learning

A pedagogical history includes space for questions and student responses in order to focus students' thinking and help them to examine the topic more deeply. It involves students in complex reasoning. It is an effective learning strategy because it actively teaches problem solving and critical thinking by introducing students to real problems (Herreid, 2004).

Concepts are developed through the use of actual experiments and data (de Berg, 2008a). Students are asked to develop tentative solutions, after which they hear of the strategies used by the scientists who were struggling with the problem. Over time students are given more data, students spend more time looking at the problem, and more of the original interpretations of the scientists are given. It was found (Herreid, 2004) that working with messy real data, developing multiple approaches to the problem, and observing model behaviour is an effective way for students to develop an inquiring mind.

A pedagogical history shows students how a chemical idea has developed from "rudimentary information into a substantive concept" (de Berg, 2004). Historical science stories can assist students in understanding today's chemistry concepts and methods. The students learn to work with incomplete data, form tentative hypotheses, refine hypotheses, collect more data, and generally follow how scientists reason through issues (Herreid, 2004). Herreid (2006, p. 43) further reports that courses with active learning strategies with an emphasis on complex real-world contexts "were far superior in producing learning gains" than courses with lecture-style techniques. The enhancement of student motivation and learning was especially noticeable amongst less able or less motivated students (Yip, 2006).

Alternative Conceptions

Students continue to struggle to understand chemistry. According to Taber (2001c, p. 132):

> "There is then a multiple barrier here: learners with limited mental working space (1), are asked to use abstract theoretical entities (2) at a level outside their direct experience (3), to explain apparently unrelated molar phenomena at another level; when they have limited appreciation of both the role of models (4) and the nature of explanation (5). Failures to learn chemistry should not surprise us."

A pedagogical history is designed to address the common alternative conceptions of the topic. Students come to science classes with alternative conceptions that act as learning impediments (Taber & Coll, 2002). It is important that teachers are aware of some of the alternative conceptions of students, because studies have shown that learners may be reluctant to change their views – even in the face of "seemingly incontrovertible evidence" (Coll & Treagust, 2002, p. 25). Interestingly, while significant work has been done on determining students' alternative conceptions, little has appeared about how to reverse or avoid alternative conceptions (Johnstone, 2000). A pedagogical history helps students journey from common sense knowledge to scientific knowledge (de Berg, 2004).

In summary, a pedagogical history is intended to be interesting. The main focus of a pedagogical history is on student learning. It assists students in their quest for understanding as it develops a story-line that makes sense to students (de Berg, 2004). Historical episodes are carefully selected and presented so that they contain ideas in context with which students will easily identify and upon which they can develop new

concepts. The story introduces students to the nature of science whilst remaining 'bite-sized'. Pedagogical histories demand that students actively engage with the text (de Berg, 2008a). Additionally, they work to transform student alternative conceptions on the topic. A pedagogical history is significant because it is a teaching device that has considerable potential to improve student learning.

Arrangement of the Report

The aim of this project is to perform the research needed to develop a pedagogical history for chemical bonding. That is, the purpose of this project is not to write the pedagogical history, but to provide some of the data for it. This chapter has identified the research aim, defined important terms and indicated the need for the study. Chapter Two explores the literature on students' alternative conceptions of chemical bonding and the history of the development of our understanding of chemical bonding. Chapter Three discusses the research design developed and the methods used for data collection and analysis. Chapter Four outlines the findings of the diagnostic test and interview and the range of chemical bonding alternative conceptions revealed. The literature review and findings of the diagnostic test and interview provides an academic context for the discussion of results that takes place in Chapter Four. Connections are made to the research literature. A conclusion is provided in Chapter Five, which summarises the major findings of the study and outlines recommendations for future studies. A number of appendices follow Chapter Five, and the final section of the thesis consists of a full list of references.

Chapter 2 - Review of Literature

A review of the literature necessary for the development of a pedagogical history of chemical bonding yielded a wealth of material. Two main bodies of research literature informed this study, that of students' alternative conceptions of chemical bonding and that of the history of the development of chemical bonding.

Students' Alternative Conceptions of Chemical Bonding Literature

Chemical bonding is one of the key concepts in chemistry, and it is also an area where students are known to commonly acquire alternative conceptions (Taber, 2002a). Many researchers have discovered that students have a wide range of alternative conceptions in the area of chemical bonding (e.g. Peterson, Treagust & Garnett, 1986, 1989; Taber, 1993, 1999, 2000a, 2001a, 2001b, 2002a, 2002b, 2002c, 2005; Tan & Treagust, 1999; Coll & Treagust, 2000, 2002; Coll & Taylor, 2001; Nicoll, 2001; Taber & Coll, 2002; Horton, 2004; Kind, 2004; Ozmen, 2004; Talanquer, 2004; Nahum, Mamlok-Naaman, & Hofstein, 2006; Pabuccu & Geban 2006; Unal, Calk, Ayas, & Coll, 2006; Frailich, Kesner & Hofstein, 2009).

An alternative conception is an idea that a student holds that is different to the established scientific opinion. Additional labels have been used by researchers to describe various aspects of beliefs that are different from the established scientific norm, such as misconceptions, preconceptions, alternate perceptions, intuitive conceptions, and children's

science, amongst many other terms. For the purpose of this study one of the more commonly used terms - the alternative conception - will be used.

Taber (2002a) advises that in any class on any given science topic, students are likely to hold a wide range of alternative ideas about the topic. Students have many preconceived ideas, for they have been studying the world around them for many years, and as a result have formed many conceptions to explain their findings. Students have a rich variety of ideas about how the world works (Taber, 2002c). Inevitably some of their alternative ideas form a significant barrier to learning scientific ideas (Pabuccu & Geban, 2006) and should be taken seriously.

Constructivism and Alternative Conceptions

Constructivist theory insists that having an understanding of students' prior knowledge is vital. The constructivist paradigm explains that students' knowledge constructs will be influenced by prior knowledge, social interactions and learning experiences (Coll & Treagust, 2002). Meaningful learning takes place when the learner actively constructs their own knowledge by using their existing knowledge to make sense of their new experiences. This means that the human brain biases us towards interpreting new information in terms of previous learning (Taber, 2001c). Therefore a fundamental step in learning is for the teacher and the student to be aware of the learner's current ideas. Teaching can then be planned appropriately in order to promote appropriate conceptual change (Ozmen, 2004). Teachers will help learners re-construct within their minds the conceptual structure of chemistry (Taber, 2001c).

A constructivist teacher will want to identify students' alternative conceptions so that they may appropriately design their instructional approach. The learning experiences will be organised in a way to minimise the likelihood of the alternative conception occurring, or alternately, to remedy the existing alternative conception. The teacher will identify students' prior knowledge in order to confirm that the planned teaching is in line with students' abilities (Peterson, Treagust & Garnett, 1989) and spend considerable time and effort trying to tune into what students are thinking.

There can often be further unintended benefits to the process of checking for students' alternative conceptions. For example, Tan & Treagust (1999) report that the process of identifying students' alternative conceptions will help the teacher to see their own views in totally new ways, refreshing the way in which the teacher presents their knowledge. In addition, Horton (2004) found that by thinking about alternative conceptions teachers were stimulated to discuss how to instruct students and to consider which models and conceptions are the "big ideas" (Nahum, Mamlok-Naaman & Hofstein, 2006, p. 584) and are therefore priorities for students to master. This means that teaching quality will be enhanced by thinking about alternative conceptions.

The Persistent Nature of Alternative Conceptions

Alternative conceptions can be extremely persistent (Horton, 2004). They are often found even after extensive quality teaching has taken place (Ozmen, 2004; Peterson, Treagust & Garnett, 1989). Students have been found to be very reluctant to change their views "even

in the face of seemingly incontrovertible evidence" (Coll & Treagust, 2002, p. 3). Basic alternative conceptions have been found in students at all levels, from primary school students through to post-graduate chemistry students. Alternative conceptions present in students at age 12 have been found to be still present in students at age 18 and beyond (Horton, 2004).

There are a number of reasons why alternative conceptions can be so enduring. To start with, students try to make sense of the science they are learning in terms of their 'everyday' world (Peterson, Treagust & Garnett, 1989). An alternative conception may be hard to change because a student may make sense of the new scientific information in terms of their own alternative way of thinking about the topic. If this occurs, the student learns new information, but not in the way that was intended. Even when students are presented with data that does not match their own explanations about the way the world works, they often unknowingly interpret that data to match their own expectations (Taber, 2002a).

Furthermore, when a student learns new scientific information they may store this information in a separate 'academic' context, separate from their 'everyday' contexts (Taber, 2002a). As time passes students tend to forget the new scientific way of thinking and return to their original way of thinking about the topic.

Additionally, alternative conceptions are common because students have difficulty with the amount of material they encounter in most chemistry courses. The amount of material coupled with the advanced nature of most of the concepts leads to students having difficulties understanding and remembering the information. This can lead to the

development of alternative conceptions (Coll & Taylor, 2001). It would be helpful if the chemistry course was designed with an optimum level of simplification, where the ideas are kept as simple as possible whilst still remaining scientifically authentic and providing a framework for later learning (Taber & Coll, 2002). A mismatch between the abilities of the students and the difficulty or pace of the information can result in the formation of alternative conceptions. The students' level of prior knowledge is a "key determinant" (Taber, 2002a, p. 2) of the quality and quantity of learning that can be expected from the student.

In addition, alternative conceptions may arise due to communication problems. There may be problems with the flow of ideas between the student and the teacher, the student and the textbook, the student and a peer, or any other source of information. Any communication difficulties experienced by the student, for example, problems with analogies or confusion over terminology, could lead to the development of new alternative conceptions (Coll & Treagust, 2002; Smith, et. al., 2001).

Changing Student Conceptions

The process of learning is a process of conceptual change (Ozmen, 2004). As students learn they replace or modify existing ideas with new concepts Students will start with their own ideas about chemical bonding, but these will need to be modified or replaced with more scientific views on chemical bonding. In order to ensure that students develop an accurate and robust understanding of chemical bonding teachers need to guide students through a process of conceptual change (Taber, 2000a).

Theorists have considered a number of different ways that students' conceptual frameworks might change. Taber (2001b) outlines two interesting and relevant models which will be briefly discussed here.

In the first conceptual framework change model, Taber (2001b) explains that conceptions held by an individual slowly 'evolve'. New conceptions are continually generated. Some of these conceptions are seen as valuable for solving problems, and therefore are 'selected' for and retained. Other conceptions are not very useful and are discarded by this process of 'natural selection'.

A second possible model for conceptual change (Taber, 2001b) is that a learner holds one theory, but gradually builds up an understanding of an alternative theory. The competing theory is constructed in the background. The student gradually builds up several alternative frameworks, and one day they may 'suddenly' shift in their thinking (Taber, 2001c). The newly constructed theory may displace the original conception if it is found to have better explanatory coherence.

It is likely that most students experience one or both of these processes of conceptual change at some stage during a chemistry course. Moreover, one should expect that the process of conceptual change may take considerable time as the student explores, develops and evaluates alternative explanatory models. In both of these models of conceptual change, the teacher can enhance the process of change by providing opportunities for a student to successfully use their new models.

Every individual that has ever studied chemical bonding is likely to have multiple models to explain bonding. A student may use separate models to explain different phenomena. The learner has had to make a judgement as to which of their manifold models is appropriate to the particular context (Taber, 2001b). What has been found with students is that some of their personal models are closer to the established scientific models than others. Conceptual development may entail a shift towards using more frequently the scientific versions of the learner's multiple conceptions. The teacher's job is to facilitate the shift towards the use of more scientific conceptions and away from alternative conceptions.

There are strategies that the teacher could use to encourage conceptual shift away from alternative conceptions. Ozmen (2004) explains that it helps if students become dissatisfied with their existing conceptions. If their alternative conceptions are shown to be inaccurate or illogical, students will be motivated towards more scientific conceptions. Another strategy for encouraging conceptual shift in students is to present new ideas in a manner that students consider understandable, useful and plausible (Taber, 1999). The learner will need to have time to develop the new framework before they are likely to replace the existing framework. Therefore conceptual change may require "months" or "years" (Taber, 1999, p. 6) as most people process complex novel information slowly (Taber, 2001c). In summary, Duit & Treagust (2003) found that an increased chance of conceptual change occurs when teaching created dissatisfaction with current ideas while simultaneously presenting new ideas as intelligible, plausible and fruitful.

Taber (1999) provides an excellent example of students using multiple conceptions to explain chemical bonding and undergoing conceptual development during a chemistry course. While one can expect that each student would have their own individual alternative conceptual framework – or multiple frameworks – he discovered that many students had frameworks that had much in common (Taber, 2005). In his study Taber (1999) described four different frameworks that he anticipated students commonly used to explain chemical bonding. As the students progressed in their understanding, the frequency of use of each framework changed. Taber found that over time students' use of more sophisticated scientific models became more frequent while the use of the less accurate models of chemical bonding diminished.

At the start of a course in chemistry, Taber (1999) discovered that most students used an alternative framework to describe chemical bonding. Typically, students explained that atoms formed bonds in order to achieve stable electronic configurations. They used the 'octet rule' to explain most aspects of chemical bonding. Bonding was said to occur between atoms as a way of getting 'full' shells of electrons (Taber, 2002a). Students believed that atoms "want" and "need" and "try" to get a full shell of electrons and are prepared to share electrons so that they "think" they have an octet of electrons (Taber, 2005, p. 5). Chemical reactions happened so that atoms could achieve an octet of electrons (Taber, 2000b). Commonly, students simplistically believed that there are just two types of bonds; ionic bonds that result from electron transfer, and covalent bonds which are the result of sharing electrons (Taber, 1999). Students used the 'octet framework' to try and explain virtually all bonding phenomena. However, this alternative framework interfered with the intended learning during the chemistry course, and octet ideas continued to be

applied throughout the course inappropriately, even by 'successful' students. Significantly, this is an alternate framework that students most likely acquired from science teachers or their textbooks (Taber, 2002c), and not from their personal experience of the world.

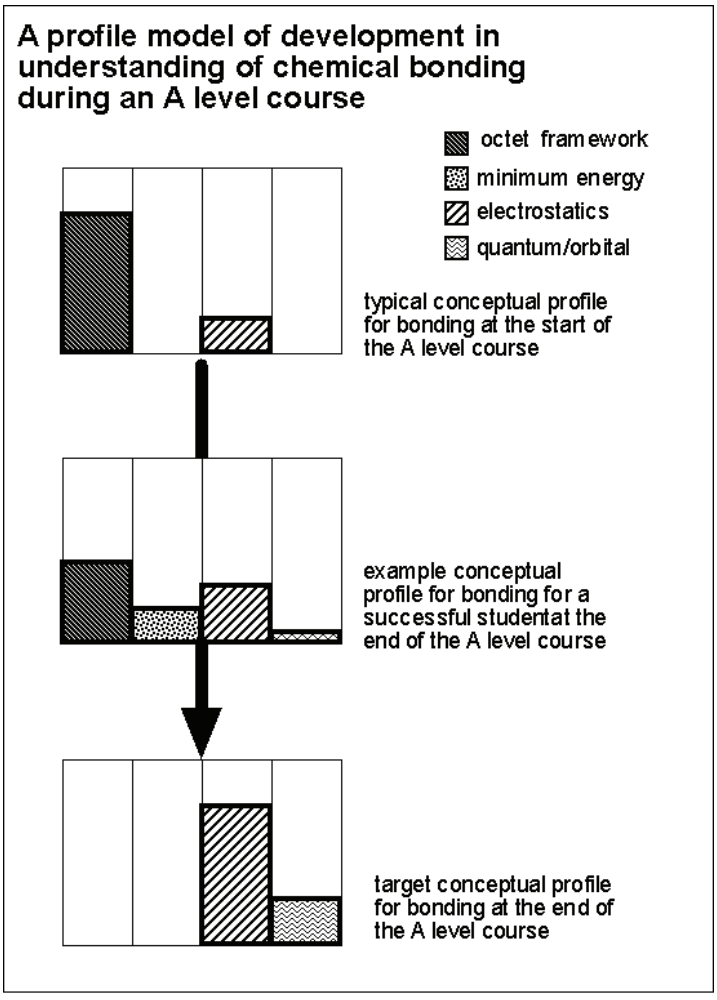
As the chemistry course progressed, Taber (1999) noticed that a new alternate framework developed, based on the idea that chemical bonds occur solely to minimise energy. The 'minimum energy framework' was seen as a separate concept to Coulombic explanations of chemical bonding, and hence while the idea of minimising energy is part of scientific explanations of chemical bonding, it is not meant to be seen as a complete explanation by itself. This fragmentation of chemical bonding theory became an impediment to students developing a deeper understanding of the subject (Taber, 2002a). It is hoped that given time the student may develop links and be able to integrate the minimum energy framework with the models that explain why minimising energy may be significant.

The target of the course described by Taber (1999) was to encourage students to use two frameworks to explain chemical bonding. The first framework was an 'electrostatics framework' where chemical bonding is explained in terms of Coulombic forces between charged particles. The second desired framework was a 'quantum/orbital framework' where students would use ideas based around the orbital and orbital overlap, energy levels and quantum rules to explain chemical bonding.

By the end of the two-year chemistry course Taber discovered that even the most successful students were frequently using the octet framework to explain chemical bonding - although the use of this framework was complemented more frequently than before by the more

scientific electrostatics framework and quantum/orbital framework. This progression in model use is shown in Figure 2. Duit & Treagust (2003) also found that students do not necessarily exchange their alternative conceptions for new scientific conceptions, but rather start using the conceptions that makes most sense to them more frequently.

Figure 2 – Conceptual Profile Change in Students During a Two Year Chemistry Course (Taber, 1999, p. 12).



It is interesting to note how stable and important the original octet framework appears to be. Fortunately the stable alternative framework did not completely block the development of more scientific frameworks. Nonetheless, topics would be best taught in such a way as to

avoid developing alternative frameworks (such as the octet framework) in students (Horton, 2004; Taber, 1999).

The persistent octet ideas that these students retained were most likely taught to them at some stage during high school. Despite octet ideas having been shown from the beginning to be largely inconsistent with the real behaviour of chemicals (Gillespie & Robinson, 2007), this model is still taught to students as fact. There are historical reasons for the persistence of this model, which will be discussed later. Taber (2001c) argues that "most alternative conceptions in chemistry do not derive from the learner's unschooled experiences of the world" (p. 128) but rather "derive from the learners' understanding of prior science teaching" (p. 129). This is a challenging idea for chemistry teachers, because in another study it was reported that alternative concepts created during students' first exposure to chemistry were found to persist even after hundreds of hours of instruction (Horton, 2004).

Nahum, Mamlok-Naaman & Hofstein (2006) found that a traditional approach to teaching chemical bonding led to the same misunderstandings being found in graduating students year after year over two decades. They established that the 'traditional' teaching approach had the main objective of preparing the student for the examination. This was done by providing students with absolute definitions and a set of rigid rules. Oversimplified instruction hid the uncertainties that exist in all bonding models. The researchers found that students could achieve high grades with this approach, but that high grades did not guarantee that students adequately understood bonding concepts.

Researchers have concluded that students should be encouraged to be more flexible in their thinking. The inflexibility of student thought has been demonstrated by a number of workers. For example, Treagust, Chittleborough & Mamiala (2002) found that a large number of students believe that a model is an exact replica. This differs from the way scientists need to think about scientific models.

A professional scientist would hold several versions of a scientific concept (Taber, 2001b). These versions may draw upon the currently accepted version of a concept as well as the past history of that concept. The scientist learns when to apply the appropriate version of a scientific concept. Often the professional uses a simpler bonding model at times when a more basic idea will be adequate, while at other times they may use a more accurate and sophisticated model. The nature of chemistry is such that every participant finds it profitable and necessary to use multiple distinct models.

Robinson (2000, p. 1110) noted that when students are presented with more complex models, students often cry "then why did we bother with the first one if it wasn't true?" Interestingly, Coll & Treagust (2000) found that learners who were able to competently describe sophisticated models for chemical bonding still preferred and tended to use simpler models. It is good for the student to have several "tools in a toolbox" (Taber, 1999, p. 12). The worker learns to choose the appropriate tool and to balance between conceptual depth and conceptual usefulness. Over time students learn to accept and use different models to explain chemical bonding, although this ability does develop slowly (Robinson, 2000).

It has been argued that many of the problems that learners experience in chemistry result from “model confusion” (p. 129). Taber (2001c) describes chemical models as “dressing up nature in a convenient way” and “a theoretical framework that helps us make sense of nature” (p. 126). Models help make sense of the world because the world does not always make sense! Chemical bonding concepts that are communicated to students are complicated and continue to be a work in progress. Each individual struggles to make sense of what is discovered in the world around them. This is the complexity that is chemistry. The subject contains multiple models that have developed over time, and often in different situations some historical models still have considerable value. Chemists build theoretical frameworks that are not reality but that try and help make sense of nature. Abstract tools are created to think about chemical particles and their behaviour - phenomena that the learner cannot directly experience. It is of little wonder that students are confused over the multiplicity of models and develop alternative conceptions.

Examples of Chemical Bonding Alternative Conceptions

A wide variety of literature was searched to provide additional examples of alternative conceptions of chemical bonding. A wealth of alternative conceptions was uncovered in a number of different studies.

The list of conceptions was extensive, therefore for easier reading the key ideas have been briefly summarised and categorised into *fourteen main themes*. The themes are listed in Table 1 below. Each theme has been supported by a number of examples of student alternative conceptions from different researchers, and a selection of these alternative conceptions is listed under each theme in Table 2 below.

A more comprehensive list of student alternative conceptions from the literature can be found in Appendix #1, sorted into sections on *ionic bonding, metallic bonding, covalent bonding, intermolecular bonding, models, bonds and energy* and *nature of bonds.* This list of student alternative conceptions has been included in the appendices because it is categorised differently and includes a far greater range of chemical bonding alternative conceptions.

Table 1 – Summary List of the Themes Uncovered in the Literature Regarding Students' Alternative Conceptions about Chemical Bonding

	Theme
1	Students believe that atoms undergo bonding simply to gain an octet of electrons.
2	Students confuse bonding with electron transfer.
3	Students do not understand the difference between intermolecular and intramolecular bonding.
4	Students see forces and bonds as somewhat different.
5	Students do not understand the nature of scientific models.
6	Students fail to differentiate between the different bond types.
7	Students find atomic structure confusing.
8	Students are confused by the idea of a molecule.
9	Students fail to differentiate between macroscopic and microscopic properties of molecules.
10	Students do not understand the energy changes that occur in bonds during chemical reactions.
11	Students think that atoms behave like people.
12	Students are confused by chemical terminology.
13	Students misunderstand the behaviour of electrons and their role in bonding.
14	Other interesting student alternative conceptions.

Table 2 - Summary of Students' Alternative Conceptions within the Themes of the Concept of Chemical Bonding

Theme #1: Students believe that atoms undergo bonding simply to gain an octet of electrons.	
Students' Alternative Conception	**Source**
Bonding is about striving to obtain a full outer shell.	Taber, 2002a
Atoms form covalent bonds to satisfy the octet rule.	Horton, 2004
Atoms lend and borrow electrons to satisfy the octet rule.	Horton, 2004
A shared electron pair holds atoms together because it enables them to have octets of electrons.	Taber & Coll, 2002
The existence of bonding which does not lead to atoms having full electron shells is something of a mystery to many learners.	Taber & Coll, 2002
The octet rule drives the chemical reaction. Reactions are caused by atoms trying to fill shells.	Horton, 2004
Every element wants to obey the octet rule.	Horton, 2004
Students use octet thinking despite knowing about a large number of examples where the octet rule does not work.	Taber, 2001a
Electrons are being moved around in metallic bonding so that the atoms take turns in having full shells.	Taber & Coll, 2002
The sodium anion Na^{7-} is more stable than a neutral atom as it has a full outer shell of electrons.	Taber, 2000a
Atoms need a certain number of bonds.	Horton, 2004
Only one electron can be removed from a sodium atom.	Taber, 2002a
A positive cation could not spontaneously attract a negative electron.	Taber, 2002a
An isolated cation is very stable.	Taber, 2002a
An atom will spontaneously emit an electron to become an ion.	Taber, 2002a

Theme #2: Students confuse bonding with electron transfer.	
Students' Alternative Conception	**Source**
Ionic bonding is defined as electron transfer.	Taber, 2002a
The reason a bond is formed between chloride ions and sodium ions is because an electron has been transferred between them.	Taber, 2002a
Covalent bond formation involves the complete transfer of electrons.	Coll & Treagust, 2002
Bonds are only formed between atoms that donate and accept electrons. For example, a chloride ion only bonds to the specific sodium ion that donated it an electron.	Taber, 2002a

Theme #3: Students do not understand the difference between intermolecular and intramolecular bonding.	
Students' Alternative Conception	**Source**
Students are readily confused about the differences between intermolecular and intramolecular forces, in part because of the linguistic similarity of the terms.	Unal, et. al., 2006
Intermolecular bonding is stronger than intramolecular bonding.	Coll & Treagust, 2002
Intermolecular forces are forces within a molecule.	Pabuccu & Geban, 2006
Students are unaware of the differences in strength of covalent bonds compared with intermolecular forces.	Unal, et. al., 2006
The strength of intermolecular forces is determined by the strength of the covalent bonds in the molecules.	Tan & Treagust, 1999
The bonding in metals involves intermolecular bonding.	Coll & Taylor, 2001

Theme #4: Students see forces and bonds as somewhat different.	
Students' Alternative Conception	**Source**
Bonds are material connections rather than forces.	Pabuccu & Geban, 2006
Chemical bonds are actually solid links between atoms.	Talanquer, 2004
Learners imagine bonds to be very small springs or lengths of string.	Taber & Coll, 2002
Atoms are glued together to make molecules.	Horton, 2004
Students do not always understand that the chemical bond is due to electrical forces.	Taber & Coll, 2002
Metallic substances are held together just by forces, rather than bonding.	Taber, 2002a
There is some form of bonding in metals, but not proper bonding.	Taber, 2002a
There is no bonding in metals.	Taber, 2002a
Metals have metallic bonding, which is a sea of electrons.	Taber, 2002a
Ionic bonds are not real bonds in the sense of covalent bonds.	Unal, et. al., 2006
Oppositely charged ions will use up each others' force and lock together in a molecule.	Horton, 2004
The attraction between two oppositely charged species results in neutralisation.	Coll & Treagust, 2002
In sodium chloride a chloride ion is bonded to one sodium ion, and attracted to a further five sodium ions. This attraction is just by forces – not bonds.	Taber, 2002a
Intermolecular bonds are just forces rather than proper bonding.	Taber, 2002a
Intermolecular forces are a type of energy.	Talanquer, 2004
Hydrogen bonds are just a type of force, they are not real bonds.	Taber, 2002a
Hydrogen bonds are an attractive force, not a bond.	Horton, 2004
Van der Waals forces are too weak to be considered proper bonds.	Taber, 2002a

Theme #5: Students do not understand the nature of scientific models.	
Students' Alternative Conception	**Source**
Students do not understand that models are only models, serving the development and testing of ideas, and are not the depiction of reality.	Horton, 2004
The study showed that 43% of students agreed that a model was an exact replica.	Treagust, 2002
There should be a one-to-one correspondence between models and reality. All models should be correct. The model is simply a representation of reality. The model may be an incomplete copy of reality.	Robinson, 2000
The main purpose of models is the communication of ideas. However, models are real-world objects as opposed to the representation of ideas.	Robinson, 2000
Models presented by experts are "true".	Robinson, 2000
Different models of the same thing show literally different aspects of real things.	Smith, et. al., 2001
There is only one correct model of an atom.	Horton, 2004

Theme #6: Students fail to differentiate between the different bond types.	
Students' Alternative Conception	**Source**
Students have many difficulties in understanding the type of bond that exists between the particles of various structures.	Frailich, Kesner & Hofstein, 2009
Students discount any type of bonding that does not fit the description of electron sharing or electron transfer.	Taber & Coll, 2002
There are only two types of bonds. Everything has to be either covalent or ionic.	Nahum, et. al., 2006
Students do not always understand that bonding may be intermediate between covalent and ionic.	Taber & Coll, 2002
Metallic bonds are like covalent bonds.	Taber, 2002a
Metallic bonds are like ionic bonds.	Taber, 2002a
Metals have covalent and/or ionic bonding.	Taber, 2002a
Metals and non-metals form strong covalent bonds.	Unal, et. al., 2006
Electrons are shared in metallic bonding.	Taber & Coll, 2002
Ionic substances such as sodium chloride possess covalent bonds.	Taber & Coll, 2002
Ionic bonding comprises sharing of electrons.	Coll & Taylor, 2001
Glass is an ionic crystalline substance.	Coll & Taylor, 2001
Molecular iodine contains 1- ions.	Coll & Taylor, 2001
The strengths of covalent bonds and intermolecular forces are similar.	Horton, 2004
Hydrogen bonds are simply bonds to hydrogen. Hydrogen bonds are a type of covalent bond.	Taber, 2002a
Hydrogen bonds are one of the strongest types of bonds.	Unal, et. al., 2006

Theme #7: Students find atomic structure confusing.	
Students' Alternative Conception	**Source**
Students invoke a solar system model of the atom.	Nicoll, 2001
Students could not indicate the specific particles that make up matter.	Frailich, Kesner & Hofstein, 2009
Atoms are like cells with a membrane and a nucleus.	Horton, 2004
Atoms can reproduce after the nuclei divide.	Horton, 2004
The size of an atom depends on the number of protons it has.	Horton, 2004
The electron shell is a matrix of some kind of stuff with electrons embedded in it.	Horton, 2004
Coulomb's law does not work inside the atom. It works in physics but not in chemistry.	Horton, 2004
Electrons are kept in orbit by gravity.	Horton, 2004
Learners tend to think of the starting materials of chemical processes as being single unbound atoms, even though this is hardly ever the case.	Taber & Coll, 2002

Theme #8: Students are confused by the idea of a molecule.	
Students' Alternative Conception	**Source**
Students do not always understand that bonding need not imply molecules.	Taber & Coll, 2002
Continuous covalent lattices contain molecular species.	Coll & Treagust, 2002
Strong intermolecular forces exist in a continuous covalent network solid.	Unal, et. al., 2006
Molecular solids consist of molecules with weak covalent bonding between the molecules.	Unal, et. al., 2006
Metals are molecular.	Taber, 2002a
Metals and non-metals form molecules.	Pabuccu & Geban, 2006
Ion-pairs are implied to act as molecules of an ionic substance. Ionic substances contain molecules.	Taber, 2002a
Ionic compounds form neutral molecules, such as Na^+Cl^-, in water.	Horton, 2004
Compounds with ionic bonds behave as simple molecules. There is no distinction between molecular formulas such as CH_4 and H_20, and ionic formulae such as NaCl and $MgCl_2$.	Kind, 2004
H^+ and Cl^- ions form molecules in HCl solution.	Horton, 2004
Metallic lattices contain neutral atoms.	Coll & Taylor, 2001

Theme #9: Students fail to differentiate between macroscopic and microscopic properties of molecules.	
Students' Alternative Conception	**Source**
Students transfer macroscopic properties to the molecular species. For example, atoms in a metal are hard, while atoms in liquids are softer. Copper is malleable because it has malleable atoms.	Taber & Coll, 2002
Atoms and molecules have macroscopic properties: they expand and lose weight when heated, have uniform densities and well-defined colours, are malleable, change their shape under pressure, etc.	Talanquer, 2004

Theme #10: Students do not understand the energy changes that occur in bonds during chemical reactions.	
Students' Alternative Conception	**Source**
Breaking chemical bonds releases energy.	Horton, 2004
Bond breaking releases energy and bond making involves energy input.	Taber & Coll, 2002
Students have no clear understanding of the nature of the chemical bonds and the energetics involved. Students struggle to relate thermodynamic ideas to bond formation.	Unal, et. al., 2006
An atom may want to bond because it 'desires' to lose energy.	Unal, et. al., 2006
Bond breaking is both exothermic and endothermic because energy is needed to break bonds initially, but once broken, energy is released.	Unal, et. al., 2006

Theme #11: Students think that atoms behave like people.	
Students' Alternative Conception	**Source**
Students make wide use of anthropomorphic language and analogy when trying to understand chemical bonding concepts.	Unal, et. al., 2006
Atoms own their electrons.	Horton, 2004
Electrons know which atom they came from.	Horton, 2004
Atoms know who owes them an electron.	Horton, 2004
Bonding electrons belong and are still part of the atom from which they originated. These atoms reclaim their own electrons when the bond breaks.	Taber, 2002a
Atoms want or need to form bonds.	Kind, 2004

Theme #12: Students are confused by chemical terminology.	
Students' Alternative Conception	**Source**
Students use the right terms and concepts but do not understand their meaning or their conceptual relevance.	Nahum, et. al., 2006
Students use the terms 'atom' and 'molecule' interchangeably and have difficulty differentiating between them.	Nicoll, 2001
Students confuse intramolecular bonds and intermolecular bonds.	Nahum, et. al., 2006

Theme #13: Students misunderstand the behaviour of electrons and their role in bonding.	
Students' Alternative Conception	**Source**
Bonding electrons sit between the nuclei.	Unal, et. al., 2006
Bonding electrons do not have any motion.	Unal, et. al., 2006
Electrons are attracted to one another when they bond.	Nicoll, 2001
Electrons move in a figure eight pattern.	Nicoll, 2001
Eight electrons in the third or higher shells gives a full shell.	Taber & Coll, 2002
Electronegativity is the attraction for a single electron.	Coll & Taylor, 2001
Electrons are ions and bonding occurs between them.	Unal, et. al., 2006
Nuclear force gets spread over a number of electrons. None is left over to attract another electron.	Horton, 2004
The positive nuclear charge is used up on core electrons.	Taber, 1993
The nucleus attracts all electrons around it equally.	Horton, 2004
Electron clouds are structures in which electrons are embedded.	Smith, et. al., 2001
Shells and orbitals are the same thing.	Nicoll, 2001

Theme #14: Other interesting student alternative conceptions.	
Students' Alternative Conception	**Source**
Students tend to overgeneralise and use rote memorisation instead of scientific explanations.	Nahum, et. al., 2006
Students mistakenly use the properties of the element to describe the properties of a compound. For example, sodium is very reactive, therefore sodium chloride will also be very reactive.	Taber, 1993
The central element is responsible for bond formation. Or similarly, the first element written in a formula is responsible for bond formation. For example, carbon in CH_4 is the more powerful element and needs four bonds. Hydrogen is the weaker partner and only needs one bond.	Kind, 2004
The charged species in metallic lattices are nuclei rather than ions.	Coll & Taylor, 2001
Metallic bonding is inferior to other forms of bonding.	Coll & Treagust, 2002
Metallic bonding is weak bonding.	Coll & Taylor, 2001
The sea of electrons is a vast excess of electrons surrounding the cations.	Taber & Coll, 2002
Ionic charges determine the polarity of the bond.	Pabuccu & Geban, 2006
Small molecules have low melting points and boiling points because covalent bonds are weaker than ionic bonds.	Kind, 2004
Molecules form from isolated atoms.	Ozmen, 2004
Polar covalent compounds contain charged species.	Coll & Taylor, 2001
Equal sharing of the electron pair occurs in all covalent bonds. All covalent bonds are non-polar.	Pabuccu & Geban, 2006
Covalent bonds are not as strong as hydrogen bonds.	Unal, et. al., 2006

Theme #14: Other interesting student alternative conceptions.	
Students' Alternative Conception	**Source**
Hydrogen bonds between water molecules are liquid or weak bonds.	Horton, 2004
Bonding in ionic substances is weak.	Coll & Taylor, 2001
Electrostatic forces in ionic substances are weak.	Coll & Taylor, 2001
The presence of ionic charge determines molecular polarity.	Coll & Taylor, 2001
Sodium chloride ion-pairs are internally ionically bonded but attracted to each other by weaker forces.	Taber, 2002b
The atomic electronic configuration determines the number of ionic bonds formed. For example, a sodium atom can only donate one electron so it can only form an ionic bond to one chlorine atom.	Taber, 2002a

After considering the types of alternative conceptions that are present in students, literature regarding the history of development of ideas about chemical bonding was examined. Some student ideas may be traceable to early ideas in the development of chemical bonding theory, and it is for this reason that a brief historical analysis follows.

The Literature on the History of the Development of Chemical Bonding

A Short History of the Development of Some Chemical Bonding Ideas

Ideas about the chemical bond have been around for a long time. More than two thousand years ago Greek philosophers such as Democritus spoke of links between atoms (Barnes, 1979). Democritus had the view that atoms were different from each other in their shape, size and arrangement of their parts (Myers, 2003). Atoms could be joined together because they contained points of attachment. Some atoms had hooks and eyes, other atoms had balls and sockets. However, this Greek philosophy was lost for two millennia before being rediscovered.

In the 17th century Descartes explained that atoms were held together by tiny hooks and barbs (Descartes, Miller & Miller, 1984). However, it was across the Channel that Newton proposed that particles attract one another at a distance due to a force (Newton, 1730). Boyle (Myers, 2003) also wrote that matter consisted of various types of particles which arranged themselves into groups. Chemical change was the result of a rearrangement within the groups of particles. Boyle rejected Newton's idea that a chemical bond could form at a distance due to a force (Pullman & Reisinger, 2001).

In the early part of the 19th century Dalton (Myers, 2003) was able to determine the empirical formula of a number of molecules. He imagined atoms hooked together to create these molecules. At about the same time Avogadro helped to distinguish between atoms and molecules (Shaik, 2007). Over the course of the 19th century scientists were able to

offer correct molecular formulae and determine possible structural arrangements for a large number of molecules, especially as they developed the concept of valency. At the end of the 19th century Boltzmann proposed that atoms must be joined by an attractive force (Boltzmann, 1995). He proposed that atoms had 'sensitive regions', and that if sensitive regions of two atoms make contact they will be chemically attracted and bonded to each other. By 1858 Couper represented a bond between two atoms as a line (e.g. H−Cl), a symbol that is now universally used (Gillespie & Popelier, 2001).

An understanding of the nature of the chemical bond was not really possible until the composition and structure of the atom had been elucidated (Gillespie & Popelier, 2001). As Thomson, Rutherford, Moseley and Bohr developed a model of the atom with a small, positive nucleus surrounded by negatively charged electrons, it became possible to better understand why atoms bond together.

The Ionic Bond

Thomson made the first attempt to explain the chemical bond in terms of electrons in 1904 (Hudson, 1992). He proposed that corpuscles (electrons) would be transferred from one atom to another as compounds form. Thomson further explained that as a result of the transfer of electrons, the electronegative atom would become negatively charged, the electropositive atom would become positively charged, and the oppositely charged atoms would be attracted together forming a compound (Shaik, 2007).

This theory of the ionic bond would become the dominant theory for the next two decades. It was used to explain bonding in every type of substance. It was widely accepted that all bonds were formed by transferring an electron - even non-polar molecules were considered to have been formed this way. For example, the hydrogen molecule was considered to be ionic, even though its lack of polar properties caused explanatory problems for chemists. Some of these difficulties led to the development of new chemical bonding concepts.

G. N. Lewis and the Covalent Bond

Gilbert N. Lewis precipitated a "revolution" (Shaik, 2007, p. 52) when he presented the first satisfactory model of the covalent bond in 1916 (Niaz, 2009). He generated a considerable amount of controversy when he introduced his ideas of a bond based on a shared pair of electrons. At first Lewis's theory was considered to be absurd. After all, how could two negative electrons 'attract' each other, and how could atoms possibly share electrons? Not all scientists appreciated the way Lewis creatively drew ideas from a wide variety of schools of thought to conceive of this novel idea (Simoes, 2007; Kohler, 1975).

Lewis's thinking began with a model of the atom which he called 'The Cubical Atom' (Lewis, 1916). The cubical atom consisted of an outer shell of electrons which were arranged symmetrically at the eight corners of a cube, as seen in Figures 3 and 4. At the centre of the atom there was "an essential kernel" of positive charge (p. 768).

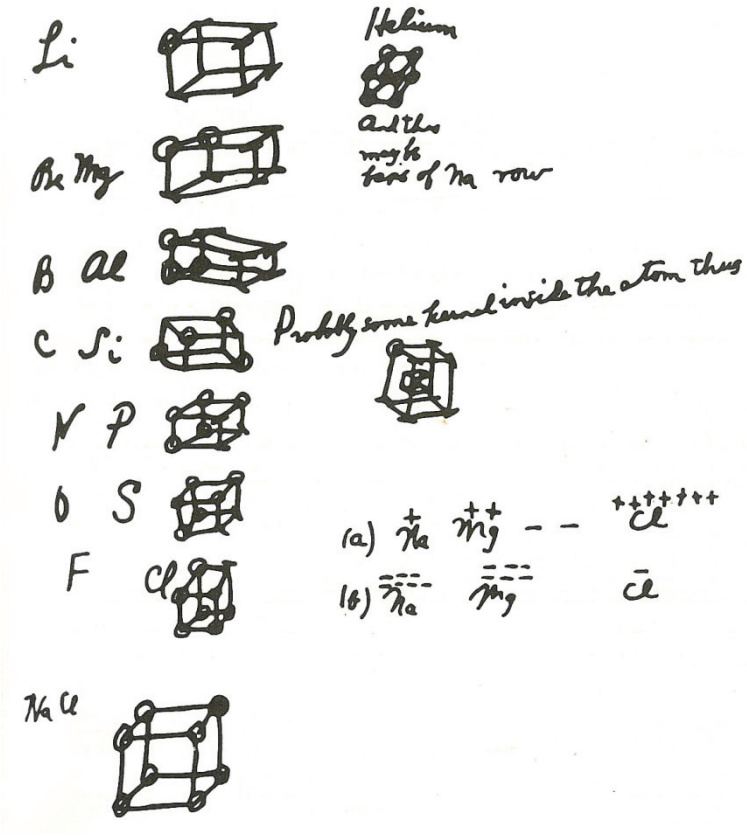
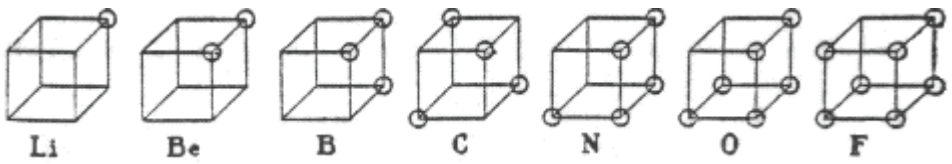


Figure 3 - A sketch of the cubic atom in a personal memorandum by Lewis (1902). In this model the electrons are arranged at the corners of the cube.

Figure 4 - A diagram of the cubical atom published in Lewis's 1916 treatise on chemical bonding.



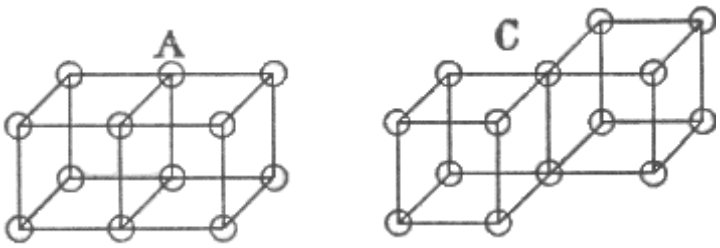
In this model chemical bonds formed when cubes joined together. According to Lewis, a single bond is formed when two cubic atoms shared an edge – one pair of electrons is shared. To form a double bond a common face of the cube – two electron pairs – is shared. These two arrangements are shown in Figure 5 below. The triple bond could not be accounted for by the cubical atom model. In order to accommodate a triple bond, Lewis proposed in the same paper (1916) that the electrons may be arranged in such a way as to

have a tetrahedral atom. The triple bond could form when three 'corners' representing three pairs of electrons were held in common by the two atoms. One of the most important features of this model was the assumption that an electron "may form a part of the shell of two different atoms and cannot be said to belong to either one exclusively" (p. 772).

Figure 5 – Lewis's Models of Covalent Bonds.

In Molecule 'A' a double bond containing two pairs of electrons is depicted. This could be a molecule such as O_2. Molecule 'C' demonstrates a single covalent bond, with one shared pair of electrons. This could be a halogen such as Cl_2.

(Lewis, 1916).



Lewis made an important observation that the vast majority of stable molecules contain an even number of electrons, which led him to suggest that electrons are usually present in pairs (Gillespie & Popelier, 2001). Molecules that contained an unpaired electron (i.e. free radicals) were termed "odd" (Lewis, 1916, p. 771). Lewis emphasised that the single most important mechanism of chemical bonding was electron pairing (Shaik, 2007). The electron pair was the "cardinal phenomenon of all chemistry" (Lewis, 1923 cited in Shaik, 2007).

Lewis had no clear idea why electrons should be found as pairs in molecules. This formation seemed to contradict Coulomb's law, according to which two electrons should repel each other. In response to this dilemma, Lewis proposed that electrical forces between particles

that are very close together do not necessarily obey Coulomb's law. He argued against strict adherence to the law, but rather said that we should first of all study the structure and arrangement of the atoms, and if needed, alter the law to make it fit the observations. It is known today that Coulomb's law is obeyed, but also that electrons can form pairs in most molecules - despite their mutual electrostatic repulsion (Gillespie & Popelier, 2001).

Meanwhile, Kossel strengthened the concept of ionic bonding. He was able to show that ions have the same electron arrangement as a noble gas - they have a valence shell containing eight electrons. He reasoned that sodium chloride consisted of positive sodium ions and negative chloride ions held together in a regular pattern by electrostatic attraction (Gillespie & Popelier, 2001). Lewis believed that this was all explained by his own model. He maintained that there was no fundamental difference between ionic and covalent bonding. After all, the electron pair is not usually shared equally. Lewis explained that it would be unusual to have a completely covalent molecule unless the two atoms are of the same element (Gillespie & Popelier, 2001).

Lewis had to battle with the firmly entrenched theory of electron transfer. His "teaching device" was considered to be "speculative" (Niaz, 2009, p. 142). Nevertheless, Lewis did not suffer from a complete lack of support. Some chemists started to argue that the ionic bonding model had been extended too far, and that there were in fact two types of bonds: 'polar' and 'non-polar' – or ionic and covalent as we call them today. There had to be more than just ionic bonding, after all how could hydrogen gas be made up of two positive atoms? Moreover, the hundreds of organic compounds that were being discovered at this time could not be explained by the model of the ionic bond. Lewis had earlier classified a large

number of substances as polar or non-polar. For example ionic salts were classified as polar, and hydrocarbons were classified as non-polar. Other chemists began to be convinced that a single model could not explain the huge difference in properties between ionic substances and organic molecules (Gillespie & Robinson, 2007). More than one model would be needed to explain the properties of different types of substances.

It did not take long for it to be shown that pairs of electrons were possible. It was demonstrated that helium contained a pair of electrons. Eventually quantum theory was able to explain how two electrons can occupy the same space. The Pauli Exclusion Principle explicated that two electrons with opposite spins could occupy the same orbital. Pauling (1931, p. 1367) used quantum mechanical equations to formulate an "extensive and powerful set of rules for the electron-pair bond supplementing those of Lewis".

It always takes time for new ideas to be accepted. While Lewis did not look to replace ideas about ionic bonding, but rather complement them, his ideas were considered to be unconventional for a number of years. Lewis readily accepted much of what had previously been taught about ionic bonding. His 1916 paper makes it clear that Lewis thought that bonding in polar (ionic) compounds takes place as a result of electron transfer, which results in oppositely charged ions. In fact, he argued that electron transfer took place to complete the cube of (usually eight) electrons. Nonetheless, Lewis waited a long time for his ideas to be accepted. His earliest sketches were drawn in 1902, his major publication written in 1916, but Lewis had to wait until the 1920s before the rivalry between the competing ideas of covalent and ionic bonding lessened and his ideas became accepted (Niaz, 2001) alongside those of the ionic bonding model.

Interestingly, Lewis was able to expand upon his ideas of covalent bonding. He suggested that polar covalent molecules resulted from unequal sharing of electron pairs. He argued that compounds such as sodium chloride could be regarded as an extreme case of unequal sharing. Indeed, it was shown that there were a number of organic molecules that contained within their structure polar and non-polar regions (Shaik, 2007). Lewis also introduced the familiar symbols of dots to represent valence electrons (Hudson, 1992), as shown in Figure 6.

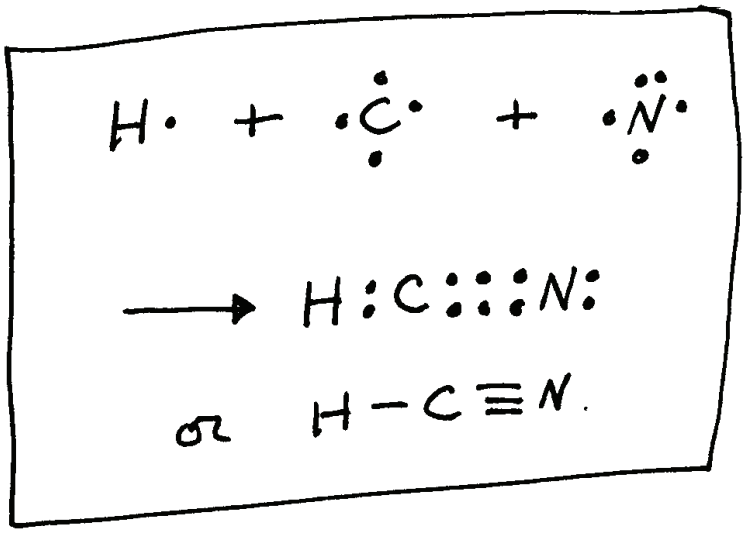


Figure 6 – Lewis dot formulae for HCN. (Combs, 1999)

Lewis's ideas were taken up by other chemists such as Langmuir. Langmuir, who had a strong rivalry with Lewis, drew a clearer distinction between covalent and ionic bonding. Lewis was a shy and reserved man, and he largely failed to publicise his theory. Langmuir, a brilliant lecturer, was more than willing to step into the gap (Gilbert N. Lewis, 2008). It was Langmuir who called the shared-electron-pair bond the covalent bond. He was adept at "coining new and catchy terms" (Shaik, 2007, p. 52).

Langmuir also manufactured the term ‘octet rule’. Lewis was amongst those who made the observation that having eight electrons provided the most stable conditions for the electron shell, although he was aware of many exceptions to this ‘rule of eight’. Langmuir also caught on to Lewis’s ‘rule of eight’ and renamed it the ‘octet rule’. Somehow an observation that many molecules contained eight valence electrons came to be regarded as a law. Lewis was uncomfortable with the way this rule and its application became more universal than ever intended (Gillespie & Robinson, 2007). The molecules that did not ‘obey’ the ‘law’ came to be considered unusual (Gillespie & Popelier, 2001). Today chemists realise that the octet rule cannot be considered a universal rule - except for the period two elements C, N, O and F (Gillespie & Robinson, 2007).

It is remarkable that ideas that are over 90 years old are still in use today. Modern chemists understand that not all electrons are paired, even in molecules with an even number of electrons. This is because, as was predicted from the beginning, electrons repel each other electrostatically. And it has been known for a long time that electrons are not localised in space like the Lewis model supposes. Nonetheless, Lewis structures still provide a useful aid for describing the bonding in molecules and the probable position of electron pairs. Lewis structures afford a quick way to determine the approximate structure of molecules (Gillespie & Robinson, 2007). While chemists today are able to explain the chemical bond in terms of the framework of quantum mechanics, the Lewis model still remains the most widely used model in contemporary chemistry (Frenking & Shaik, 2007; Bader, Hernandez-Trujillo & Cortes-Guzman, 2007).

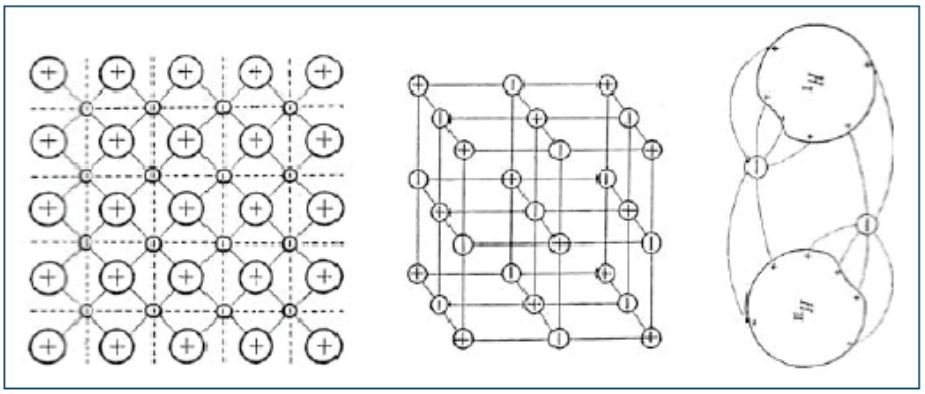
It is worthwhile to note that in addition to introducing the idea of electron pairs, Lewis had a hand in many other important breakthroughs (Simoes, 2007), which is evidenced by the fact he was nominated for the Nobel Prize 35 times. Moreover, many of Lewis's students received Nobel Prizes. Lewis is perhaps one of the most deserving chemists to never receive a Nobel Prize (Coffey, 2008; Malmström & Andersson 2001). He may have missed out on a Nobel Prize due to his making an enemy out of one of the chemists on the prize committee (Coffey, 2008). In addition to his work on covalent bonding, G. N. Lewis was also a contributor to ideas that were developing at about the same time on metallic bonding.

The Metallic Bond

Early work on metallic bonding was done by Drude and Lorentz (Jensen, 2009), who realised that metals contained weakly bound electrons which could conduct electricity. Whilst the main thrust of Lewis's work on chemical bonding centred around getting the covalent bonding model to be accepted, Lewis argued in 1913 that we should consider three types of bonding – polar (ionic), non-polar (covalent) and metallic. He explained that in ionic bonding the electrons would occupy fixed positions within the atom. In covalent bonding the electrons would move freely from atom to atom within the molecule. And in metallic bonding he argued that the electron was free to move even outside of the molecule. All molecules would fall into at least one of these three categories (Lewis, 1913).

Other scientists independently expressed the same idea. For example, Stark made the first attempt to visualise the three bonding situations, which can be seen in Figure 7 below.

Figure 7 – The first attempt to visualise all three types of bonding situations – metallic, ionic and covalent.
(Stark, 1915 cited in Jensen 2009)



Fernelius and Robey (1935) also published a bond-type triangle, as can be seen in Figure 8, where the corners of the triangle corresponded to the ionic, covalent and metallic extremes. They also explicitly indicated intermediate bond types along the edges (Jensen, 2009).

Figure 8 – Bonding-type triangle that explicitly outlines the three types of primary bonds and the intermediate types of bonds between the extremes.
(Fernelius & Robey, 1935)

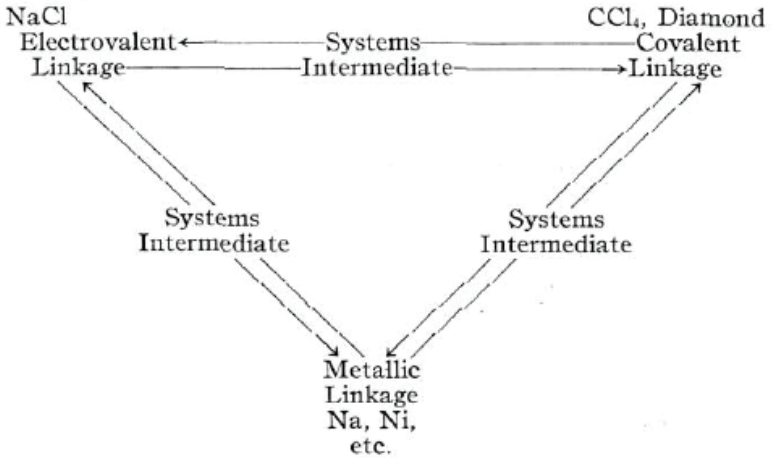


FIGURE 17.—TYPES OF VALENCE LINKAGES

Further work is still required on metallic bonding, and in particular its relationship to bonding in other molecules (Shaik, 2007).

Other Bonding Models

Chemical bonding models continued to develop. For example, Latimer and Rodebush (Hudson, 1992) introduced the concept of the hydrogen bond to explain the bonding between molecules of water or ethanoic acid. Sidgwick proposed the coordinate bond to explain bonding where both shared electrons originate from the same atom (Hudson, 1992).

However, it was the 'new' science of quantum mechanics that had the most impact on modern chemical bonding theories. It is now recognized that nothing more can be determined than the probability of finding an electron (Gillespie & Popelier, 2001) in a given region of space. Two main approaches have developed under quantum mechanics, namely valence bond theory and molecular orbital theory. At first these two approaches were seen to be in competition, but subsequently it was appreciated that the two methods are closely related.

Pauling and other researchers developed valence bond theory which was able to explain the properties and structure of many molecules. Pauling dedicated his monograph to Lewis, and described the electron pair bond as a superposition of ionic and covalent forms of bonding (Shaik, 2007). Mulliken and others developed the molecular orbital approach, and the subsequent ligand field theory, which was able to explain the absorption spectra of molecules, something that valence bond theory was unable to do (Hudson, 1992).

New methods to describe chemical bonding, for example those based on electron density, are constantly being pursued. Clearly chemical bonding concepts will continue to develop. However, many of these new theories have yet to have an appreciable impact on high school curricula.

The Link Between the History of Chemical Bonding Theory and Students' Alternative Conceptions of Chemical Bonding

It is interesting to note how inaccurate historical ideas about chemical bonding are reflected in current students' alternative conceptions. Many older and less accurate theories of chemical bonding are still being used by modern students of chemistry.

Bonds are Physical Objects

One example of a historical idea which will not die is the picture of a chemical bond as a physical link. Just as Democritus, Descartes and Dalton imagined atoms that were physically joined, perhaps with hooks and barbs, some students still believe that chemical bonds are solid links between atoms. (This alternative conception was established in Table 2). Bonds are believed to be material connections rather than forces. Other students imagine bonds to be very small springs or lengths of string, or in some minds atoms are believed to be glued together to make molecules.

Bonds and Forces are Different

Similarly, some students believe that bonds and forces are somewhat different. Students have been reported to think that some substances are simply held together with forces rather than bonds (as seen in Table 2). For example, students have reported that hydrogen bonds are just a type of force – they are not real bonds. Similarly, metallic substances are held together with forces – not bonds. Another common idea is that dispersion forces are too weak to be considered proper bonds. In fact, some students believe that all intermolecular bonds are just forces rather than proper bonding. Just as Newton and Boltzmann worked to convince others that a bond is an attractive force, so teachers continue to work to transform students thinking about the nature of bonds.

Electron Transfer is Bonding

Another idea that has its roots in history is the way that students confuse electron transfer and bonding. Many students define ionic bonding as electron transfer (refer to Table 2 for more information). Since the time of J. J. Thomson, ionic bonding has often been described as a process of electron transfer. It is often explained that the more electronegative atom receives an electron from the less electronegative atom, therefore one atom becomes positively charged and one atom negatively charged, and then the oppositely charged atoms are attracted together forming a compound. G. N. Lewis also argued that bonding in ionic compounds takes place as a result of electron transfer.

However, using the idea of electron transfer to explain the idea of ionic bonding ignores the fact that the majority of ionic substances are not created from neutral elements. For example, sodium chloride is rarely made in the school laboratory by reacting sodium metal with chlorine molecules. Sodium chloride would most likely be produced through a neutralisation reaction followed by the evaporation of water. In this case we do not need to invoke the separate concept of electron transfer to explain the presence of ionic bonding in the product (Taber, 2002a).

Some students take on board the confusion between electron transfer and bonding and further explain that the reason a bond forms between a sodium and chloride ion is because an electron has been transferred between these two ions. A number of students believe that the chloride ion bonds only with the specific sodium ion that donated it an electron. Some students even confuse electron transfer with covalent bonding, describing covalent bond formation as a process that involves the complete transfer of electrons. The two concepts of electron transfer and bonding need to be separated in the minds of many students.

The Number of Bond Types

Throughout history there has been debate about how many types of bonds exist. For many years the idea of the polar (i.e. ionic) bond was the only acceptable model to describe bonding. G. N. Lewis had to fight hard for his concept of the non-polar (i.e. covalent) bond to take hold. Further bond types were later described, but some students are still convinced that there are only two bond types: covalent and ionic bonding. Either electrons are shared

or they are transferred (see Table 2). Students discount any other type of bonding that does not fit into one of these two categories, and they have difficulties with bond types that may be intermediate between these two. For example, some students have stated that hydrogen bonding is a type of covalent bond; electrons are shared in metallic bonding; bonding results in molecules; metallic bonds are like covalent bonds; or metallic bonds are like ionic bonds. The range of possible bond types needs elucidation.

Atoms Bond to Follow the Octet Rule

Another problematic historical artefact is the Lewis-Langmuir octet rule and the way that it is often seen as the overarching guiding principle to explain bonding. It was Lewis that noted that having eight electrons provided the most stable conditions for the electron shell. He was well aware that there were many exceptions to this rule. Nonetheless, Langmuir popularised the octet rule and this rule of thumb soon appeared to have the status of a scientific law. For a large number of students the octet rule is still seen as the most important bonding principle that they know. Students believe that the purpose of bonding is to obtain an octet of electrons (see Table 2). For example, students state the following: atoms lend and borrow electrons to satisfy the octet rule; a shared electron pair holds atoms together because it enables the atoms to have octets of electrons; every element wants to obey the octet rule; the octet rule drives chemical reactions; the sodium anion (Na^{7-}) is more stable than a neutral atom as it has a full outer shell of electrons; and eight electrons for elements in periods three and above is enough to fill the valence shell. Students continue to use octet thinking despite being aware of a large number of examples where the octet rule does not work.

The Laws of Physics are Suspended in Bonding

One of G. N. Lewis's greatest contributions to chemistry is the idea of the electron pair (as discussed earlier). Some students still do not understand the idea of an electron pair. Lewis made the unfortunate suggestion that a pair of electrons exists because Coulomb's law does not operate between paired electrons. Only later did quantum mechanics have a valid explanation for the existence of a pair of electrons. Nonetheless, students have been reported to have said that Coulomb's law does not work inside the atom (refer to Table 2). In fact, students have suggested that Coulomb's law does not work in chemistry at all – only in physics. And this is not the only time that the laws of physics have been suspended in chemical bonding! Students have written that oppositely charged ions will use up each other's force and lock together in a molecule. Similarly, nuclear force is used up on electrons and none is left over at the end. So it appears that incorrect historical ideas can indeed have a long life.

Summary

This research project seeks to provide the information required to develop a pedagogical history of chemical bonding. To construct such a teaching device, research is needed regarding students' alternative conceptions of chemical bonding and the history of the development of ideas about chemical bonding.

Within the literature of the history of the development of ideas about chemical bonding many interesting stories were uncovered. Many of these narratives involved themes that would be of interest to students today, such as anecdotes of conflict between researchers, renowned scientists with incomplete understandings, and the resistance met by new ideas. These accounts will help to further develop students' appreciation and knowledge of chemical bonding theories.

The research literature on students' alternative conceptions gives many indications as to the types of alternative conceptions that students are likely to possess, and we have noted the historical roots of some of these conceptions. A diagnostic test and interview protocol using sub-microscopic representations was developed to potentially confirm and extend the data already present in the literature on students' alternative conceptions in the area of chemical bonding. The next chapter presents the research design for the part of this research project that tested Victorian students for alternative conceptions of chemical bonding.

Chapter 3 - Research Design

This chapter delineates the research design used to determine the range and type of students' alternative conceptions of chemical bonding in the researcher's local context. It begins with describing the theoretical framework for the study, which involved a mixed method approach where both qualitative and quantitative approaches were utilised. Next the data collection techniques are outlined, including the development of the two research instruments employed. The characteristics of the population and sample are explored. Finally the data analysis procedures used are described.

Theoretical Framework

Constructivist Approach

Much of the research into learning in science is "underpinned by constructivist notions of learning" (Taber, 2008, p. 3). While the term constructivism is credited with a multitude of meanings, the "cornerstone" of this research approach is the active role of the learner (Taber, 2006, p. 173). Taber (2008, p. 3) provides a convenient summary of the common assumptions of a constructivist approach:

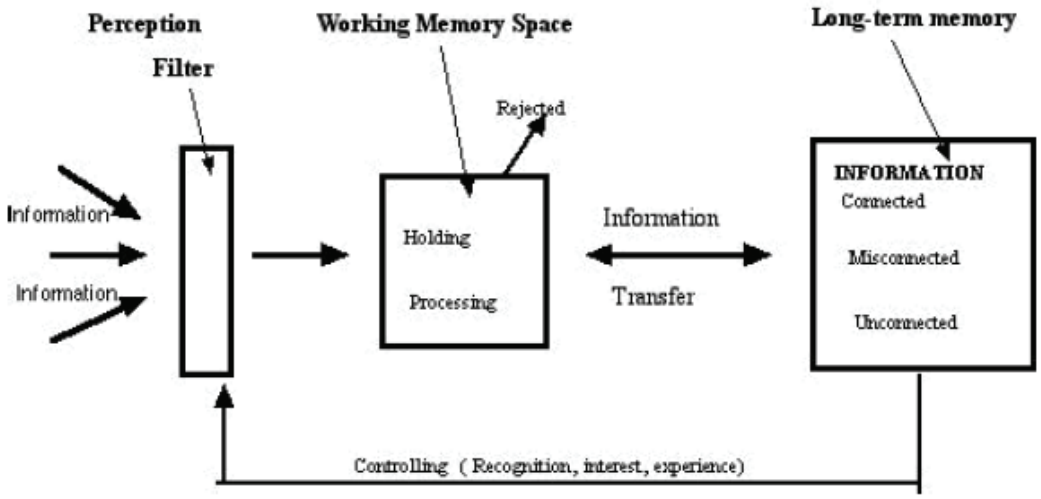
- Learning science is an active process of constructing personal knowledge.
- Learners come to science learning with existing ideas about many natural phenomena.
- The learner's existing ideas have consequences for the learning of science.
- It is possible to teach science more effectively if account is taken of the learner's existing ideas.

- Knowledge is represented in the brain as a conceptual structure.
- Learners' conceptual structures exhibit both commonalities and idiosyncratic features.
- It is possible to meaningfully model learners' conceptual structures.

Sub-microscopic Representations of Bonding

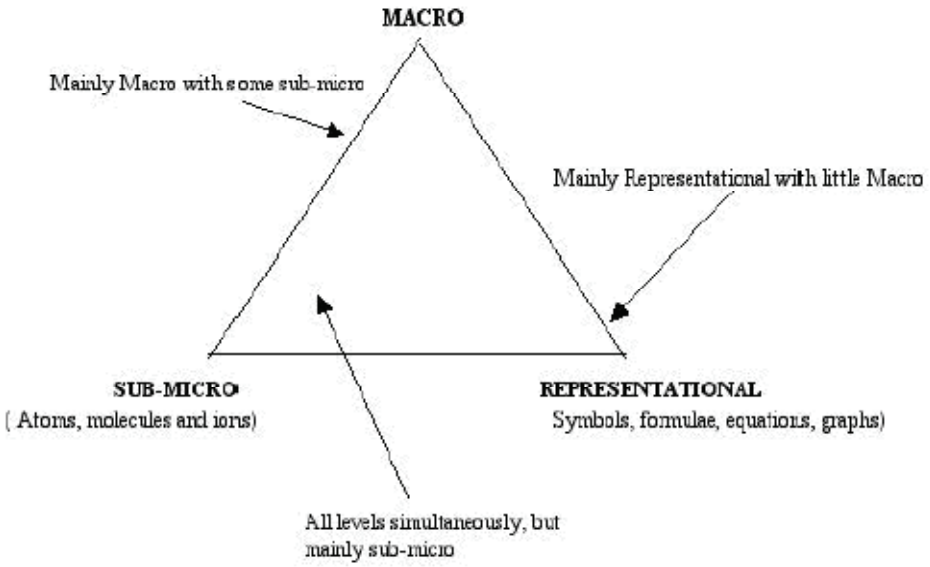
Johnstone (2006) expands upon the importance of preparing the learner before new teaching takes place. In his information processing model (see Figure 9 below), new information is attached to some point in the students' long term memory. During the process of learning new information, the student will need to recall information from the long term memory in order to make sense of the new information. Then the new information is stored alongside existing knowledge and understanding. If the learner thinks the new information is valuable, but cannot link it to existing information, the information enters the long term memory as rote learning. Such information is hard to recall. If the learner attaches the new information to some other knowledge in a faulty way, this creates an alternative conception. This faulty attachment is very hard to undo because the alternative conception makes sense to the student.

Figure 9 –Information Processing Model (Johnstone, 2006)



In Johnstone's model information is processed in the working memory. The working memory can be very easily overloaded because of the requirement of different *levels of thought* when studying science (Johnstone, 1991, 2006). Students are simultaneously introduced to new substances (the *macro* level), are required to describe these new substances in terms of molecules (the *sub-micro* level), and then represent new substances using symbols and chemical formulae (the *representational* level). A student may find themselves stranded at the *macro* level of thought, while the teacher sweeps across all three levels of thought. The different levels of thought are shown in Figure 10 below.

Figure 10 – The Three Conceptual Levels of Chemistry (Johnstone, 2006)



By introducing all three experiences simultaneously, there is great potential to overload the working memory of a student. "Why must we inflict all three levels simultaneously on young people?" wonders Johnstone (1991, p. 78). Learners find it difficult to enter all three modes of thought at once without experiencing overload or coming up with rationalisations (Johnstone, 2006). Rationalisations lead to alternative conceptions.

This study is positioned close to the *sub-micro* corner of Johnstone's conceptual levels of thought triangle, probably just to the right of Johnstone's arrow which is labelled "all levels simultaneously, but mainly sub-micro". The diagnostic instrument developed in the course of this study uses multiple *sub-microscopic representations of bonding*. Students are required to think about the way that particles are arranged in common metallic, ionic or covalent substances.

Additionally, the sub-microscopic representations of bonding used in this study are instances of *modelling* in chemistry. There has been considerable recent interest shown in modelling. Chemists are constantly modelling their observations using the sub-microscopic level of thinking. Justi & Gilbert (2002) explain that learning chemistry involves coming to understand the major models, their scope, limitations and roles. Creating and testing models is what chemistry is all about. Modelling has become the principal way of thinking in chemistry and one of the most important tools for probing the properties and uses of new materials. Modelling, including computational models, is one of the most important areas of chemical research (Justi & Gilbert, 2002).

Historical Approach

Justi & Gilbert (2002) argue that the historical aspects of the development of scientific knowledge (e.g. chemical models) do not receive adequate emphasis in most text books. Rather science is presented as a serious of true and complete facts. A pedagogical history traces the progress of development of scientific ideas. Thus it enables students to achieve a deeper understanding of a topic. Research was conducted to find interesting and relevant stories of scientists developing models of chemical bonding. Information was recorded about the models in their early stages of development - where ideas about chemical bonding may still be incomplete or inaccurate. Factual errors made by the early scientists were noted, particularly if these were the same errors made by students today. Historical information was noted that may well help students develop a deeper understanding of chemical bonding concepts. Primary and secondary sources related to the history of chemical bonding were consulted and reviewed in chapter two.

Diagnostic Assessments

Diagnostic instruments have been developed in science to assess what students are *thinking* rather than simply to determine if students possess certain information (Treagust, 2006). Treagust (2006) explains that by using diagnostic instruments during a science course teachers can gain a better understanding about the nature of students' understanding and the existence of any alternative conceptions in a particular topic. He further argues that diagnostic assessments have a valuable role to play in improving teaching, improving learning and maintaining student interest.

Diagnostic instruments have been produced by a number of workers. For example, in the area of chemical bonding Tan & Treagust (1999) and Peterson & Treagust (1989) have produced two-tier multiple choice diagnostic instruments to examine student understanding. Further examples of different types of diagnostic instruments will be discussed later.

The development of a diagnostic instrument to determine students' thinking about chemical bonding was an integral part of this study. This took the form of questions about sub-microscopic representations of ionic, metallic and covalent substances. This study adds to the current body of literature on students' understanding of chemical bonding because sub-microscopic representations have rarely been used in diagnostic tests.

Two Phase Approach

This research took place in two phases. The first 'confirmatory' (Taber, 2008) phase involved a multiple-choice test where the research focused on finding the frequency with which conceptions previously detected, according to the literature, could be found in the sample. The purpose was to determine the frequency with which the students could offer the scientific response, as opposed to a range of common alternative conceptions. The second 'exploratory' (Taber, 2008) phase looked at what ideas individual students held, teasing out a detailed view of what each individual was thinking. This approach entailed using an in-depth interview to identify and understand the thought processes and viewpoints of each student. This research was intended to confirm and extend the work on alternative conceptions already present in the literature.

This two phase research procedure enabled a mixed method approach to be used for collecting data regarding students' alternative conceptions of chemical bonding. This study utilised the strengths of both quantitative research and qualitative research. The quantitative research phase of this project produced an easy to use and reuse test able to survey a large number of students quickly, thus producing a large amount of data analysed using quantitative methods. The qualitative research phase used an interview process with qualitative analysis of the data to gain an authentic idea of student thinking about chemical bonding models. Qualitative research has the strength of building a complex, holistic picture, analysing detailed views of respondents in their natural setting (Creswell, 1998).

Instruments

Two research instruments were developed in this study. Firstly, a diagnostic multiple-choice test consisting of twenty questions was developed to determine the frequency with which students choose the scientific answer as opposed to alternative conceptions of chemical bonding. Secondly, an interview lasting approximately half an hour was used to probe more deeply into students' thinking about chemical bonding.

The Diagnostic Multiple-Choice Test

The multiple-choice diagnostic test is a methodology that has been developed to help science teachers measure students' understanding of science concepts and identify alternative conceptions (Peterson, Treagust & Garnett, 1989). Pencil and paper surveys are commonly used to address students' conceptions (e.g. Unal, Calk, Ayas & Coll, 2006; Martinez, 2001). A number of multiple-choice test types are used by researchers, varying from those that use a likert-type scale (e.g. Treagust, Chittleborough & Mamiala, 2002), true-false questions (e.g. Taber, 2002b), two-tier tests (e.g. Treagust, 1988), or multiple-choice responses that cover the range of possible answers (e.g. Montanero, Perez & Suero, 1995). A multiple-choice test instrument was carefully developed so that the range of answers contained common alternative conceptions as well as the scientific conception. Distracters were based around published common alternative conceptions.

By choosing to use a multiple-choice test a large number of respondents were examined in a short amount of time. Multiple-choice tests are easier to administer and score than most

other methods (Tan & Treagust, 1999). The test was able to be used in a number of classrooms and administered by different classroom teachers. The test was cross-sectional; 172 students from two different schools across four different year levels were tested all about the same time. Information regarding gender, age and year level was collected. Coding of the responses was quite straight forward. One mark was awarded for a correct answer, and zero for an incorrect answer. Multiple-choice responses for each individual were entered into a spreadsheet for further analysis using Excel functions and SPSS (release 17.0).

The limitation of multiple-choice tests is that they cannot distinguish between those students that guess the answer and those students that hold the genuine alternative conception. Students are also limited in their responses to the range given to them by the researcher.

The twenty multiple-choice questions were developed from a synthesis of the commonly reported alternative conceptions of chemical bonding reported in the literature. The test was drafted with the assistance of an expert researcher in this field of study. The multiple-choice test was then trialled by two classes of senior (year 11 and 12) chemistry students at a high school that otherwise did not take part in the research project. The pilot test data was analysed and some modifications to the instrument were made.

The chemical bonding test consisted of three separate parts. Part A was collected before handing out Part B. Similarly, Part B was collected before handing out Part C. This ensured that students could not use information given later in the test to answer the earlier test

questions. Each student was given a participant number to write on the top of each test section. The test was generally completed by students in less than fifteen minutes.

The diagnostic instrument employed sub-microscopic representations of chemical bonding. The representations used were adopted from a year eleven chemistry text book commonly used in Victoria (Lukins, Elvins, Lohmeyer, Ross, Sanders, & Wilson, 2006). Fifteen students from this study had purchased the text book from which these illustrations were borrowed. Other publishers of chemistry text books used in Victoria use diagrams that are almost identical to the representations used in this study. In addition, a number of junior science text books reviewed also used very similar diagrams. This is due in part because the diagrams utilised for the diagnostic test were very typical representations for metallic, ionic and covalent bonding. These models contained basic features used commonly in many text books.

The first part of the chemical bonding test asked students to identify three models of bonding as either covalent, metallic or ionic bonding. In Part B of the test students were given three photos of different substances and were asked to identify the covalent, metallic or ionic substance. They were also given three bonding models, and asked which model illustrated water, copper and salt. Part C of the chemical bonding test asked further questions about a metallic bonding model (of copper), an ionic bonding model (of sodium chloride), and a covalent bonding model (of water). A full copy of the chemical bonding test can be found in Appendix #2.

The Interview

A number of researchers (e.g. Frailich, Kesner & Hofstein, 2009) have used a mixed method approach of combining an interview with a test. They use these two techniques to get a clearer picture of students' thinking. Interview methodologies have been used by many researchers to ascertain students' understanding of science phenomena. The interview is a flexible and adaptable method of discovery (Robson, 2002). The ability to ask follow-up questions to investigate interesting responses is one reason the interview technique is able to probe so deeply into students' thought processes. The interview is able to provide rich and highly illuminating material (Robson, 2002). It has the ability to provide a detailed account that provides real insight into the thinking of learners (Taber, 2008; Unal, Calk, Ayas & Coll, 2006).

The approach used was the case study method. In the case study method, attention is focused on just a few individuals (Babbie, 2001). In this study seven students were interviewed. The aim of the case study is description (Bouma, 1993). The researcher attempted to probe and elucidate the thought processes of the individual. One person was interviewed at a time, which Unal, Calk, Ayas & Coll (2006) recommend to maintain an empathetic environment. The interview took place in the natural setting (Creswell, 2003) of the science laboratory. Additionally, a number of prompt cards and chemical samples were used depicting bonding models or events. Unal, Calk, Ayas & Coll (2006) have observed that these prompts allow the participants to focus on the cards or samples and talk freely about what they know. The interview protocol was examined by an expert in the field, and a pilot was conducted by interviewing a student teacher.

The interview protocol used in this study was semi-structured and open-ended. This is similar to studies done by the researchers Nicoll (2001), Coll & Treagust (2000, 2002), Coll & Taylor (2001), Taber (1993, 1999), Duit & Treagust (2003) and a significant number of other researchers as listed by Unal, Calk, Ayas & Coll (2006). A set of questions was produced, with appropriate follow-up questions written down. After each question the interviewee was given opportunity to talk as much as desired to answer the question. The interviewer was free to ask further follow-up questions to encourage the interviewee to expand upon their explanations or clarify points of interest. Flexibility was required to allow the interviewer to test the limits of the respondents' knowledge and to build rapport with the student.

It has been noted by researchers that the usefulness of the interview method is limited due to the time required to administer the interview. It takes significant time to produce transcripts, categorise data, and interview students (Unal, Calk, Ayas & Coll, 2006). This limits the number of students that can be interviewed. It is also not possible to generalise the findings from an individual case study (Taber, 2008).

Nevertheless, according to Unal, Calk, Ayas & Coll (2006) in their review of chemical bonding studies, the interview in one form or another was the most commonly used method for probing students' mental models. It was seen as an efficient way of eliciting students' conceptions. The interview process is also useful to validate particular measures used in the test, and to shed more light on the findings of the test (Robson, 2002).

The first few interview questions explored how students defined a chemical bond, why atoms form chemical bonds, and how many different ways atoms bond together. The next section of the interview centred on a sample of potassium iodide that was presented to students. All of the questions were designed to probe their thinking about ionic substances. Next students were presented with a sample of aluminium and questions were asked to explore their thinking about metallic substances. Subsequently students were provided with a sample of hexane to investigate their knowledge of covalent substances.

The next set of questions involved showing students sub-microscopic representations of metallic, ionic and covalent bonding. Students were challenged to identify the type of bonding, and further questions about metallic, ionic or covalent bonding were administered. The final set of questions, also using sub-microscopic representations, discerned students' knowledge of the chemical and physical properties of metallic, ionic and covalent substances.

The students were guided through the questions in order, but the interviewer asked follow-up questions where necessary to probe more deeply. A full copy of the interview questions, including photos of the chemicals shown and model diagrams used, can be found in Appendix #3.

Additionally, it was intended for students to gain a better understanding of chemical bonding as a result of taking part in the interview process. Robson (2002) argues that the interviewee should get something out of the interview. Therefore, at the end of each section the interviewer stopped asking new questions, and previous responses were

discussed. Students were briefly coached where misunderstandings were identified. In addition, questions in relation to the diagnostic test were raised. Test questions that students answered incorrectly were further discussed to probe the thinking behind their responses. If there were inconsistencies between test and interview responses further questions were asked.

Avondale College Human Research Ethics Committee approval was gained before commencing data collection.

Data Collection

The first step in collecting data was to locate literature on two main topics: the history of the development of theories about chemical bonding and students' alternative conceptions of chemical bonding. Local universities and internet databases were searched to find data from primary and secondary sources. The results of this search constitute much of the literature review in Chapter 2.

The second data collection step involved using the test instrument to collect data from high school students. Students that had already studied chemical bonding in their science or chemistry courses were chosen. Students from two high schools were surveyed to determine the frequency with which they chose the scientific response or an alternative conception. This involved a total of 172 students. The test was done as an in-class activity under regular teacher supervision. This approach produced very 'clean' data, that is, there

were very few questions left unanswered or answered unintelligibly, and every student that was present on the day of the test voluntarily participated giving a response rate of 100%.

The third data collection step was to interview seven high school students to gain an in-depth view of their thinking about chemical bonding. The interview process took approximately thirty minutes. At the start of the interview the purpose of the study was explained. The student was assured that the responses would remain anonymous, and that the identity of the respondent would be treated in strictest confidence. It was explained that the researcher wanted the student to talk as much as possible because the researcher wanted to understand the thought processes of the interviewee. Permission was granted by each interviewee to record the interview.

The interviewer attempted to ask the questions in the same way for all interviewees. However, at times the interviewee asked for clarification of a question, in which case the researcher was free to reframe the question.

Population

The population was identified as any student who had studied chemical bonding in Victoria. According to the Department of Education and Early Childhood Development (2009) there are more than 385,000 full-time equivalent students enrolled in high schools around Victoria. It is difficult to identify how many of these students have encountered chemical bonding lessons during science. The Victorian Essential Learning Standards (Victorian Curriculum and Assessment Authority, 2008) do not specifically mention the term chemical

bonding; however, most students study the topic in years nine or ten. It is probably safe to assume that about half to two-thirds of the Victorian high school student population have studied chemical bonding ideas.

Sample

A non-random sample was chosen. Students that had studied chemical bonding in two schools were chosen to undertake the test. While it is believed that the results of the students from these two schools are likely to be typical of classrooms around Australia, the purposive sampling technique (Bouma, 1993) means care needs to be taken in generalising these results to other students in other schools. As Taber (2008) notes, it is often difficult to choose a random sample of the entire population. In this case, the researcher was able to gain access to all students at two high schools in Melbourne. The two high schools were in very different locations, and all students that had studied chemical bonding topics were tested.

Student Profile

A total of 172 students were tested regarding their knowledge of covalent, metallic and ionic bonding. A similar number of students from each school participated in the test, as is shown by Chart 1.

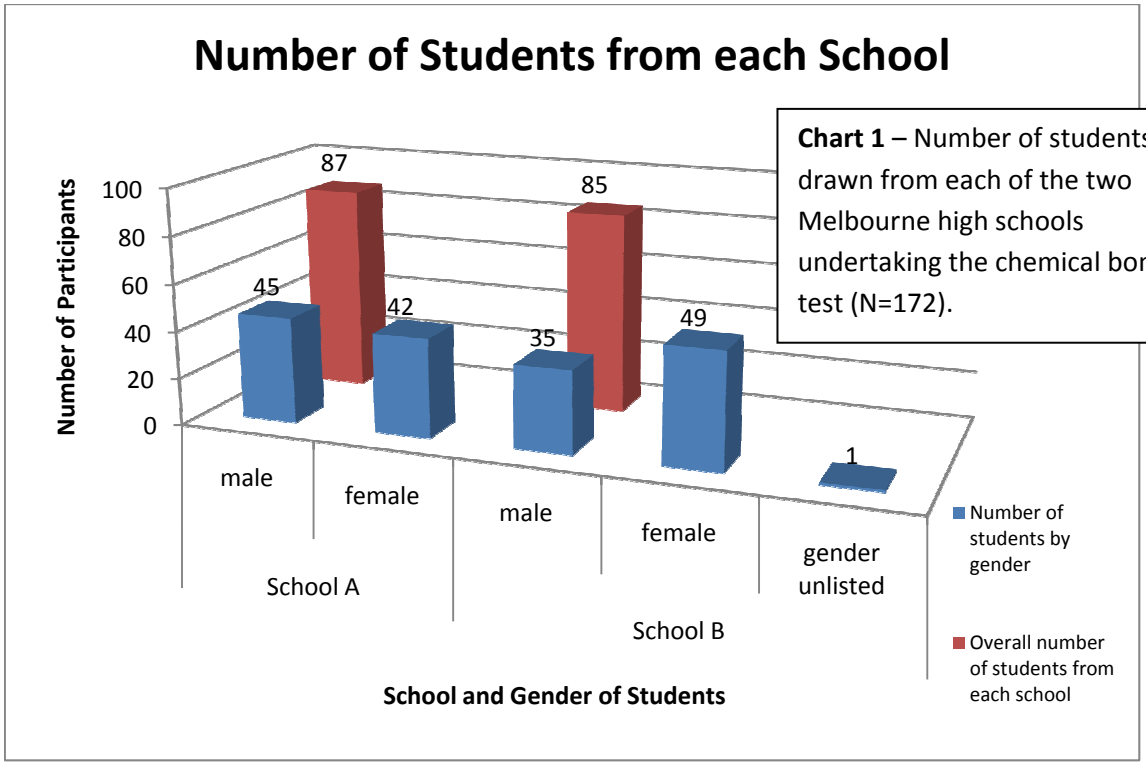


Chart 1 – Number of students drawn from each of the two Melbourne high schools undertaking the chemical bonding test (N=172).

The majority of the students that participated were from year ten (N=106). Smaller numbers of senior students (year eleven and twelve) participated in the test. This distribution was a function of class size, as the number of students undertaking senior chemistry classes at the two Melbourne schools surveyed was relatively small (N=34 present on day of testing). Year nine students (N=32) from only one school participated, as students from the second school had not yet studied the topic of chemical bonding. Chart 2 shows the age distribution of the participants, and Chart 3 shows the year level distribution of the participants.

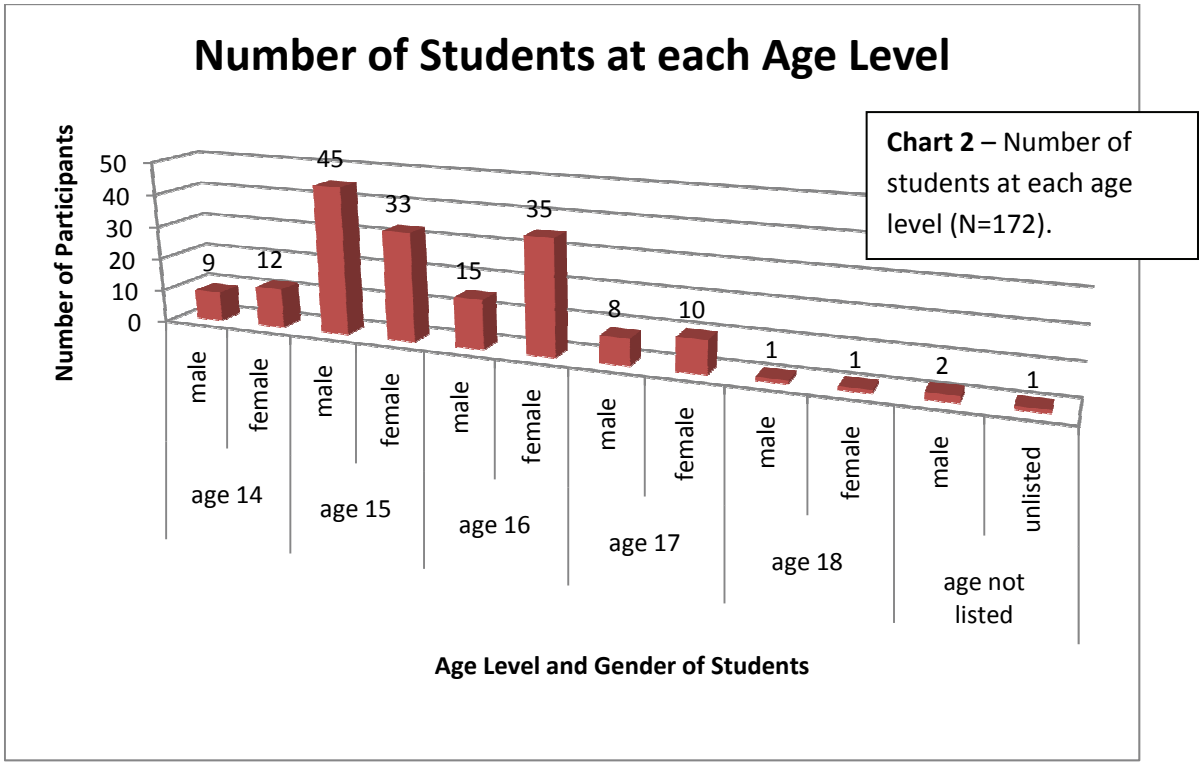


Chart 2 – Number of students at each age level (N=172).

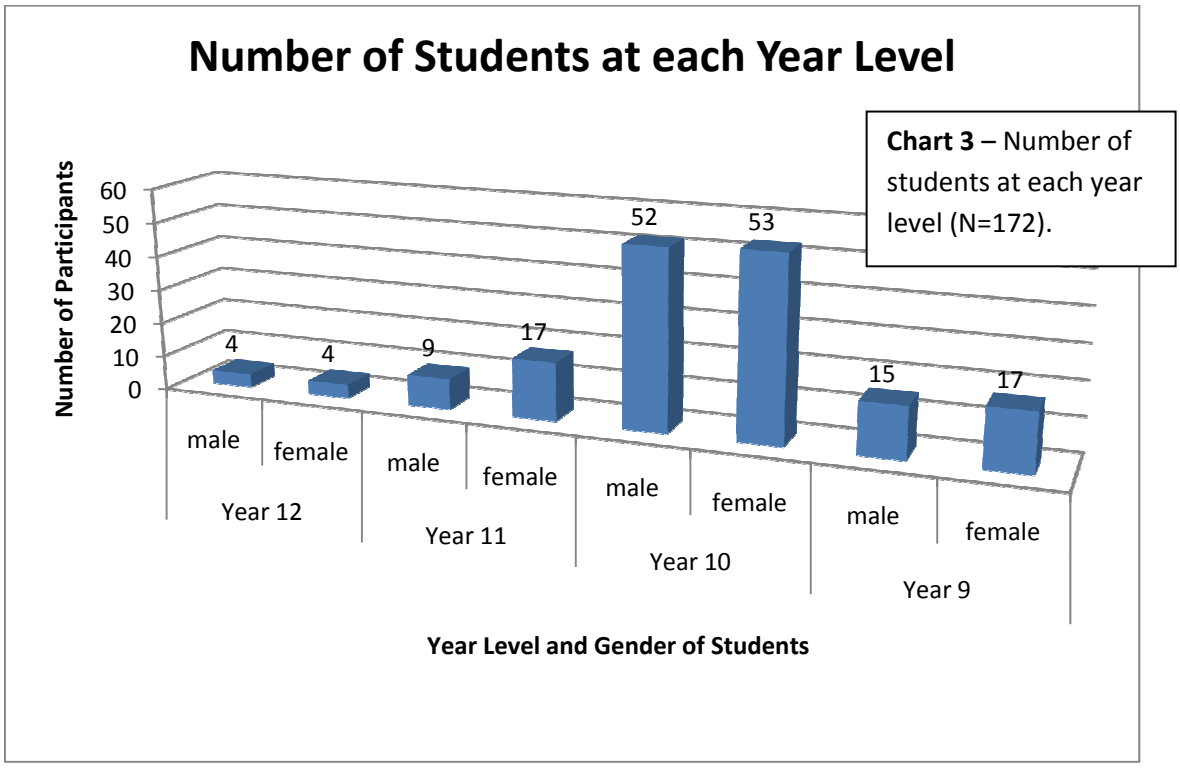


Chart 3 – Number of students at each year level (N=172).

Slightly more females than males sat the test, as is shown by Chart 4.

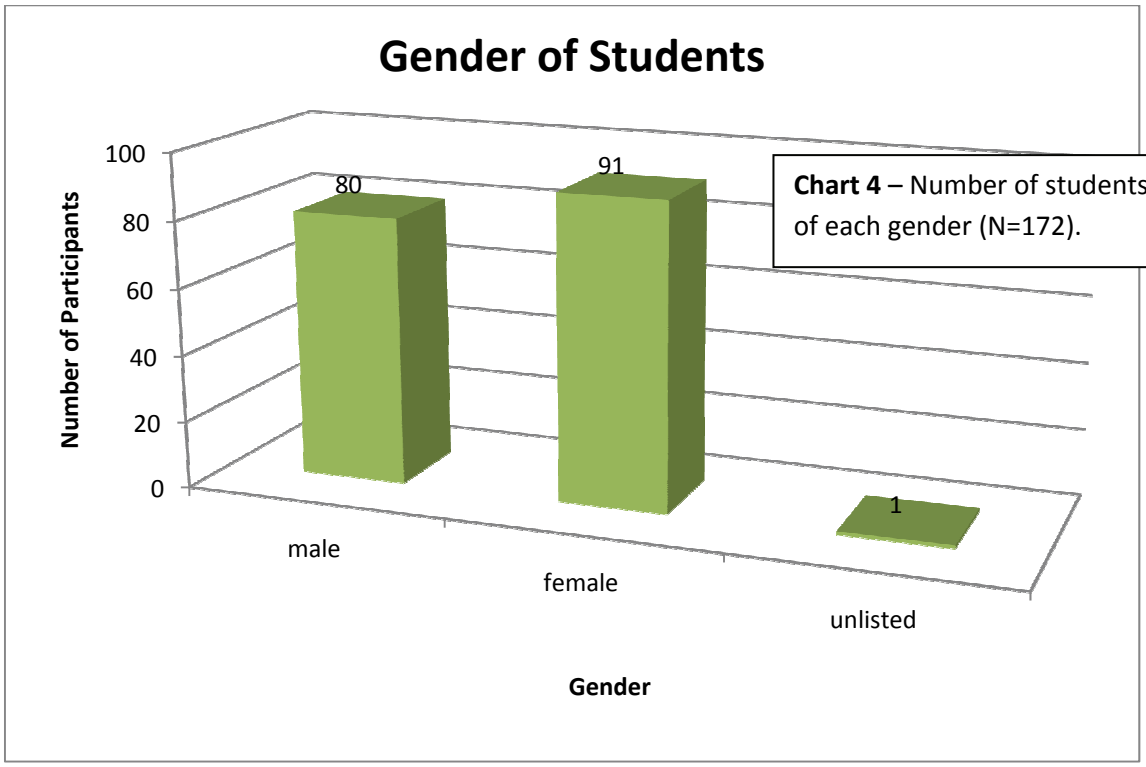


Chart 4 – Number of students of each gender (N=172).

From the sample of 172 students that undertook the chemical bonding test, seven students were selected for the interview. Senior (year eleven and twelve) students were chosen for the interview. Interviewees were selected on the basis of their test results. A spread of students was chosen – students who answered poorly as well as students who answered accurately. Also some students were chosen because they answered inconsistently during the test, and further investigation was needed to probe their thinking. Year nine and ten students were not selected for the interview because their level of knowledge of chemical bonding was very low. It was far more difficult to get meaningful reflection about chemical bonding from these students. Table 3 gives an overview of the gender and year level of the seven interviewees.

Table 3 – Overview of the Year Level and Gender of Interviewees

Year level	Gender	Number of Students
12	Male	2
	Female	1
11	Male	1
	Female	3
	Total	7

Data Analysis

The Multiple-choice Test

The test data was entered into an Excel spreadsheet. Initial analysis of the data was possible using Excel. For example, the software was used to count responses, graph data and calculate averages. Analysis was done using Excel's filter function, for example if students answered incorrectly for one question, to check what those students answered for a following related question.

More advanced analysis was done using SPSS (Statistical Package for the Social Sciences, Release 17.0). The software was used to further describe and analyse the data, for example, to look at the distribution of scores and frequency of responses. Tests were conducted to check for significant differences, such as differences in test scores between students of different year levels, genders or schools.

The Interview

The interview was recorded into an mp3 file. This allowed the interviewer to concentrate fully on the student and their responses during the interview. The interview was completely transcribed, except for instances such as when students 'ummed' or when the researcher repeated the question. These fragments were left out to improve the readability of the transcript.

Subsequent analysis of the transcripts took place. The qualitative research process is fundamentally interpretive (Creswell, 2003). The case study research approach uses detailed descriptions, followed by analysis of the data for themes or issues (Creswell, 2003). The intention was to fully understand the thought processes of individual students. As the analysis took place, the researcher noted students' alternative conceptions. In particular, the researcher noted if there was a pattern of alternative conceptions. The data was specific enough and the amount of data from seven interviews was not so great as to require the researcher to code the responses or use computer software to analyse the responses.

In order to generate conclusions from the interview data, the researcher noted patterns, themes and trends for specific interview questions and for individuals. An alternative conception was noted in the summary table if it was apparent in two out of the seven interviewees. The researcher was looking for patterns (Creswell, 1998) by observing the frequency (Babbie, 2001) of certain alternate conceptions. The aim was to reduce the

information into patterns (Creswell, 1998). This study focused more on scientifically inaccurate responses than on those that were accurate.

The next chapter presents the analysis of the data from the research instruments, and discusses the results in light of the literature review.

Chapter 4 - Results: Analysis of Data and Discussion of Results

Introduction

This chapter presents the results of the analysis of data obtained from the two research instruments used in the study along with a discussion of the results. The chapter begins by describing the response rates to the diagnostic test and interview. This is followed by the analysis and discussion of the students' tests results using two main approaches – a question-by-question approach and an analysis of the results of the different groups (e.g. year level, gender) of students undertaking the diagnostic test. Subsequently the interview results are analysed by studying the individual student's responses and looking for alternative conceptions of chemical bonding, and additionally looking for differences between their interview data and test data. Each section of the interview data is also analysed for commonalities. The chapter concludes with a brief summary of the results, and discusses the differences between the results of this study and the published literature.

Response Rates

Due to the nature of the testing, response rates of 100% were gained for both research instruments. The student diagnostic test was conducted as a voluntary in-class activity in two Melbourne high schools. All students who had studied the topic of chemical bonding were invited to participate. A total of 172 students undertook the test. Due to the whole-class activity approach taken, all students present in the targeted year levels on the day of the test participated in the activity. The classroom teacher monitored the students and

collected the tests. After the results of the student test were analysed, seven students were invited to participate in an interview process. All seven students and their caregivers gave permission for an interview to take place.

Student Diagnostic Test: Analysis of Data and Discussion of Results

A summary of the average test results by year level is given in Chart 5. As might be expected, the senior chemistry students performed much better than the junior science students on the chemical bonding test. Year eleven chemistry students demonstrated the greatest understanding of chemical bonding. This can be readily explained because chemical bonding is discussed in more detail in the year eleven chemistry course than at any other level. Year twelve students did not perform as well as year eleven students, presumably because it was a year since they studied bonding concepts in detail. In addition, a box plot is provided (Chart 6) showing the distribution of scores for each year level. Each correct answer in the diagnostic test was allocated one mark so that the maximum score for the test was 20.

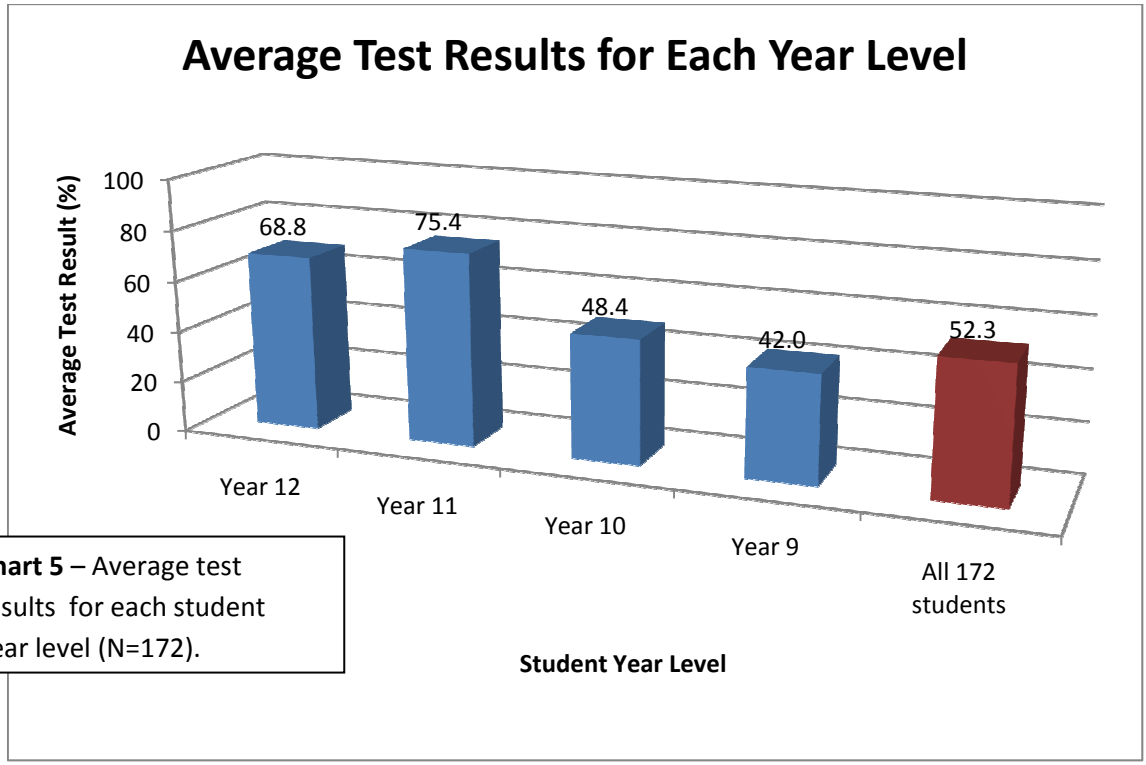
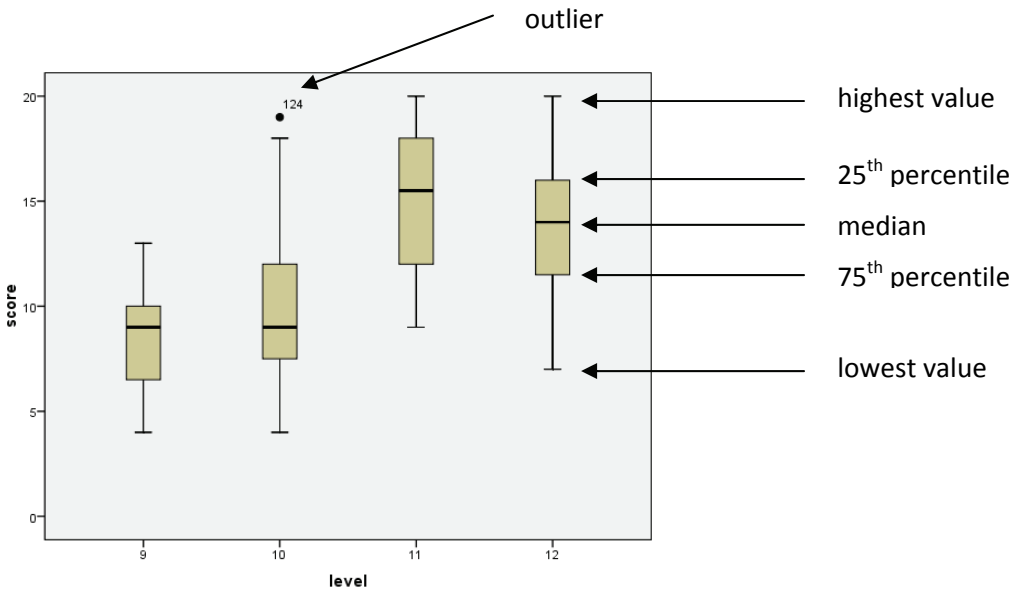


Chart 5 – Average test results for each student year level (N=172).

Chart 6 – Distribution of Scores For Each Year Level Sitting the Test.

There were twenty questions in the chemical bonding test. A score out of 20 shows how many questions were answered correctly.



The differences observed in Charts 5 & 6 across year levels were checked for statistical significance using a one-way analysis of variance (ANOVA). This showed that the different results across year levels were statistically significant at the .01 confidence level ($F(3, 168) = 28.5$, $p<.001$). In other words, there is a significant difference between the test scores of students from different year levels.

A Very Brief Explanation of the Statistical Data

There was a statistical difference in test scores across year levels at the .01 alpha level ($F(3, 168) = 28.5$, $p<.001$).

This means the probability that the reported statistical difference above is due to chance has been reported to be less than 0.001. The chance that a *F* value of this magnitude would represent a non-significant difference is very small. The *F*-ratio tests whether the group means are the same. The *F*-ratio for this test of statistical difference was 28.5. The probability that this *F*-value happened by chance is less than 0.001, which is a very small likelihood that this reported difference in group means happened by chance.

The degrees of freedom from which this *F*-value was calculated have also been reported above. The degrees of freedom for the effect of the model df_M=3 while the degrees of freedom for the residuals of the model df_R=168. The degrees of freedom shows us how many values in the final calculation are free to vary. This number is related to but less than the number of values used in the final calculation.

A Scheffe multiple comparisons test found that there was a significant difference between multiple year levels. There was a significant difference between year levels nine and eleven ($p<.001$), nine and twelve ($p<.001$), ten and eleven ($p<.001$), and ten and twelve ($p=.007$). In each case the senior students attained better scores than the junior students. There was no significant difference between year levels nine and ten ($p=.252$) and levels eleven and twelve ($p=.777$).

Similarly, the average test scores for the different age groups shown in Table 4 below were analysed to determine if the different average test results were statistically significant. A significant difference was established at the .01 significance level ($F(4, 164) = 12.5$, $p<.001$). This shows that there is a significant difference in test scores for different age groups.

A Scheffe multiple comparisons test found that there was a significant difference between the performance of students aged 14 & 17 ($p<.001$), 15 & 17 ($p<.001$) and 16 & 17 ($p<.001$). Students aged 17 years old performed at a much higher level than all other students.

Table 4 – Average Test Scores for Each Age Level

Student Age	Mean Test Score (/20)	Standard Deviation
14 (N=21)	8.29	2.493
15 (N=78)	9.81	3.167
16 (N=50)	10.72	3.985
17 (N=18)	15.39	3.238
18 (N=2)	11.00	5.657

These test results suggest that students do not have a very good grasp of chemical bonding ideas. Although sub-microscopic representations of chemical bonding have been studied in class, students demonstrated limited understanding of these representations. Even the year eleven students who achieved the highest average test score answered one-quarter of the questions incorrectly. This intimates that these students do not fully understand the

bonding models they have learnt. The year nine and ten students demonstrated a poor understanding of the models learnt.

This lack of understanding at all levels is consistent with the general direction of the published research. For example, Coll & Treagust (2002) conducted an interview where the learners were presented with chemical samples or focus cards. They found that alternative conceptions amongst secondary school learners were common. However, to their surprise, they also discovered "that alternative conceptions were prevalent for undergraduates and postgraduates, particularly for relatively simple concepts" (p. 31). Taber (1999) found during interviews over two years with A-level chemistry students that alternative frameworks such as the octet framework interfered with the intended learning during the course. He found that alternative ideas continued to be applied by successful students throughout the two year course. The lack of understanding of chemical bonding uncovered by this present study is consistent with that reported in the literature.

A frequency distribution of test scores is shown in Chart 7, and the associated descriptive statistics are shown in Table 5.

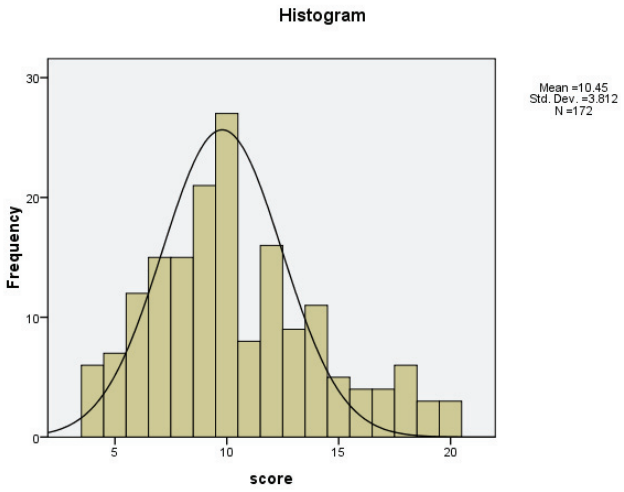


Chart 7 – Frequency distribution of scores from the chemical bonding test.

There were twenty questions in the chemical bonding test so a score out of 20 shows how many questions were answered correctly.

Table 5 - Descriptive Statistics Associated with Chart 7

	N	Range	Minimum	Maximum	Mean		Std. Deviation	Variance	Skewness		Kurtosis	
score	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
	172	16	4	20	10.45	0.291	3.812	14.530	0.569	0.185	-0.186	0.368

The distribution of scores shown above can be considered to be close to a normal distribution as far as the statistical analysis of the results is concerned. This satisfies an important criterion for applying an ANOVA statistic to the data.

Results From Part A of the Chemical Bonding Test

The first test question required students to identify three models as covalent, ionic or metallic bonding. (A copy of the diagnostic test can be found in Appendix #2). Chart 8 shows the percentage of students that could correctly identify each type of model.

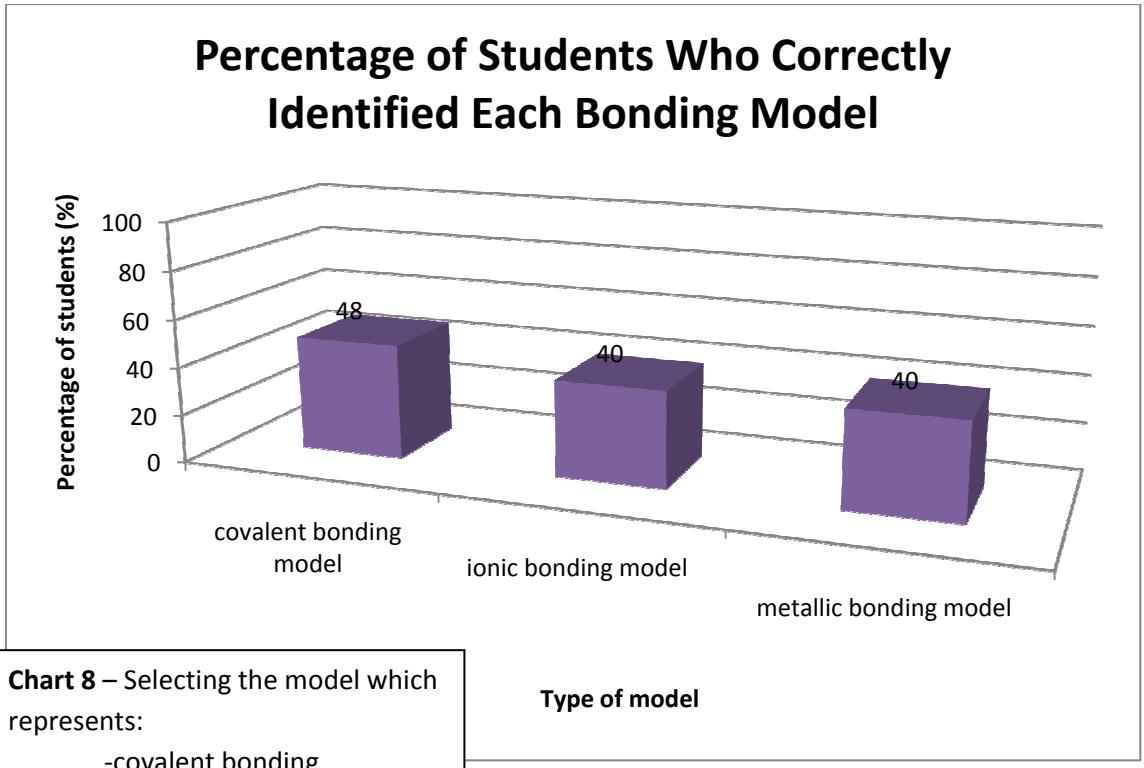


Chart 8 – Selecting the model which represents:

-covalent bonding
-ionic bonding
-metallic bonding.

Chart 8 shows that 48% of students correctly identified the covalent bonding model. Students found it easier to identify models for covalent bonding than any other type of bonding, presumably due to the presence of discrete molecules. However, 28% of students thought the covalent bonding diagram represented metallic bonding and 25% of students thought the covalent bonding diagram was ionic bonding.

Fewer students (40%) correctly identified the ionic bonding model. The ionic bonding model was labelled metallic bonding by 32% of students, and classified as covalent bonding by 28% of students.

The exact same number of students correctly identified the metallic bonding model (40%). However, 36% of students incorrectly chose the ionic bonding model for metallic bonding, and 25% thought the metallic bonding model was covalent bonding.

Chart 9 shows that student performance in Part A of the diagnostic test follows trends discussed earlier. For example, Year 11 students outperformed all other year levels.

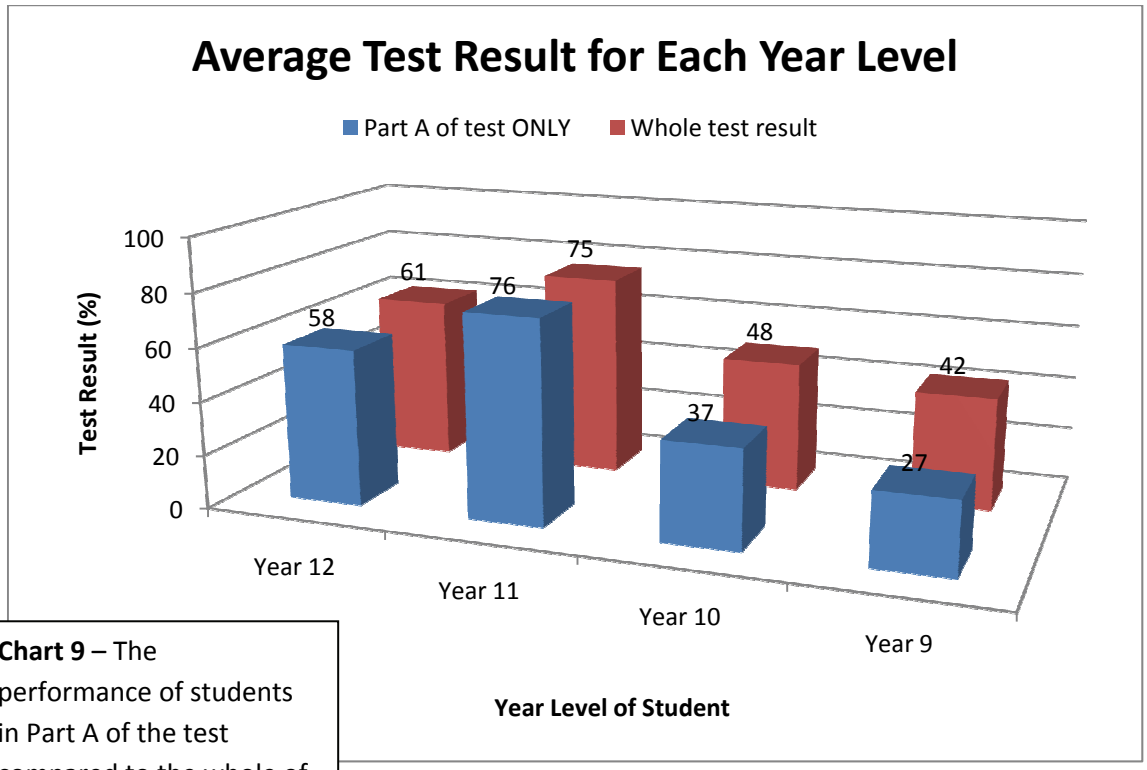


Chart 9 – The performance of students in Part A of the test compared to the whole of the test.

Results From Part B of the Chemical Bonding Test

The first task in Part B of the chemical bonding test was to correctly identify a photo of water, copper and salt. Almost all students were able to correctly identify water (99%), copper (98%) and salt (97%). This was a useful question to see if the students were filling

out the test correctly. It also demonstrates that the students are familiar with everyday objects at the macroscopic level, but have some trouble moving from the concrete ideas of the real substances (macroscopic) to the theoretical models of the same substances at the sub-microscopic level.

The difficulty that students have with sub-microscopic representations was adequately demonstrated in the next question, where students were asked to identify the bonding model diagram that represents water, copper and salt. Chart 10 shows the percentage of students that could correctly identify the sub-microscopic representation of water, copper and salt, compared to the number of students that could correctly identify the macroscopic representations of the same substances.

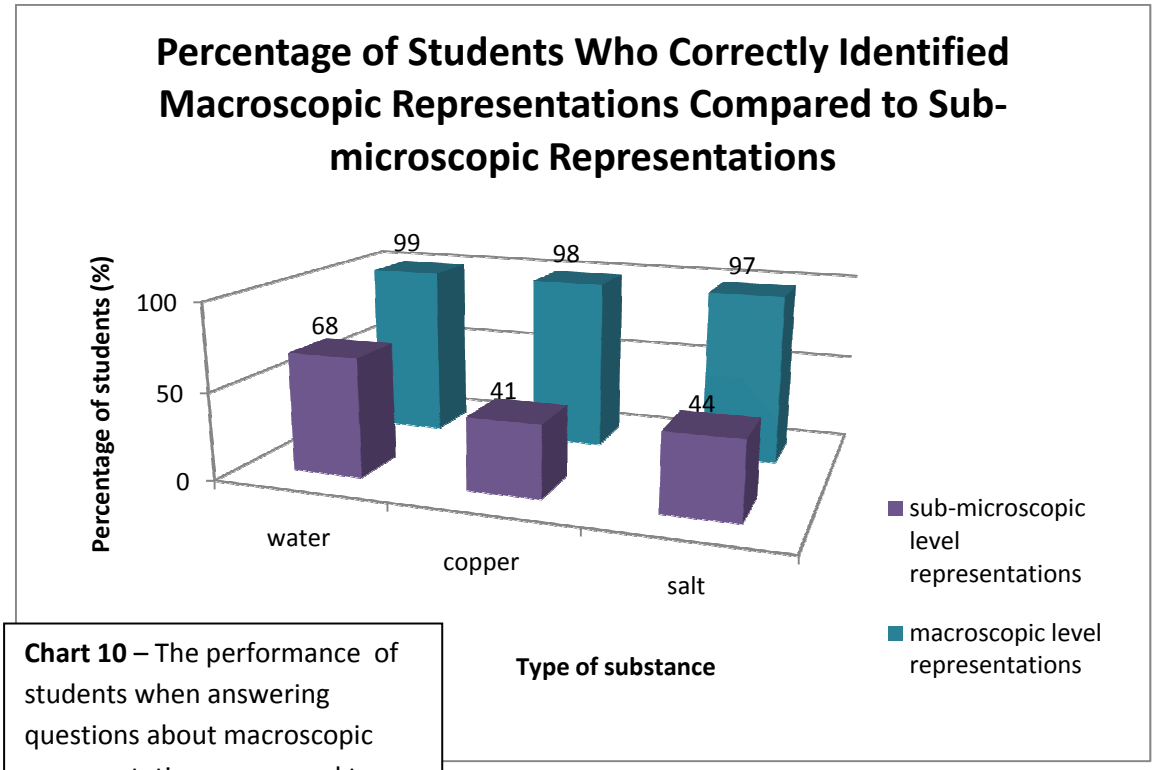


Chart 10 – The performance of students when answering questions about macroscopic representations compared to sub-microscopic representations of water, copper and salt.

There was an obvious difference in the students' level of performance when working at the sub-microscopic level compared to the macroscopic level. 68% of students were able to correctly identify the sub-microscopic representation of water, while 25% of respondents selected the metallic bonding representation for water and 8% selected the ionic bonding representation for water.

However, students had far more trouble identifying bonding models that included lattices. They easily confused the two types of lattices that were used in this diagnostic test. When students were asked to identify the correct sub-microscopic representation for copper, the most common response (48%) was to incorrectly choose the ionic bonding model, followed by 41% who chose correctly the metallic bonding model, and 11% the covalent bonding model. In addition, only 44% of students chose the correct sub-microscopic representation for sodium chloride (salt). Almost as many students (35%) chose the metallic bonding model for salt, and 22% chose the covalent bonding model.

In summary, there was much confusion over bonding models, particularly those involving lattices. Students experienced the greatest difficulty in differentiating sub-microscopic representations of copper and salt. Nonetheless, students performed much better overall in Part B of the test than in Part A, as Part B did start with some simple questions. The performance of students in Part B of the chemical bonding test followed similar trends to that shown previously, with senior students outperforming junior students. However, for the first time, Year 12 students performed slightly better than Year 11 students. A comparison of student performance across different year levels is shown by Chart 11.

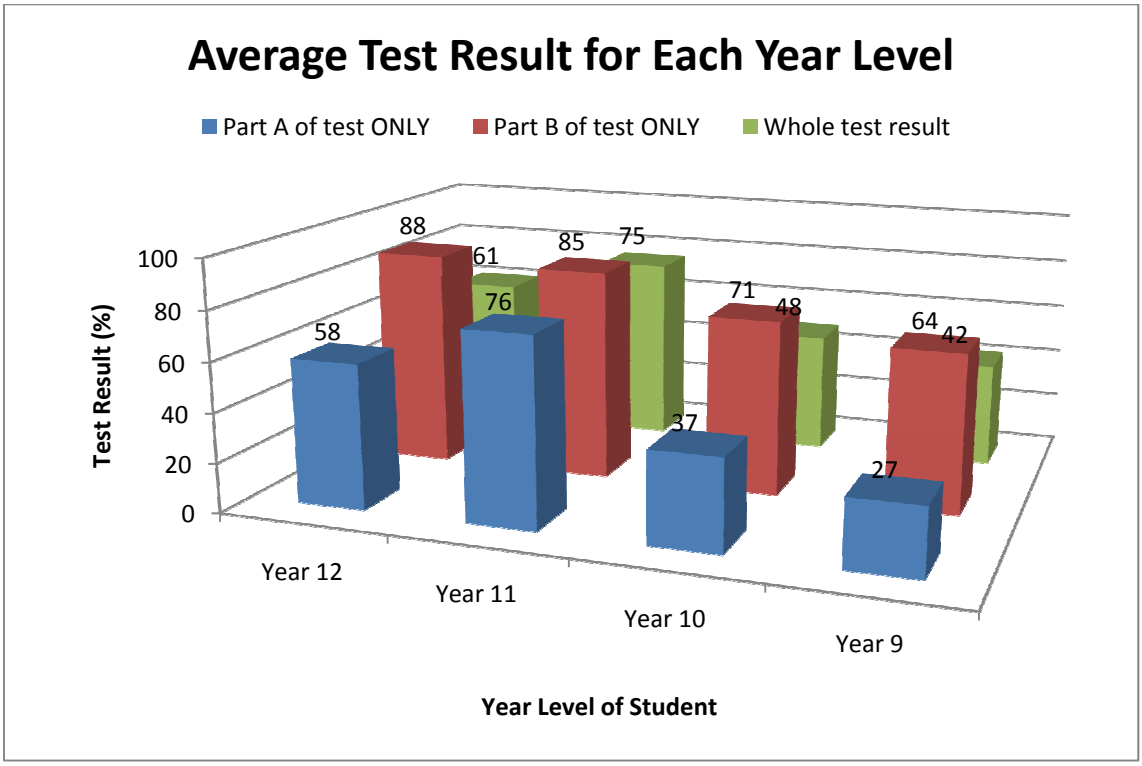
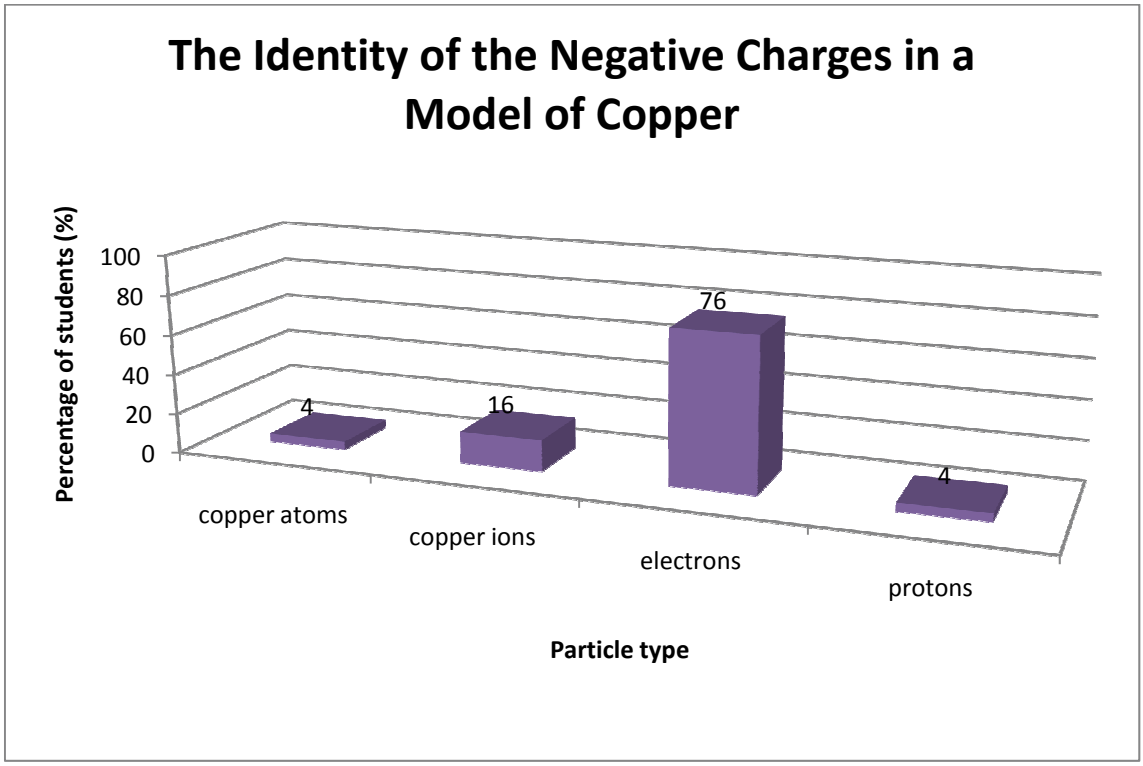


Chart 11 – A comparison of student performance across different year levels for the different parts of the chemical bonding test.

Results from Part C of the Chemical Bonding Test

The final section of the chemical bonding test consisted of eleven questions. The first three questions were on the subject of a metallic bonding diagram with the label 'this is a model that represents copper'. In the first question respondents were asked to identify what the negative charges represented. The majority of students (76%) correctly identified that the negative charges were electrons. Chart 12 reports that the most common incorrect response was to say that the negative charges were copper ions.

Chart 12 –The negative charges in copper represent:



The second question was very similar. Students were asked to identify the positive charges in the sub-microscopic representation of copper. Interestingly, only 13% of students answered this question correctly, with a majority of students (66%) stating that the positive charges were protons, as displayed in Chart 13.

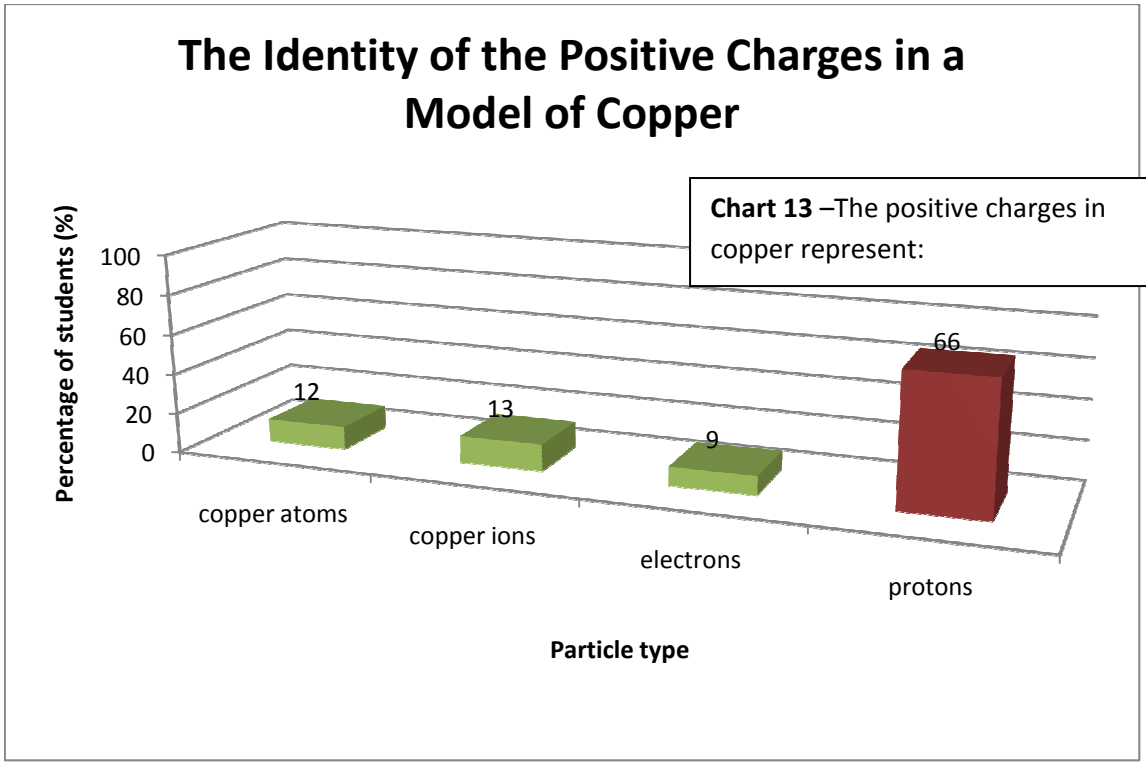


Chart 13 –The positive charges in copper represent:

These results show that students are confused about the identity of the positive charges in a metallic lattice. Fortunately, as presented by Chart 14, most students knew that attractive forces between positive and negative particles hold together the metallic lattice.

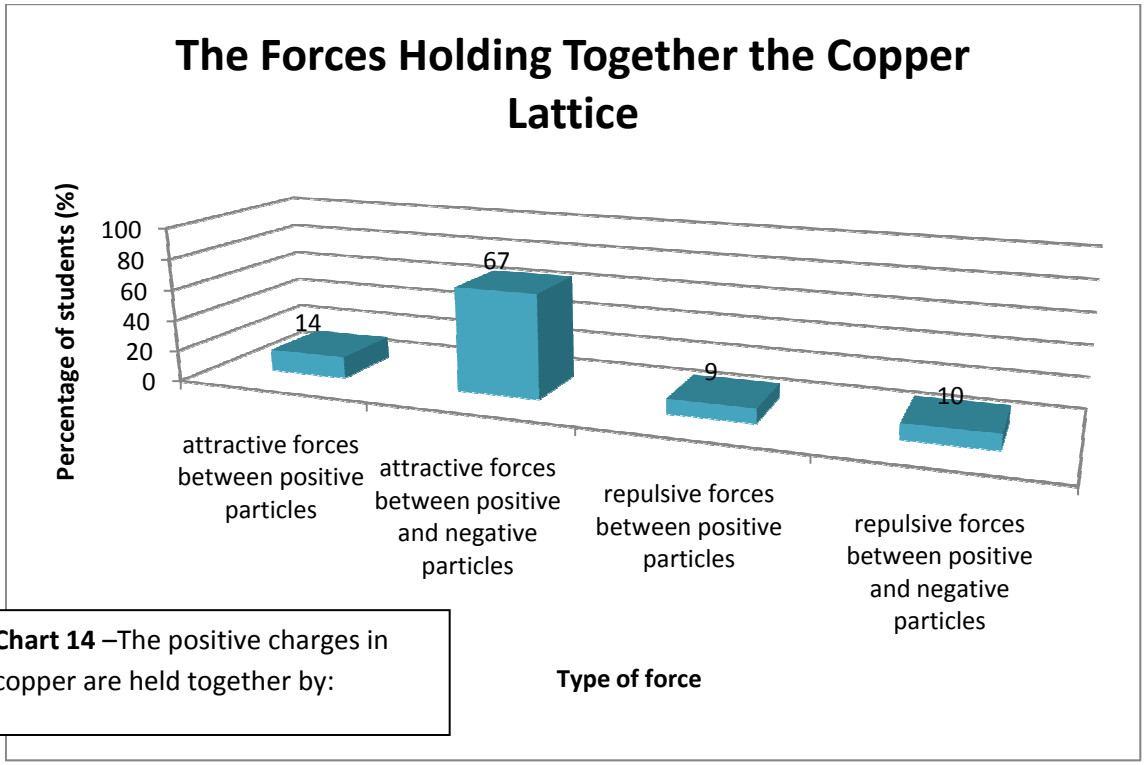


Chart 14 –The positive charges in copper are held together by:

The next three questions in the chemical bonding test followed a similar pattern to the last three. They all asked questions about an ionic bonding model which had the label "this is a model that represents common table salt, sodium chloride". Question four of the test asked what the negative charges represented. Chart 15 displays the range of answers selected by participants. The most frequently chosen answer (only 33%) was also the correct answer - chloride ions. However, nearly as many students (30%) said that the negative charges in the ionic bonding model were electrons. 19% of students thought the negative charges were sodium ions.

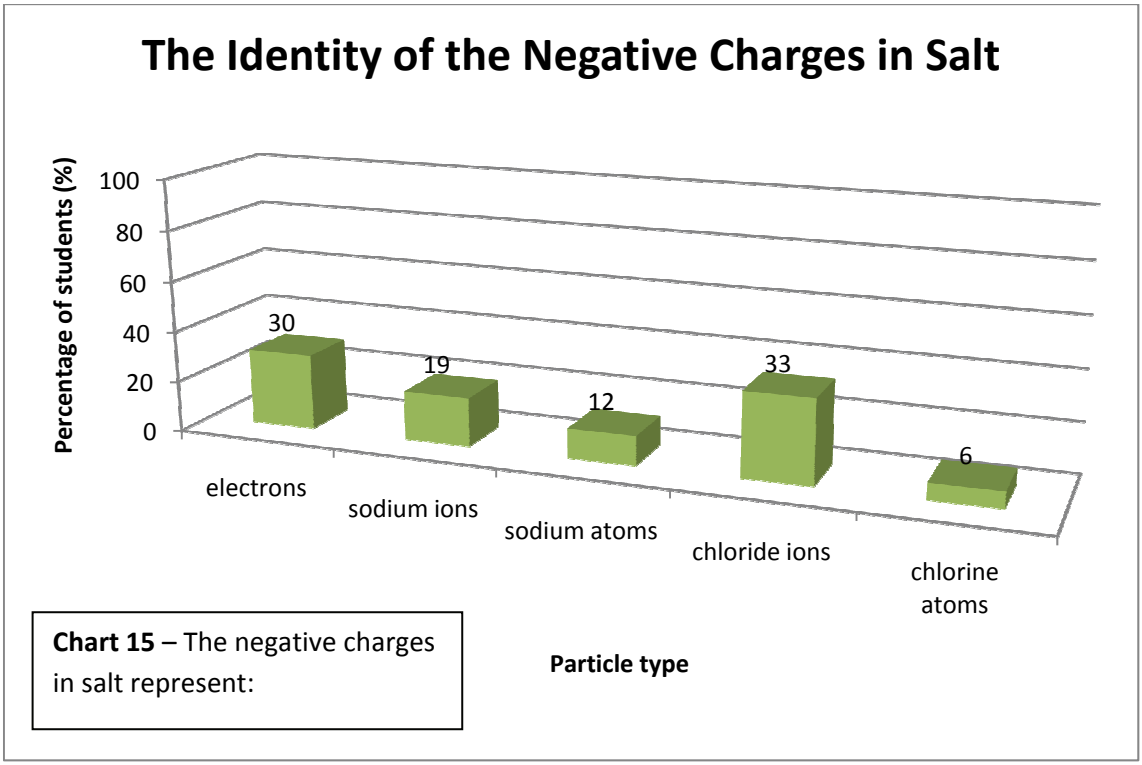
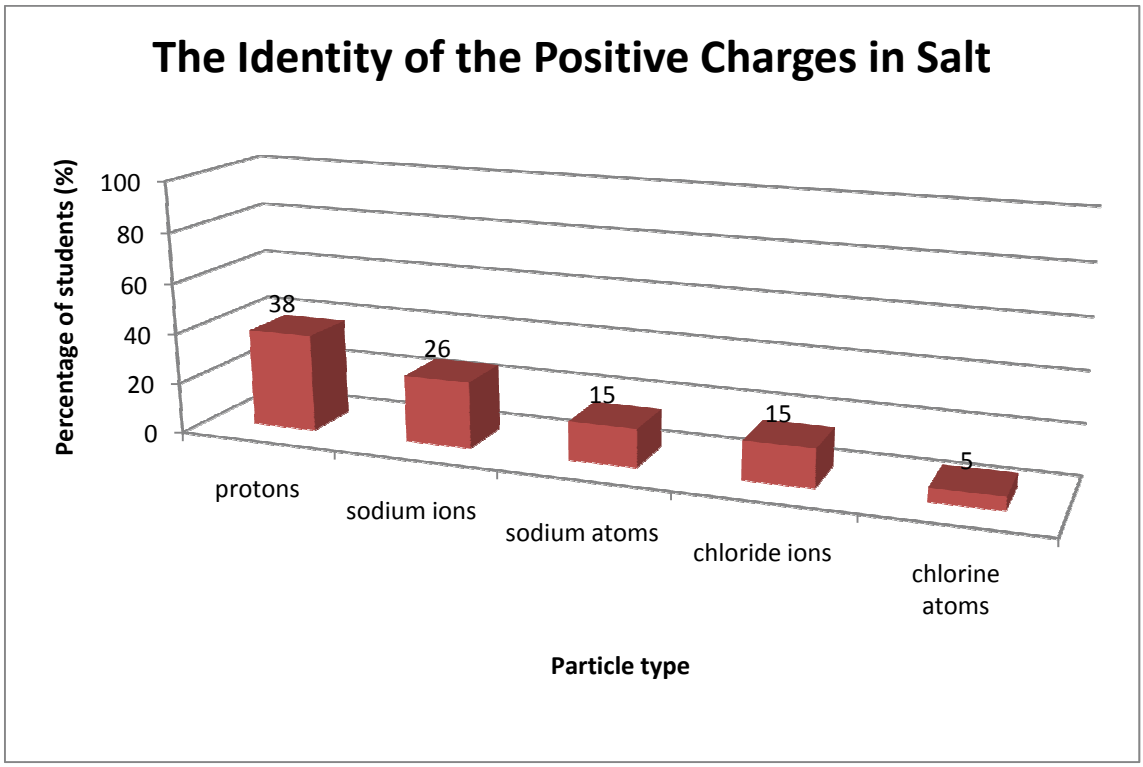


Chart 15 – The negative charges in salt represent:

It is apparent that there was considerable confusion about the identity of the negative charges in salt. Of the students who stated that the negative charges were electrons (N=51), a vast majority (88%) went on to say that the positive charges were protons. Additionally, for those students who stated that the negative charges were sodium ions (N=33), many thought that the positive charges were chlorine atoms (42%) or chloride ions (21%).

Given a model of salt, most students were unable to identify that the positive charges were sodium ions. Rather, the most frequent response (38%) was that the positive charges were protons. Only 26% of students answered this question correctly, as shown by Chart 16.

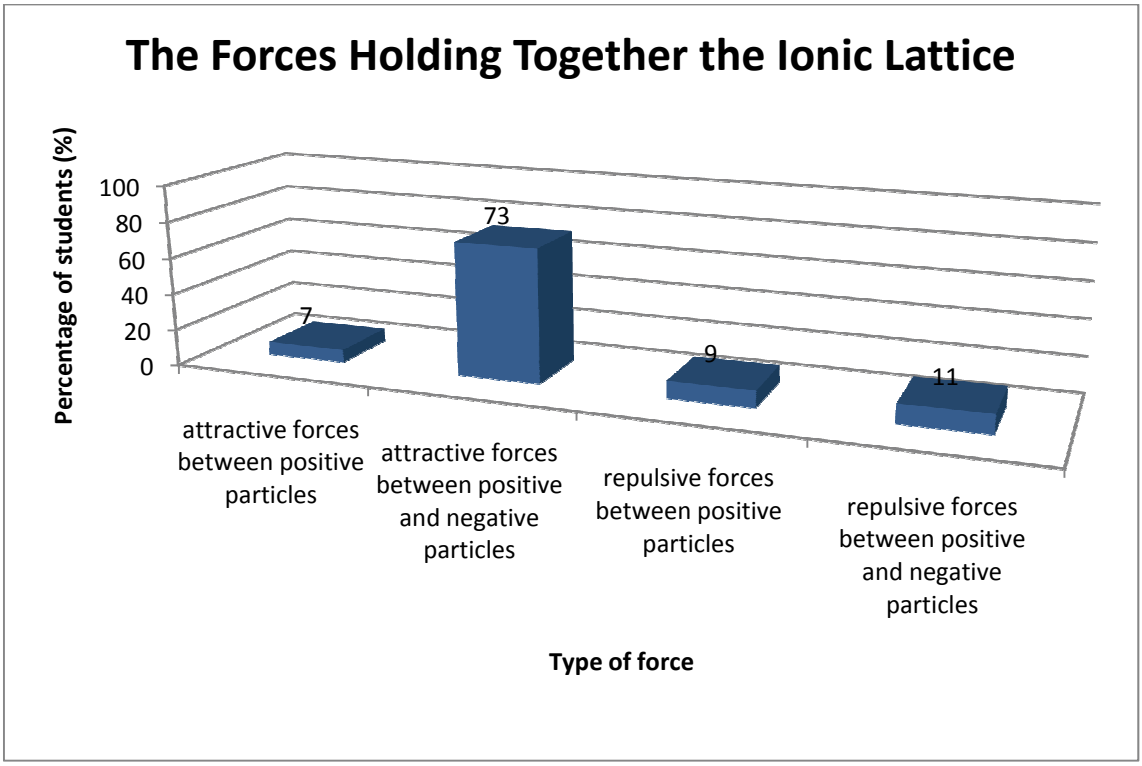
Chart 16 – The positive charges in salt represent:



By linking these last two questions, it can be shown that many students believe that an ionic substance consists of a lattice of positively-charged protons and negatively-charged electrons. An important alternate conception has been discovered here. In total, 26% of students thought that salt's ionic lattice consists of protons and electrons. A similar alternative conception was seen in metallic bonding where most students stated that the positive charges were protons which were attracted to the negative electrons.

The next question regarding ionic bonding was designed to establish what the students thought held the positive and negative charges together. This question was well answered. As can be seen in Chart 17, 73% of students stated that attractive forces between positive and negative particles were responsible for holding together sodium chloride.

Chart 17 –The positive and negative charges in salt are held together by:

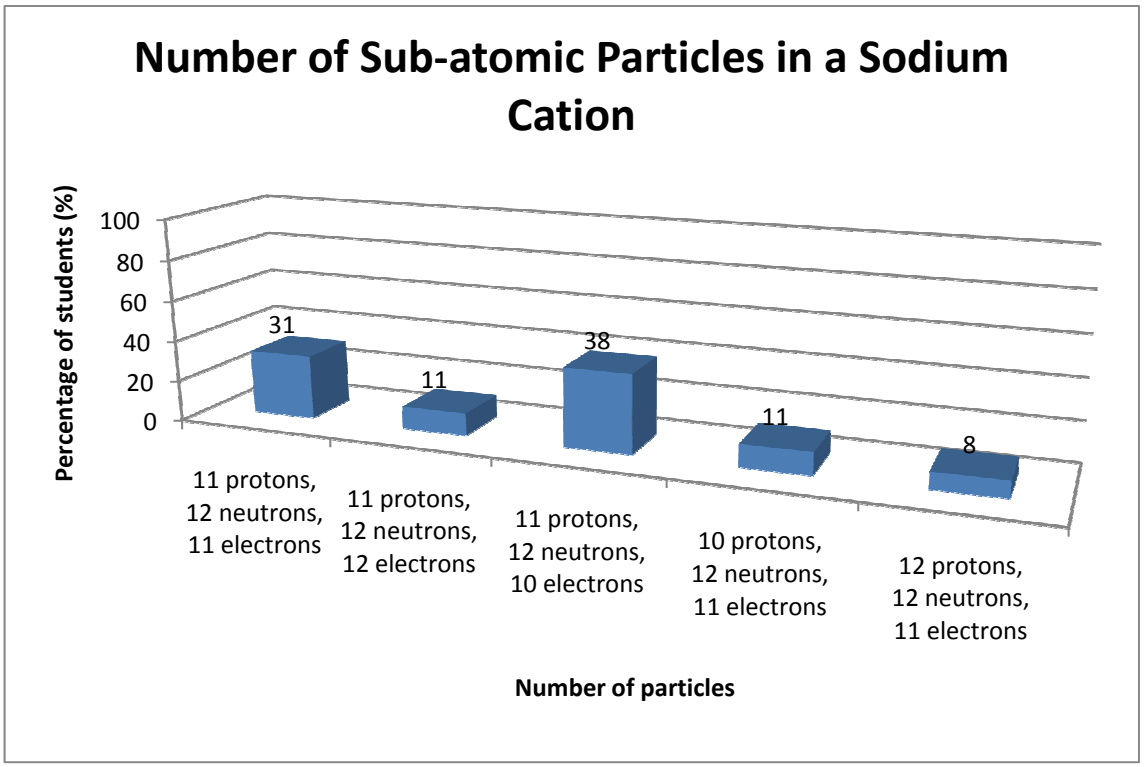


The relatively high percentage of students that answered this question correctly suggests that students probably understand ionic bonding better than any other type of bonding. While 73% of students answered this question correctly about ionic bonding, 67% students chose the correct answer in a similar question about metallic bonding, and only 20% of students chose the correct answer for a similar question about covalent bonding.

For question seven of the chemical bonding test, students were told how many sub-atomic particles a neutral atom of sodium has. They were then asked for the number of protons, neutrons and electrons in the sodium of sodium chloride. The participant responses are given in Chart 18. Question eight was worded very similarly, except it

asked for the number of sub-atomic particles in the chlorine of sodium chloride, given the number of protons, neutrons and electrons in a neutral chlorine atom. The test responses to this question are displayed in Chart 19.

Chart 18 –The number of sub-atomic particles in the sodium of sodium chloride:



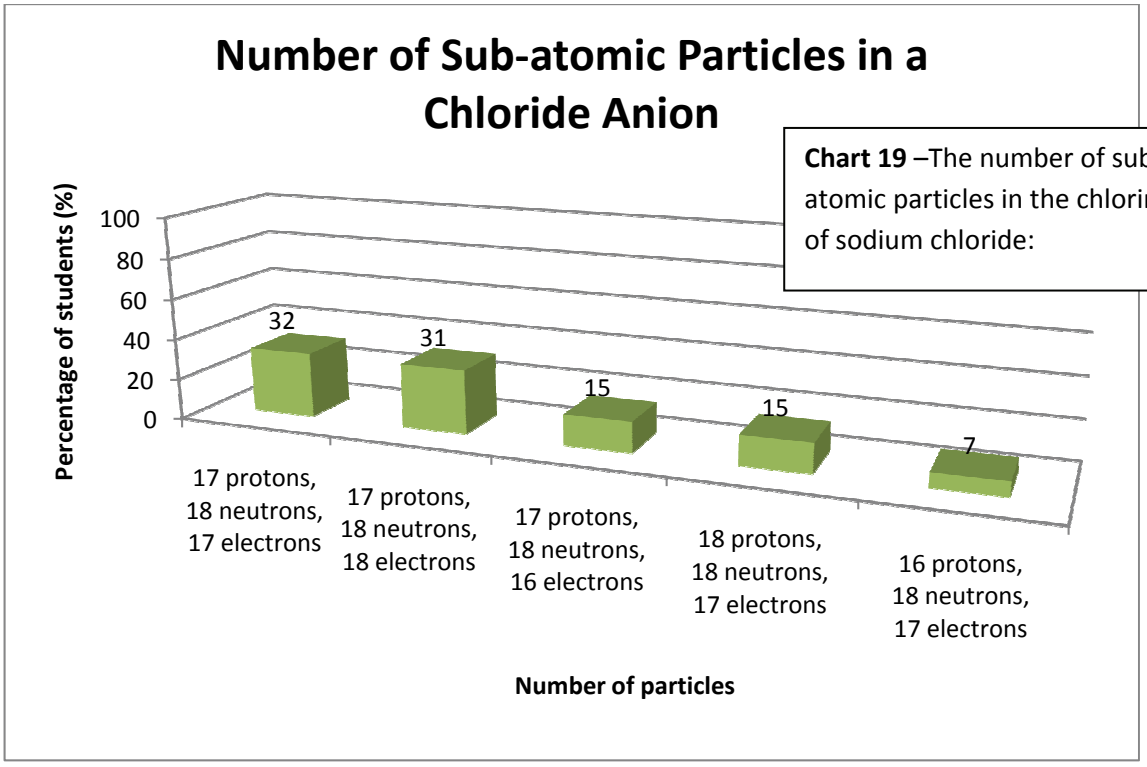


Chart 19 –The number of sub-atomic particles in the chlorine of sodium chloride:

For both of these questions a large number of students thought that the number of protons, neutrons and electrons was the same for the neutral element as it was for the ion. 31% of students said that the sodium element and the sodium ion had the same number of sub-atomic particles, while 32% said that the chlorine element and the chloride ion had the same number of sub-atomic particles. Overall, 26% of students indicated that both sodium and chlorine have the same number of subatomic particles as the ions in sodium chloride. This highlights another common alternative conception – students believe that there is no difference between neutral elements and ions in a lattice.

A number of students also believed that a chlorine atom would either have one less electron (15%) or one more proton (15%) than the neutral element. This would leave us with a chlorine cation in the first case, and in the second instance a nuclear change would be required.

The final three questions were on the subject of covalent bonding. A sub-microscopic representation of a water molecule was shown. Students were asked which sphere or spheres represented a hydrogen atom. The responses are shown below in Chart 20.

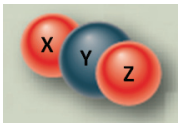
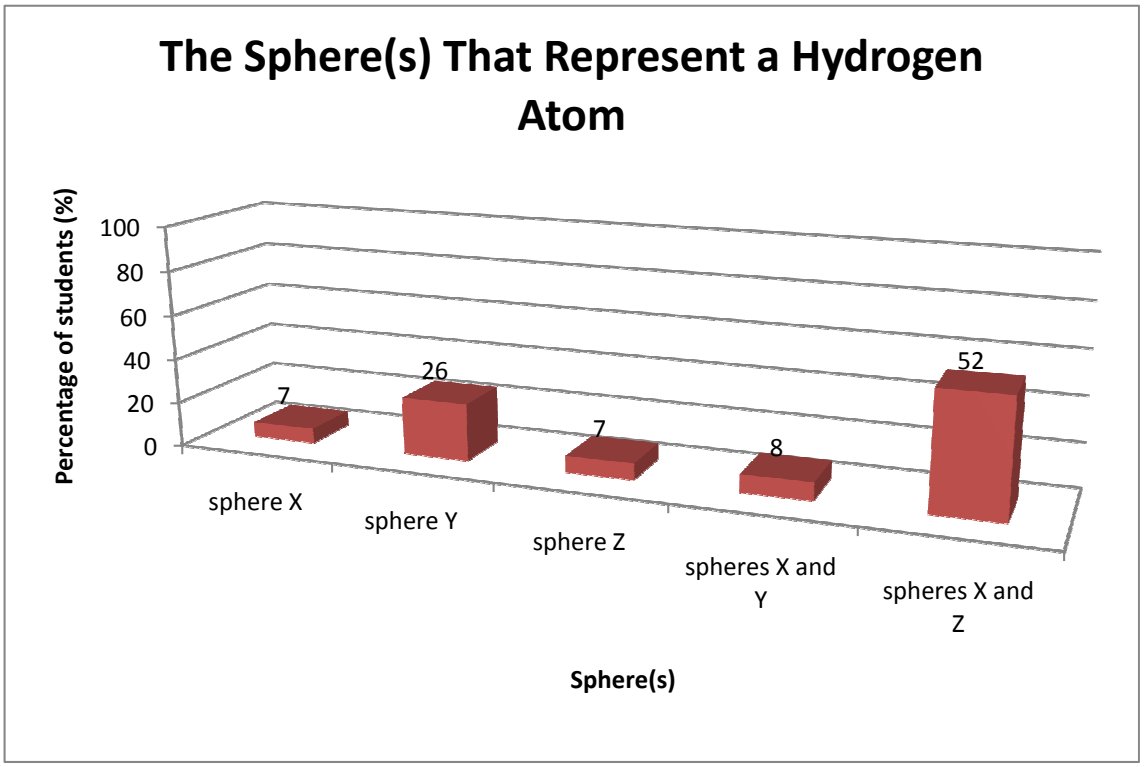


Chart 20 – The sphere or spheres that represent a hydrogen atom:



For what appears to be such a simple question, it is disconcerting that only 52% of students were able to answer this correctly. A considerable number of participants

(26%) thought only sphere Y was a hydrogen atom, forgetting that water has two hydrogen atoms. It would appear that students struggle to interpret sub-microscopic representations. Even simple diagrams such as water are confusing.

Question ten asked students to identify the oxygen atom. More students (61%) were able to identify the oxygen atom than were able to identify the hydrogen atoms. Nonetheless, Chart 21 shows that 22% of students thought that the two peripheral spheres were two oxygen atoms.

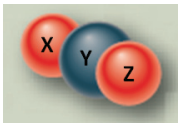
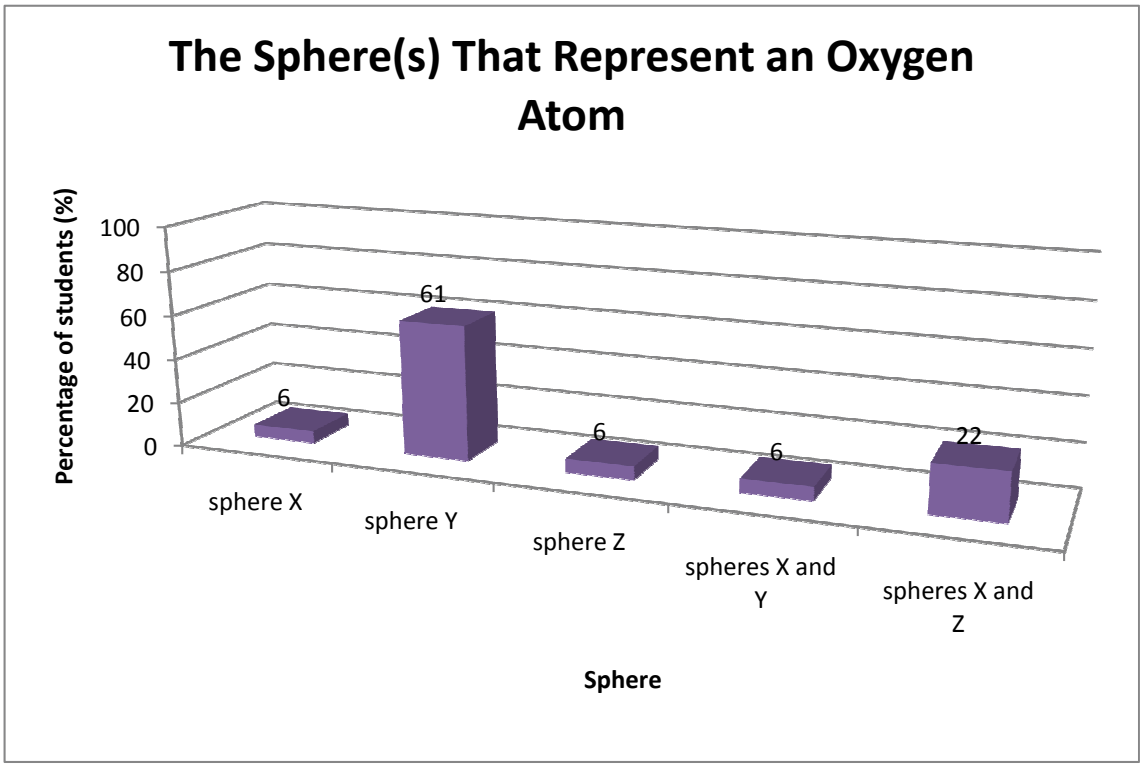


Chart 21 – The sphere or spheres that represent an oxygen atom:



Although most students can correctly quote the molecular formula of water, there may be a problem with students not being sure whether the '2' in H_2O refers to hydrogen or oxygen. Once again, students are struggling with symbolic representations - no matter how basic - used to explain chemistry.

The final question required students to choose the correct description of the chemical bond holding together the hydrogen and oxygen atoms. Chart 22 reveals the high level of inaccuracy in answering this question.

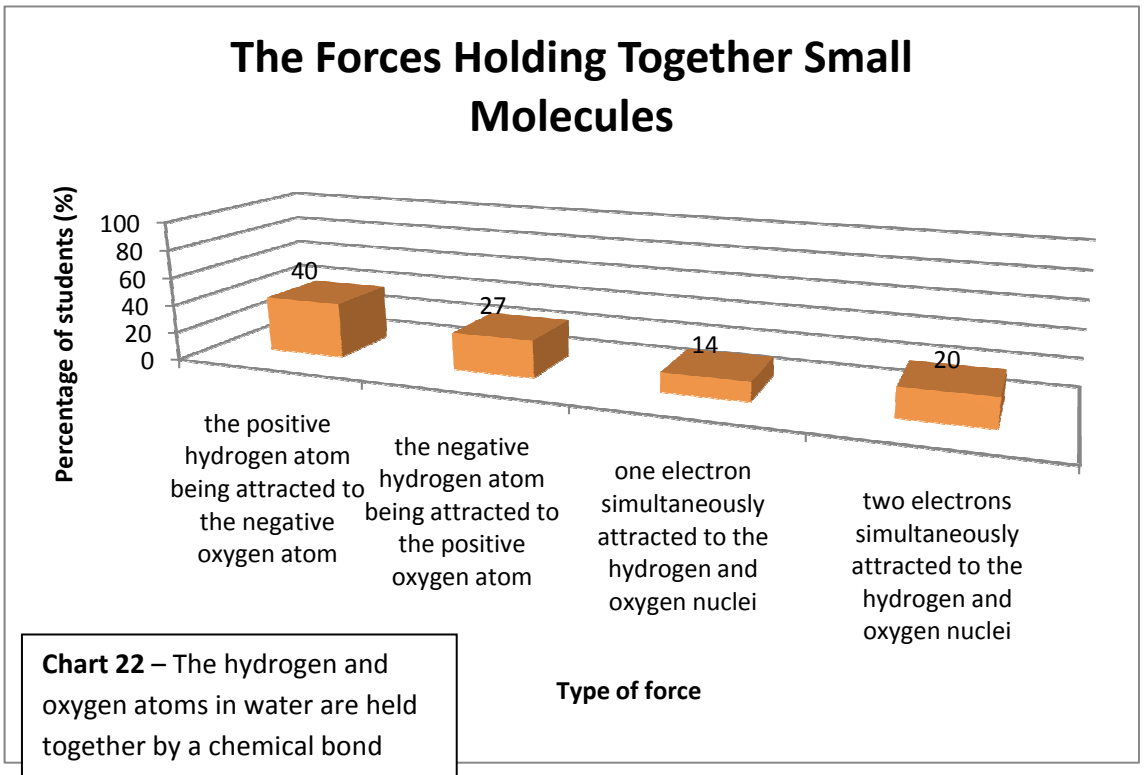


Chart 22 – The hydrogen and oxygen atoms in water are held together by a chemical bond consisting of:

Only 20% of students chose the correct description of a covalent bond out of the four descriptions provided. A very common alternative conception (40% of students) was that the hydrogen is positively charged and the oxygen is negatively charged, and the

attraction between the positive hydrogen and negative oxygen holds the water molecule together. When this is combined with those who stated that the hydrogen was negative and the oxygen was positive, then 66% of students thought water was held together by the attraction between a positive and negative atom. It would appear that students may not differentiate between covalent and ionic substances, or believe that water is an ionic substance. Senior students may have been additionally distracted by their learning about the polar nature of water, where hydrogen and oxygen do have slight charges.

A chi-square test was conducted to check if there was a significant difference in the level of accuracy between senior and junior students on this question. No significant difference was found (*chi-square*=.054, *df*=1, *p*=.817) in the performance of senior students compared to junior students. Senior students could not accurately describe a covalent bond any more than junior students. Chart 23 shows that for this question there appears to be very little difference in the performance of students across years ten to twelve.

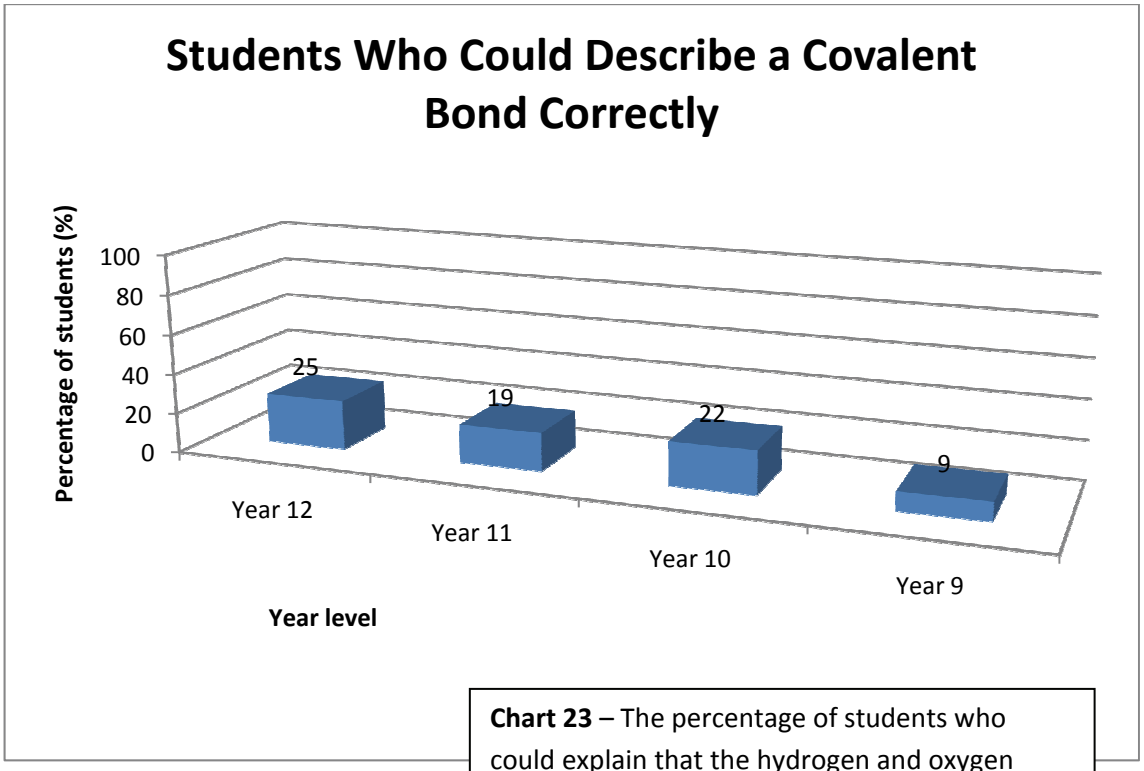


Chart 23 – The percentage of students who could explain that the hydrogen and oxygen atoms in water are held together by a chemical bond consisting of *two electrons simultaneously attracted to the hydrogen and oxygen nuclei.*

There were three related questions on bonding (Q3, 6, and 11) that asked what holds together the particles in a metallic, ionic or covalent substance. It is interesting to compare students' responses across the three similar questions. Chart 24 compares the number of students that could accurately describe each bond. There were only 17 students (10% out of the total of 172 students) that answered all of these three bonding questions accurately.

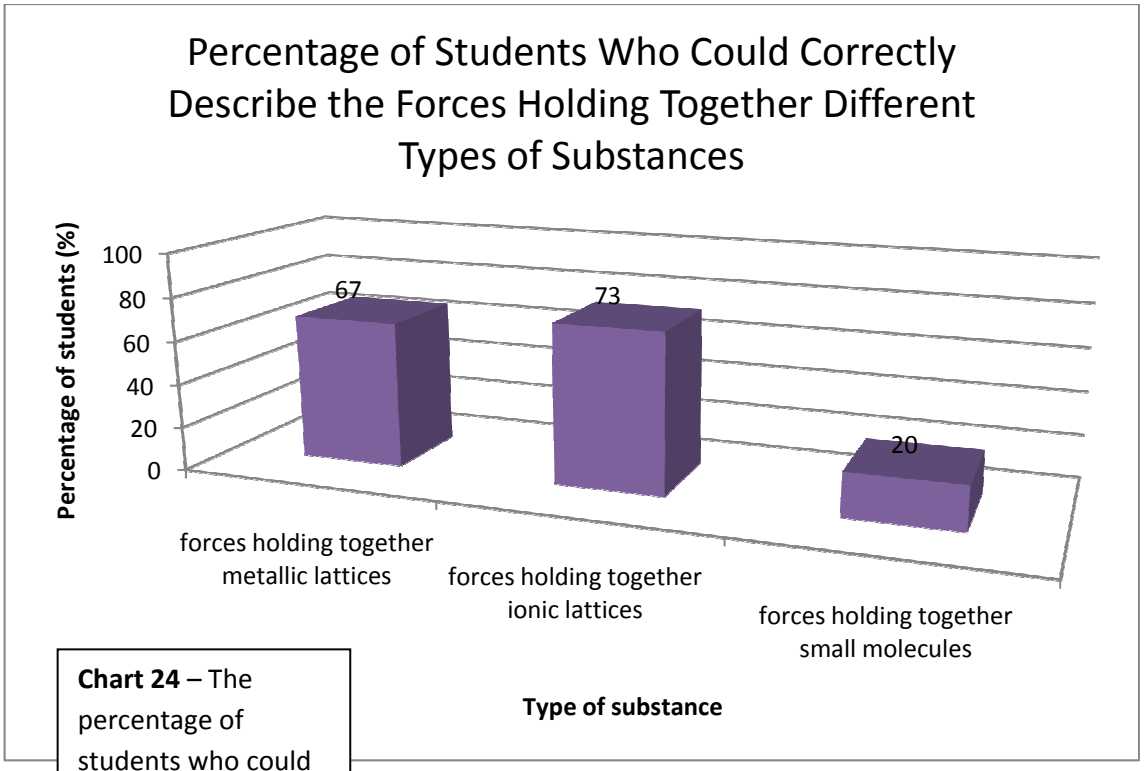


Chart 24 – The percentage of students who could describe metallic, ionic and covalent bonding.

There is some evidence of contradictory thinking in these responses. While 67% of students described accurately how a metallic substance is held together, 14% of students (or 24 respondents) claimed that attractive forces between positive particles hold together the copper ions. This was the most common incorrect response. However, it is valuable to note that of these 24 students, 17 of them (71%) later in the diagnostic test stated correctly that attractive forces between positive and negative particles hold together the ionic lattice.

Furthermore, these 24 students do not seem to really believe that positive particles could attract each other, because in the very last question of the diagnostic test, 16 of these original 24 students went on to say (incorrectly) that the attraction between

positive and negative atoms hold together water molecules. It appears that these 24 students clearly believe that positive and negative particles attract and hold together substances in cases of ionic and covalent bonding, but two positive particles could attract in metallic bonding. This shows some inconsistent thinking or a major misunderstanding about the fundamental nature of forces between two positively charged objects.

Overall, a familiar trend in performance was seen across the year levels for Section C of the test. Year 11 students outperformed other year levels, as shown in Chart 25.

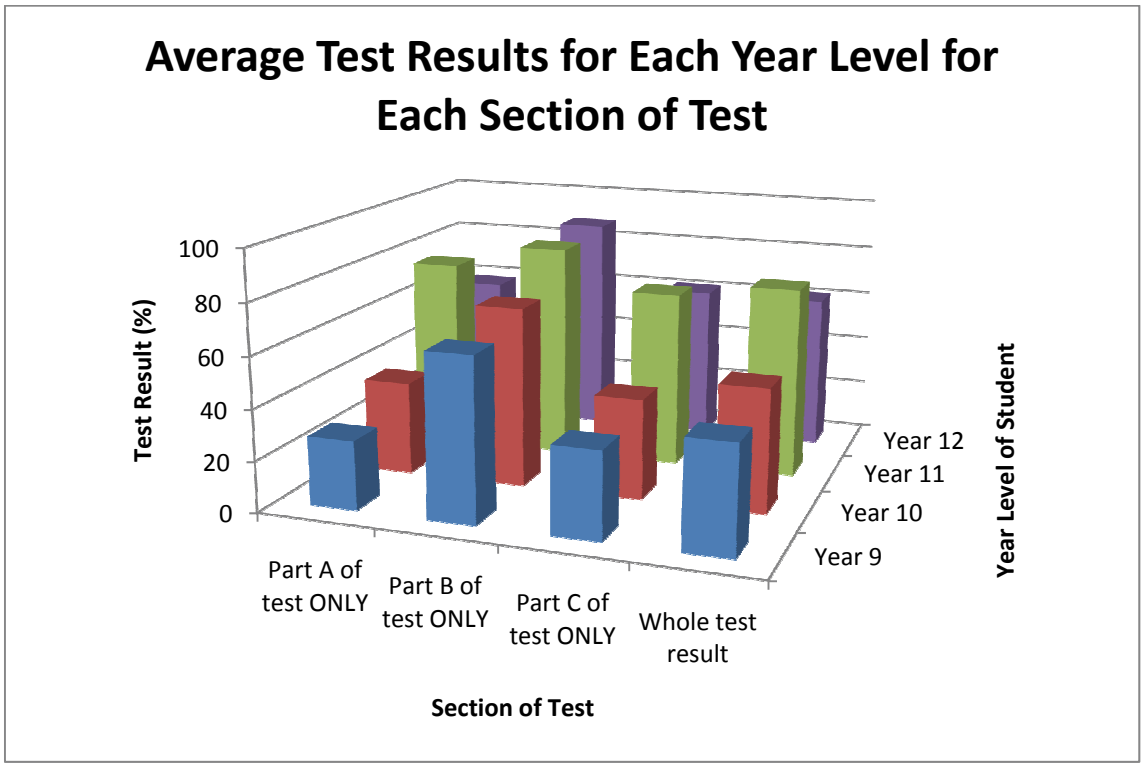


Chart 25 – Average test results for each section of the test.

Performance of Senior (Yr 11/12) Students

It is worth considering the questions where the senior students struggled. If these students are consistently getting certain questions wrong, it might reveal some persistent alternative conceptions. Table 6 shows the percentage of students who gave incorrect answers across the twenty questions.

Table 6 – Senior Student Responses to Chemical Bonding Test (N=34)

The table below indicates the percentage of senior students who chose each option. The correct answer is indicated by shading.

Question	% A	% B	% C	% D	% E	% No answer
Part A						
1a *covalent bonding model*	3	18	80			
1b *ionic bonding model*	21	59	21			
1c *metallic bonding model*	77	24	0			
Part B						
1a *photo of water*	4	0	97			
1b *photo of copper*	6	94	0			
1c *photo of salt*	91	6	3			
2a *model of water*	3	6	88			3
2b *model of copper*	74	21	3			3
2c *model of salt*	21	71	6			3

Question	% A	% B	% C	% D	% E	% No answer
Part C						
1 *copper – neg. charges*	0	9	91	0		
2 *copper – pos. charges*	6	29	0	65		
3 *metal bonding forces*	12	74	15	0		
4 *salt – neg. charges*	9	3	3	79	6	
5 *salt – pos. charges*	18	74	6	3	0	
6 *ionic bonding forces*	3	97	0	0		
7 *cation - no. subatomic*	18	15	59	6	3	
8 *anion - no. subatomic*	21	56	15	9	0	
9 *hydrogen in water*	0	6	0	3	82	9
10 *oxygen in water*	0	85	0	0	6	9
11 *cov. bonding forces*	56	9	6	21		9

In Part A of the test we can see that most students were able to correctly identify the model of a covalent, ionic or metallic substance. Of these three bonding models, the most difficult model to identify was the ionic bonding model.

Most students correctly identified the photos of salt, water, or copper in Part B of the test. Nevertheless, one student did not correctly identify the photo of water, two students did not identify copper and three students did not identify the photo of salt.

When students were asked to identify the models representing water, salt or copper, students found it easiest to identify the model representing water - with its discrete molecules. Students had a harder time distinguishing between the two types (metallic and ionic) of lattices.

In Part C of the test students were asked questions regarding metallic bonding. Senior chemistry students were proficient at identifying the 'sea of electrons' (91% correct). However, they had less success when identifying the positive charges in the lattice. Only 29% of senior students correctly identified the positive charges as being copper ions. 65% of senior students thought the positive charges in the metallic lattice were protons. This highlights a persistent alternative conception. Of course these students are not completely incorrect. Certainly the positive charges in copper are due to protons. But the positive particles in the model of metallic bonding are cations. It is the theoretical core charge of the atom, that is, the number of protons minus the number of inner electrons, which attracts the sea of electrons. The valence electrons are delocalised and it is the core charge that attracts these electrons. It is likely that this notion of core charge may not have been made explicit during the teaching of chemical bonding.

Most senior students fared much better when asked questions about the ionic bonding model. Generally they correctly concluded that the negative charges were chloride ions (79%) and the positive charges were sodium ions (74%). 97% of senior students could identify the description of the ionic bond.

Year eleven and twelve students had difficulty identifying the number of sub-atomic particles in the sodium (59% correct) and chlorine (56% correct) of sodium chloride. 18% and 21% of students respectively stated that the sodium and chlorine in sodium chloride had as many protons, neutrons and electrons as the sodium and chlorine neutral elements.

Finally, senior students had little trouble (nor should they) in identifying oxygen and hydrogen in a sub-microscopic representation of water. They have learnt to understand models of molecules and different types of bonding structures much more thoroughly than junior students. However, the very last question of the test was answered universally poorly. 56% of senior students thought that a covalent bond resulted from the positive hydrogen being attracted to the negative oxygen atom. This indicates a lack of differentiation between models of ionic or covalent substances. Perhaps they believe that water is an ionic substance, or they could be thinking of the slight positive charge on the hydrogen atom and the slight negative charge on the oxygen atom which helps water undergo strong intermolecular bonding. The role of intermolecular bonding was not dealt with in this diagnostic test – it needed to be clarified in the interview.

Performance of Junior (Yr 9/10) Students

It is worth considering the questions with which junior students struggled. Consistent errors would shed light on persistent alternative conceptions. Table 7 shows the percentage of junior students who gave incorrect answers across the twenty questions.

Table 7 – Junior Student Responses to Chemical Bonding Test (N=138)

The table below indicates the percentage of junior students who chose each option. The correct answer is indicated by shading.

Question	% A	% B	% C	% D	% E	% No answer
Part A						
1a *covalent bonding model*	33	26	39			1
1b *ionic bonding model*	34	35	30			1
1c *metallic bonding model*	30	38	30			2
Part B						
1a *photo of water*	1	0	99			1
1b *photo of copper*	1	99	0			
1c *photo of salt*	98	1	1			1
2a *model of water*	28	7	57			8
2b *model of copper*	30	51	12			8
2c *model of salt*	36	33	24			7

Question	% A	% B	% C	% D	% E	% No answer
Part C						
1 *copper – neg. charges*	5	17	73	5		
2 *copper – pos. charges*	13	9	12	66		
3 *metal bonding forces*	15	65	8	12		
4 *salt – neg. charges*	35	23	14	22	7	
5 *salt – pos. charges*	44	15	17	18	7	
6 *ionic bonding forces*	8	67	12	13		
7 *cation - no. subatomic*	35	10	33	12	9	
8 *anion - no. subatomic*	35	25	15	16	9	
9 *hydrogen in water*	8	29	9	9	41	4
10 *oxygen in water*	7	51	7	7	24	4
11 *cov. bonding forces*	33	29	15	19		5

This analysis of the junior students' responses illuminates the fact that students are generally confused about the different bonding models. In part A only about one-third of students were able to correctly identify each bonding model, which is no higher than would be expected if students were randomly guessing answers.

Junior students were readily able to identify the photos of different substances. In addition, 57% of students were able to identify the bonding model which represented water. Only 30% of junior students were able to identify the bonding model representing copper. More students (51%) thought that the ionic bonding diagram represented copper. Similar results

were obtained when students tried to identify the bonding model representing salt. 33% of students correctly identified the model of salt, while 36% said the metallic bonding diagram represented salt. Once again, this level of accuracy could be expected from random guessing.

In Part C of the chemical bonding test, most (73%) students were able to identify the negative charges in a metallic lattice. Most (65%) students picked the accepted description of metallic bonding. However, only 9% of students were able to correctly identify the positive charges in a metallic lattice. The overwhelming majority (66%) thought that the positive charges were protons. This has big implications for the teaching of this topic. Once again, students are not completely wrong – protons are responsible for the positive charge. However, the positive particles in the sub-microscopic representation of metallic bonding are cations. Students are finding it difficult to differentiate between copper ions and protons.

Similarly, most students could not recognise the negative charges in salt. More students thought the negative charges were electrons (35%) or sodium ions (23%) than chloride ions (correct answer, 22%). Likewise, more students believed that the positive charges in salt were protons (44%), chloride ions (18%) or sodium atoms (17%) than sodium ions (15%, correct answer). It is apparent that most students believe that chemical bonding occurs between positive particles and negative particles. 67% of students correctly identified the description of an ionic bond. However, they believe that the particles in a sub-microscopic representation of sodium chloride are protons and electrons.

The last set of questions was about bonding in water. Only 41% of junior students understood that a water molecule has two hydrogen atoms, and 51% of students understood that it has one oxygen atom. A number of students (29%) believed that the central atom in a water molecule is a hydrogen atom, and 24% of students believed that the hydrogen atoms were two oxygen atoms.

In the final question, more junior students believed that water is held together because the positive hydrogen atom is attracted to the negative oxygen atom (33%) or the negative hydrogen atom is attracted to the positive oxygen atom (29%) than believed that covalent bonding exists because two electrons are simultaneously attracted to both the hydrogen and the oxygen nuclei (19%). Once again it is seen how poorly covalent bonding is understood, and how rarely it is differentiated from ionic bonding.

It has become evident from the questions on metallic and ionic bonding that junior students believe this bonding occurs between protons and electrons. Most year nine and ten students believed that a metallic lattice is composed of protons and electrons. More junior students believed that an ionic lattice is composed of protons and electrons than any other type of particle. In addition, the majority of junior students believed that covalent substances are held together because of an attraction between positive and negative atoms.

Performance of Males and Females

Slightly more females (N=91) sat the test than males (N=80). A summary of the average test results for each year level for males and females is shown in Table 8. A fuller description of the test scores is given in Table 9.

Table 8 – Average Tests Results for Each Year Level for Males and Females

Year Level	**Male Average (%)**	**Female Average (%)**
Year 12	77.5	60
Year 11	77.2	74.4
Year 10	45.9	50.9
Year 9	41.3	42.6
All year levels	**50.1**	**54.2**
	52.3	

Table 9 – Mean Test Score and Standard Deviation for Males and Females

Gender	Mean Score (/20)	Median Score	Minimum Score	Maximum Score	Standard Deviation
Males	10.10	10	4	20	3.709
Females	10.84	10	4	20	3.911

An independent data t-test at the 0.05 level showed that there was no significant difference between the performance of males and females in the chemical bonding test. The

difference between the mean male score and mean female score was -.810 (t=-1.387, df=169, p=.167). In fact, further t-tests (also at the 0.05 confidence level) showed that there was no significant difference between males and females in year 9 (t=-.281, df=30, p=.781), or in year 10 (t=-1.651, df=103, p=.102), or for the senior students (years 11 and 12 combined; t=1.713, df=13, p=.110).

The literature on gender differences in science seems to be fraught with disagreement. Barnett & Rivers (2004b) found no differences of any magnitude between genders, even in areas of maths that are supposedly 'male domains'. Barnett & Rivers (2004a) argue that basic similarities, rather than differences, prevail between males and females. This contrasts with research which does indicate an achievement gap between males and females in science and maths (Bower, 2007), with females lagging behind males (Thom, 2002).

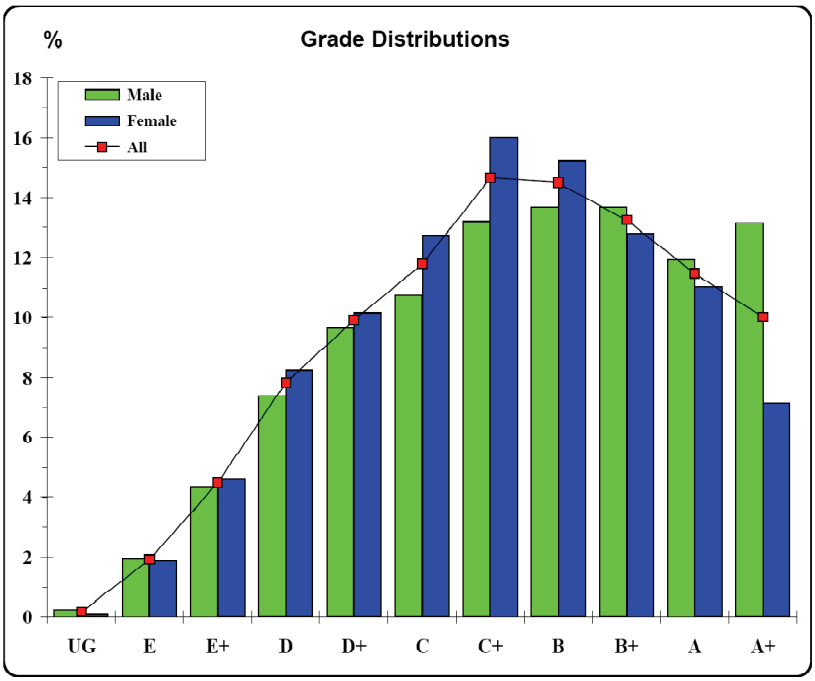
Further analysis was conducted to check whether there was a difference between the performance of males and females in science at one of the schools where the students sat the chemical bonding test. The performance of males and females was compared for students studying science in years nine and ten and chemistry in years eleven and twelve. It was discovered that over one school semester females outperformed males in year nine (by 8%), year eleven (20%) and year twelve (5%), but not in year ten (-1.3%). An independent data t-test was used to determine if there was a significant difference between the mean semester marks of male and female students. It was found (at the 95% confidence level) that males were outperformed by females (t = -2.186, df=93, p = 0.031).

However, one semester's results from a single school cannot be generalised. Therefore, additional state-wide data was gathered for comparing the performance of males and females in chemistry. Charts 26 and 27 summarises the end of year chemistry exam results for all year 12 VCE (Victorian Certificate of Education) chemistry students in 2008 and 2009. It shows that males tend to outperform females at the top end of the scale, but females tend to outperform males in the middle.

Chart 26 – Grade Distributions for the 2008 End of Year VCE Exam for Males and Females

These are the grade distributions for Victorian year 12 students' final chemistry exam. A total of 9078 students were enrolled in the subject, including 4371 males and 4707 females.

The graph shows the percentage of the population achieving each grade.

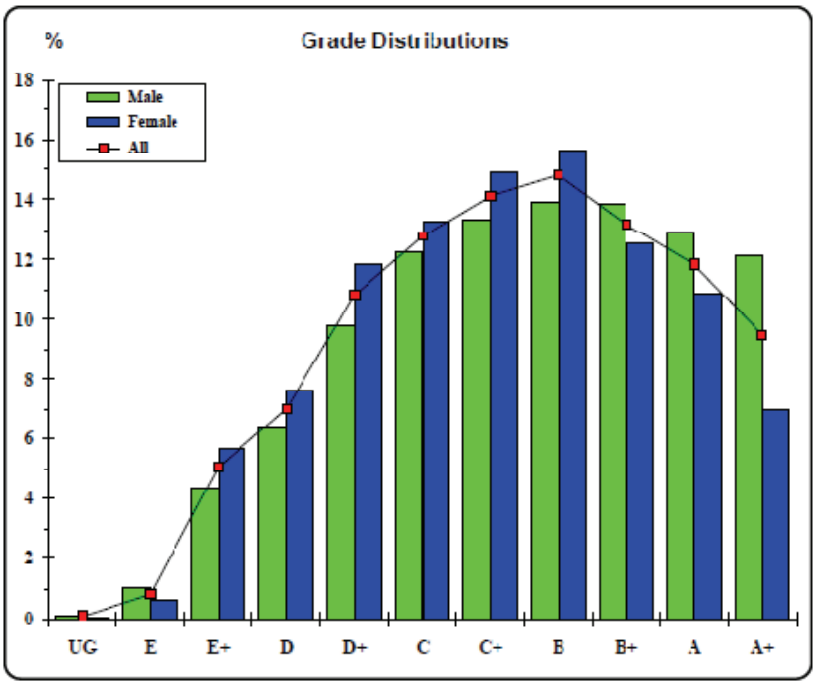


(Victorian Curriculum and Assessment Authority, 2009)

Chart 27 – Grade Distributions for the 2009 End of Year VCE Exam for Males and Females

These are the grade distributions for Victorian year 12 students' final chemistry exam. A total of 8863 students were enrolled in the subject, including 4308 males and 4555 females.

The graph shows the percentage of the population achieving each grade.



(Victorian Curriculum and Assessment Authority, 2010)

Nonetheless, in this particular study, no significant difference was found in the chemical bonding test scores between males and females at any year level. All the information obtained suggests caution needs to be taken when interpreting gender data.

Performance of Students at Different Schools

An independent data t-test was conducted to determine if there was a significant difference between the scores of the two schools. The test was restricted to year levels ten to twelve, as no year nine students from the second school took part in the diagnostic test. It was discovered (when excluding year nines) that there was no significant difference (at the 0.05

level) between the test scores of students at the two schools (t = -0.829, df=1380, p = 0.409).

Finally, after looking at the senior students' individual responses in the chemical bonding test, seven students were chosen for an in-depth interview.

Interviews: Analysis of Data and Discussion of Results

Three year twelve and four year eleven students were chosen for a follow-up interview. The names of the interviewees have been changed to maintain privacy.

Year 12 Student – Jack

Before this interview took place, Jack scored 75% in the chemical bonding test. Some of his test responses showed that he might believe some of the more common alternative conceptions. For example, Jack thought that the positive particles in a lattice of sodium chloride and copper were protons. He thought water was held together by an attraction between a positive hydrogen and a negative oxygen atom. Jack was selected for an in-depth interview to shed some more light onto his thought processes.

Right from the start of the interview Jack demonstrated a classic alternative conception when he stated that the reason that atoms form chemical bonds is to get a full shell of (eight) electrons.

Interviewer: Why do atoms form chemical bonds?

Jack: To have a full shell...

Additionally, Jack thought that there are only two ways for atoms to bond together.

Interviewer: How many different ways can atoms bond together? In other words, how many different types of bonds are there for holding together atoms in molecules?

Jack: There is the sharing of electrons one, and the one that gives up electrons... Two ways.

He struggled to answer questions regarding the ionic nature of potassium iodide. Jack stated that when a potassium atom gives up electrons, it goes from being positive to neutral.

Interviewer: In what form do the potassium atoms and iodine atoms exist in potassium iodide?

Jack: They are neutral. Potassium is giving up electrons. It becomes neutral. It donates some electrons. It is a positive charge first, and it becomes neutral. Iodine is minus two I think, it receives electrons, it receives a positive charge from potassium and becomes neutral, since they neutralise each other.

Similarly, to become an iodide ion an atom of iodine has to receive one electron "to be neutralised". He understood that iodine becomes neutral since iodine and potassium neutralise each other.

Interviewer: What does an iodine atom have to do with its atomic structure to become an iodine ion?

Jack: It has to have a full shell. It has to receive one electron to be neutralised.

However, Jack was able to explain that positive and negative potassium and iodide ions are attracted to each other in this substance.

Interviewer: What is holding the potassium and iodide ions together in this substance?

Jack: The electron bond. The electrons hold them together. The bonding. The bonding that holds them together. They both have, potassium is plus one, so that donates electrons to iodide, to have a full shell, the other one receives that one, they attract each other. It is positive and negative.

Once again he has reiterated the idea that potassium gives up its electrons to iodine in order to gain a full shell of electrons. Upon further questioning, he maintained that this type of bonding was covalent. It appeared that he could not yet recall other types of bonding at this stage of the interview.

Jack continued to struggle with metallic bonding and covalent bonding. When he was asked questions about a sample of aluminium he tended to think that it was held together due to "cations and ions - positive charges connecting to negative charges", mixing up ionic bonding concepts with metallic bonding concepts. Furthermore, when asked questions about a sample of hexane, he tended to think that hydrogen atoms had to donate electrons and that is why hydrogen atoms are attracted to carbon atoms.

Interviewer: This is a sample of hexane. What is holding the carbon and hydrogen atoms together in a molecule of this substance?

Jack: The carbon has four, and the hydrogen is plus one. The carbon has to receive electrons, hydrogen has to donate electrons, so that is why they attract.

Interviewer: Once the carbon has the electrons, what keeps it attracted to the hydrogen?

Jack: Sharing electrons. I forgot what it is called. No, hydrogen does not share electrons, it has to give electrons.

Finally, when he was questioned he remembered to call this type of bonding covalent bonding. There seemed to be little difference in his mind between covalent, metallic and ionic bonding.

After each section of the interview correct answers for each question were discussed. This process was important, because this way the students were able to gain benefit from the interview process. For most students the interview became a valuable revision session.

As the interview process continued, it was obvious that Jack was starting to remember more of the bonding concepts that he had learnt. Next he was shown diagrams depicting different types of bonding, and he was able to correctly identify models of metallic, ionic and covalent bonding. He was able to remember that metals use metallic bonding, and he identified the cations and the sea of electrons. He knew that cations and anions were contained within an ionic substance, although he thought that it was only non-metals that used ionic bonding. Regarding the model of a covalent substance, he was able to identify the "sharing bonds", but he thought that carbon, metals and non-metals use covalent bonding. Jack was confused when asked to compare ions to elements.

Interviewer: The larger green spheres [in a diagram of sodium chloride] could represent chloride ions. Is there a difference in the number of protons, neutrons or electrons between chloride ions and the chlorine element?

Jack: No difference. No, there is. The chlorine has less electrons. More pluses. So mix together they will be neutralised. It has less one. Chloride gains? I'm confused.

Jack answered the final questions regarding the properties of metallic, ionic and covalent substances more easily than the beginning questions. He did slip back into the habit of calling the sea of electrons 'anions', and while he aptly described bonding between HCl molecules, he called this bonding 'hydrogen bonding' rather than dipole-dipole bonding.

The final section of the interview involved looking at his earlier test responses. In the chemical bonding test he labelled the positive charges in a metallic substance 'protons'. However, during the interview he identified them correctly as cations. When this inconsistency was highlighted and he was asked what he thought the positive charges were, he said he was sure they were actually protons.

Another inconsistency between the test and the interview regarded the forces holding together the metallic substance. In the interview Jack explained that metallic substances are held together because of the attraction between 'positive' (cations) and 'negative' (referring to 'anions'). However, in the test he said that a metallic substance is held together by repulsive forces between positive particles. When quizzed about this he was sure his test answer was correct, and that repulsive forces could hold together a substance.

Interviewer: You told me something different in the interview than what you wrote here. In the test you said that the positive charges [in a metallic substance] are held together by repulsive forces between positive particles. Does that sound right to you?

Jack: Yes.

Interviewer: But what do repulsive forces do to a substance? Does it actually hold it together.

Jack: Yes.

In the course of the interview Jack explained that during the process of creating an ion, an element starts with a charge, but the ion that is created by electron transfer would be a neutral particle. Later on when reviewing his test answers, the interviewer further examined Jack's thoughts about what happens when an element becomes an ion. He could not decide which answer he should have selected in the test.

Interviewer: In question seven [of the chemical bonding test] you said that sodium would gain one electron to become a sodium ion. Do you still think that?

Jack: They should be all neutral. Should be [answer] (a) - 11 protons, 12 neutrons and 11 electrons.

Interviewer: So it [the number of sub-atomic particles] stays the same?

Jack: No it should be more. 12 protons, 12 neutrons and 11 electrons.

Interviewer: So it [a sodium ion compared to a sodium atom] gains a proton?

Jack: Mm.

Interviewer: You told me earlier that it might lose an electron. Let me tell you now that you will never lose a proton in a chemical reaction.

Jack: So it [the number of sub-atomic particles] will stay the same?

Despite this confusion, he understood that an atom of chlorine would need to gain an electron to become a chloride ion.

Finally, Jack had stated in the test that a water molecule contains a positive hydrogen atom attracted to a negative oxygen atom. After he was reminded that he himself had said during the interview that in covalent bonding electrons are shared, he changed his mind and said that in water two electrons are simultaneously attracted to the hydrogen and oxygen nuclei.

Year 12 Student - James

James was chosen because he had gained a score of 100% in the chemical bonding test. The interview process was able to test his knowledge to check if he really understood chemical bonding in detail. As it turned out, James did have an excellent understanding of chemical bonding.

First of all, he explained chemical bonding in terms of an attraction between positive and negative particles where the energy state of the electrons is lowered. He showed a good understanding of a range of intramolecular and intermolecular bond types. He demonstrated an awareness of the general properties of substances (e.g. metals are hard) whilst understanding that there are limitations to these generalisations (e.g. although you can get softer metals). He confirmed a level of understanding entirely appropriate for a year twelve student, and no alternative conceptions were uncovered during his interview.

Year 12 Student - Chloe

The final year twelve student achieved a chemical bonding test score of 65%, which is a little below average for a senior student. This interview was able to highlight a few more alternative conceptions, and provide a necessary revision exercise for this student.

To start with Chloe had great trouble in trying to explain what a chemical bond was. She said that atoms bond together to "form bigger amounts that are useful", as you cannot use just "one atom for anything". She knew that chemical bonds had something to do with an attraction, but she couldn't put her finger on what was attracted together. At first she said that atoms "like" lone electrons to be bonded, and later she said that atoms have an affinity for each other and are attracted together – "the atoms just go 'whoosh' together". She knew that a chemical bond was some kind of attraction, but was unable to provide any further detail about this attraction.

Chloe demonstrated an understanding of ionic bonding.

Interviewer:	What is holding the potassium and iodide ions together in this substance [potassium iodide]?
Chloe:	Ionic bonding. Potassium would have a positive charge, and iodine would have a negative charge. Therefore they are attracted, and they just kind of "boom".

With metallic bonding, while she knew that aluminium contained Al^{3+} cations, she thought that the metallic bond consisted of a triple bond between the aluminium cations.

Interviewer: What is holding the aluminium ions together in this substance [a sample of aluminium]?

Chloe: Metallic bonding. So there is aluminium cations that have a three plus charge, and then I guess they would bond with another atom that has a three plus charge, and they kind of create a triple bond. Is that it? It is a triple bond, I guess. Because aluminium is in group three, it needs three bonds, so two aluminium atoms would create three bonds. A triple bond.

Later during the interview, when looking at a model of metallic bonding, she remembered the basis for metallic bonding – the attraction between the cations and the sea of electrons.

With hexane, a covalent substance, she was able to say that the bond consists of a pair of electrons attracted to the positive nuclei of the carbon and hydrogen atoms. Nevertheless, she called this type of bonding dipole-dipole bonding.

A common alternative conception was revealed when Chloe looked at a depiction of ionic bonding. She thought that the positive particles were protons. Then she tried to work out what the negative particles could be - considering that the positive particles were protons. She initially said electrons, but realised that this did not make sense, so she changed her answer to neutrons, but was still unsatisfied, and then she gave up.

Chloe answered questions regarding the properties of different substances with less difficulty. She occasionally called the cations in a metallic substance 'protons' - although she was usually quick to correct herself. Chloe also did not understand how a metallic substance could conduct electricity; she surmised that perhaps the cations carried the charge because they could "kind of 'bounce' it to one another".

Interviewer: Will a substance with this type of bonding [metallic] typically conduct electricity? Why?

Chloe: Yes, it would because of the cations can, well they're next to each other, so the charge can be carried along the thing.

Interviewer: What carries the charge?

Chloe: The protons? Oh, the cations. I don't know. Yes, I suppose the cations carry the charge. Maybe.

Interviewer: Can cations move?

Chloe: No they can't. Maybe the electrons. The cations they are in their little form, and then they are kind of next to each other, so I suppose they can kind of bounce it to one another.

Apart from that, she answered the rest of the interview questions accurately.

In the final part of the interview Chloe's chemical bonding test was reviewed. For many of the questions she was able to recognise her mistakes and find the correct response. However, she was not able to identify her error in the very last question.

Interviewer: Looking at question 11, you said that what is holding together water is a positive hydrogen being attracted to the negative oxygen atom. Do you still think that?

Chloe: Yes.

Interviewer: Now you gave a beautiful description of a covalent bond. Water uses covalent bonding. Do you remember what your description of covalent bonding was?

Chloe: No. The attraction between non-metals.

Interviewer: What holds the two atoms together in a covalent bond?

Chloe: I can't believe I can't remember this. How sad.

Year 11 Student - Thomas

Thomas scored quite well on the chemical bonding test (85%), although in the test he demonstrated some classic alternative conceptions. Firstly, he claimed that the positive particles in a metallic lattice were protons, although he did not make the same mistake in the interview. Secondly, he thought that the number of protons, neutrons and electrons in sodium ions and chloride ions remains unchanged compared to the elements sodium and chlorine. However, he quickly picked up on that mistake during the interview and changed his response.

Thomas did well in the interview and explained bonding in terms of an electrostatic attraction between negative and positive particles. He also stated that atoms bond to enter "the lowest energy state possible". However, he went further and started to give atoms human qualities. Thomas explained that when a negative atom sees a positive atom, they become enthusiastic and "hug each other and become bonded".

When discussing ionic bonding, Thomas started to say that the particles in potassium iodide become neutral because "the positive charge of the potassium is negated by the negative charge of the iodide". Then as he continued to discuss ionic bonding, unhappy with his initial response, he found words to explain that "the charges balance mathematically".

He also discussed metallic bonding and covalent bonding accurately. However, he was under the impression that in a single covalent bond there was just a single electron. In the

case of a single covalent bond between carbon and hydrogen, he surmised that the electron must have come from hydrogen because carbon is more electronegative.

> Interviewer: This is a sample of hexane. What is holding the carbon and hydrogen atoms together in a molecule of this substance?
>
> Thomas: They have covalent bonding, means they are sharing an electron between the nucleus, a single covalent bond. Probably hydrogen's electron because carbon is more electronegative. They share an electron between which gives them a covalent bond. You have the electron whizzing around, pretty much the electron moves in and out of both of them, making sure the hydrogen is attracted to the electron, but so is the carbon. So they are both attracted to the same electron that is spinning in between. Only one electron [in a single covalent bond].

It is interesting to note that he did not make this same mistake on the chemical bonding test. In the test Thomas correctly identified a covalent bond as two electrons rather than one. This seems to suggest an element of instability in student thinking. Thomas explained that when he sat the test "I remembered doing that", but the interview came later and by then "we hadn't done bonding for a little while, so I forgot that you can get two electrons between those [nuclei]. I was thinking that one bond, one electron".

Year 11 Student - Grace

Grace was another year eleven student who showed a good understanding of chemical bonding in her test, achieving a score of 90%. She made two errors in the test. This included stating that to become a chloride ion an element of chlorine would need to lose one electron. At the conclusion of the interview she was shown this question. She quickly

corrected her answer without any assistance. The other error Grace made in the test was to think that the chemical bond in water consisted of a positive hydrogen atom being attracted to a negative oxygen atom. This was a very common alternative conception found amongst many students. When she was told that her selected answer was not correct, she thought that the bond must then consist of a negative hydrogen atom being attracted to a positive oxygen atom. When she discovered that this was also incorrect, she was very unsure as to what the correct answer might be, but she did finally deduce the correct answer from the remaining two possible choices.

Grace explained chemical bonding in the following way:

Interviewer: What does the term 'chemical bond' mean to you?

Grace: It's the bonding between two different elements or chemicals. The way that they bond, obviously all different ways. Covalent is where they share electrons and they form bonds between each other, and ionic is the electrostatic attraction between the cations and anions, and metallic bonding is between the sea of electrons and anions [she meant cations and later on used the correct term].

Interviewer: Why do atoms form chemical bonds?

Grace: To get the lowest energy level state.

When Grace discussed ionic bonding, she showed the common alternative conception that the ionic particles are neutral.

Interviewer: This is a sample of potassium iodide. In what form do the potassium atoms and iodine atoms exist in potassium iodide?

Grace: They're neutral I think. They're not charged.

Interviewer: What is holding the potassium and iodide ions together in this substance?

Grace: Ionic bonds, so it is cation and anions. Electrostatic attraction.

Similarly, whilst stating that a metallic substance is held together by the attraction between the cations and the sea of electrons, she still thought that the aluminium atoms in a sample of aluminium were neutral.

Interviewer: This is a sample of aluminium. In what form do the aluminium atoms exist in aluminium metal?

Grace: Solid. Oh, neutral.

In the discussion of covalent bonding, she explained covalent bonding in terms of sharing of electrons.

Interviewer: This is a sample of hexane. What is holding the carbon and hydrogen atoms together in a molecule of this substance?

Grace: Single bonds in there... Covalent? The sharing of electrons. They're forced together because they're sharing. Their shells are close together and that holds them in.

At length Grace had to explain why diamond has a higher boiling point than hydrochloric acid. She correctly identified diamond as having a covalent network lattice.

Grace: Well the carbon is a covalent network lattice, so it is very strong, and would withstand a lot of heat.

She was also debating with herself whether the intermolecular bonds shown between hydrochloric acid molecules were dispersion forces or dipole-dipole bonds.

Grace: The dotted line I am either thinking they are dispersion forces because they are different charges or that is dipole-dipole, I am not really sure which one it is. The bonds aren't as strong, the red ones, the dots.

However, in the end she decided that diamond had a higher boiling point because it contained double covalent bonds between atoms, while hydrochloric acid only contained single bonds between molecules.

Grace: And they're double bonds [between diamond's carbon atoms] so they are a lot stronger, and they're [HCl] single bonds.

While she recognised the existence of intermolecular bonding, she did not use its presence to explain the difference between the two substances' boiling points.

Year 12 Student - Emily

Emily was another student who performed extremely well in the test and interview. She scored 100% for the test, and she was chosen for an interview so the depth of her knowledge of chemical bonding could be ascertained. Emily showed that she did indeed have an excellent knowledge of chemical bonding.

Interviewer: What does the term 'chemical bond' mean to you?

Emily: A chemical bond, the way that substances are joined together. It can be metallic bonding, covalent bonding, or ionic bonding. It is the interaction between the cations and anions, or the sea of electrons and the cations, or covalent bonding the electrons and the attraction between the nucleus.

Interviewer: Why do atoms form chemical bonds?

Emily: Is it to achieve stability? A full shell valence shell of electrons. More attracted to other things.

It may have been better if she had not added to this last statement a reference to 'full shells'.

During the rest of the interview Emily gave a range of excellent answers with a fine degree of detail. For example, when asked about how many different types of bonds there are for holding atoms together in molecules, she was quick to answer.

Emily: Inside a molecule? Ionic bonding, covalent bonding, metallic bonding. Between molecules there is dipole-dipole bonding, ion-dipole bonding... hydrogen bonding, and dispersion forces.

Year 11 Student - Sophie

This final student that was interviewed only achieved 45% in the chemical bonding test, well below average for a year eleven student. This is why she was chosen as an interview candidate.

Sophie explained that chemical bonding was an "attraction", although she was unable to elaborate on what was being attracted. When explaining why atoms bond, she used two common explanations that are discouraged.

Interviewer: Why do atoms form chemical bonds?

Sophie: To fill their valence shell. So that they're at a happier state, less energy.

The final part of her answer, that particles bond to reduce energy, is the start of an appropriate explanation for a year eleven student. Explaining that atoms bond to "fill their valence shell" or so that they are "happier" should not be encouraged, given the many exceptions to this full shells 'rule' and atoms known inability to feel emotion.

This student was quite unsure about the sample of potassium iodide. She thought that it might contain covalent bonds and a sea of electrons. Additionally, she proposed that the potassium ion was formed by losing one proton, and the chloride ion was formed by gaining one proton.

Sophie was equally unsure about aluminium. She knew it contained metallic bonds, but could not give any more detail about this substance. She knew that aluminium needed to lose electrons to become an aluminium ion, but she did not know how many electrons were lost.

At this stage the interviewer paused and reviewed Sophie's answers to the first few questions to help her understand where she went wrong. Next Sophie was presented with diagrams of bonding models. She was now appearing more confident, thinking more clearly and giving much better answers. She accurately answered all of the questions about the metallic bonding model. Sophie also answered most of the questions about the ionic bonding model correctly. However, she did incorrectly think that if a sodium ion is formed by losing one electron, a chloride ion must be formed by losing two electrons. She answered half the questions about the covalent bonding model correctly, although she did say that water molecules were held together internally by hydrogen bonding.

Sophie also answered the questions about properties of covalent, metallic and ionic substances quite accurately. She only made a couple of small errors, such as thinking that hydrochloric acid molecules were held together with intermolecular hydrogen bonds, and

thinking that ionic substances conduct electricity because moving electrons “allowed the charge to pass”.

When reviewing the chemical bonding test, Sophie was able to answer more of the questions correctly, although she did continue to make a significant number of mistakes. For example, she still thought that the positive particles in the metallic lattice were protons. Sophie still had little idea about how to change an element into an ion. It is clear that this student was still struggling to understand chemical bonding concepts.

Interview Item Analysis

It is interesting to see that some of the same trends observed in the test were also observed during the interview. While the test and the interview did not cover exactly the same ground, a number of alternative conceptions uncovered were found in common between the two research instruments. Each interview item was analysed to make evident some common themes.

1. Description and Purpose of a Chemical Bond

In the interview students were asked to describe the chemical bond. Almost every student used ideas of ‘attraction’ and talked about ‘electrons’. The particles undergoing ‘electrostatic attraction’ were listed. Students frequently agreed bonding occurred so atoms could find a lower ‘energy state’. Similarly, in the chemical bonding test students

were accurately able to describe an ionic and metallic bond, although few students were able to pick the description of a covalent bond within a water molecule.

In contrast to these excellent answers, during the interview it was also common to hear that atoms were 'happier' or obtained a 'full shell' when they bonded. Other researchers have reported similar findings. For example, Unal, Calk, Ayas, & Coll (2006) found that students make wide use of anthropomorphic language when describing chemical bonding. Taber (2001a) has made extensive comment on students using octet thinking. Students have often been found to believe that eight electrons always gives a full shell (Taber & Coll, 2002), and to universally apply the octet rule despite knowing about a large number of examples where the octet rule does not work (Taber, 2001a).

Almost all interviewees were able to list a range of intramolecular and intermolecular bond types. Some students had to think harder to recall intermolecular types of bonding. One interviewee thought there were only two bond types: covalent and ionic. Nahum, Mamlok-Naaman, & Hofstein (2006) and Taber & Coll (2002) are amongst researchers who have reported that students often believe that all chemical bonds are either covalent or ionic.

2. Describing the Bonding in Potassium Iodide, Aluminium and Hexane

During the interview students were asked questions about a sample of potassium iodide, aluminium and hexane. Five out of seven participants answered questions about potassium iodide competently. A common misconception that students held, however, was that potassium iodide consists of neutral particles. Coll & Treagust (2002) have reported that

some students believe the attraction between two oppositely charged species results in neutralisation.

Questions about aluminium were well answered by four out of the seven students. There was one student who thought that strong triple metallic bonds would form between aluminium cations, and another student who believed that aluminium consisted of neutral particles.

Questions about hexane were of particular interest. In the chemical bonding test most students could not describe the bond within a water molecule. Most students stated that water is held together due to the attraction between positive and negative atoms, a description that fits ionic substances. Subsequently, it was fascinating to see that in the interview five out of the seven students were largely able to describe the sharing of electrons that occurs between the carbon and hydrogen atoms of hexane. There was only one interviewee that explained that electrons are transferred from hydrogen to carbon, resulting in an attraction. Another student explained that there was only one electron per covalent bond, while another student was unable to explain anything about the bonding within hexane, except to note that it contained dispersion forces.

3. Sub-microscopic Representations of Metallic, Ionic and Covalent Bonding

The next set of questions revolved around cards depicting bonding models. In the interview students were asked to consider unlabelled diagrams showing metallic, ionic and covalent bonding. The results of these questions should be particularly illuminating, because one of

the most common alternative conceptions in the chemical bonding test was to think that the positive particles in a metallic lattice are protons. Only 9% of year nine and ten students could identify the positive particles in a metallic lattice as cations, with 66% of students thinking they were protons. Year eleven and twelve students performed little better, with only 29% of students able to correctly identify the positive particles in a metallic lattice, and 65% of participants believing they were protons. Similarly, 44% of junior students incorrectly believed that the positive particles in an ionic lattice were protons, although only 18% of senior students reported this same alternative conception.

Consequently, it was interesting to see how well students described the bonding in metallic substances during the interview. In every instance the interviewee correctly identified the positive particle in the metallic lattice as a cation. However, one student did start calling the cation a proton, but only later on during the interview when discussing the properties of metallic substances.

In the diagnostic test four out of the seven interviewees had stated that the metallic lattice consisted of protons. When the interviewees were subsequently shown their test again, two of the participants were able to accordingly correct their answer without any help. However, another two of the students remained convinced that their test response was correct. This is despite correctly identifying the cation in a metallic lattice diagram earlier in the interview. This important alternative conception does not appear to be reported in the literature on chemical bonding.

Interviewees were consistently able to name the particles in an ionic lattice. Only one student thought that the positive particles in the ionic lattice were protons, which was a commonly reported alternative conception in the diagnostic test. The alternative idea that cations and anions are neutralised by mixing appeared. It was reported earlier that students believed that ionic substances contain neutral particles.

The question about the ionic bonding model that interviewees found most challenging was in determining the difference in number of sub-atomic particles between an ion and an element. One student thought a chloride ion had to lose one electron to form from the neutral element. Another student thought the chloride ion was formed by losing two electrons. The rest of the interviewees determined the correct change in the number of electrons between element and ion. In the diagnostic test, only 59% of senior students and 33% of junior students were able to work out the difference between a sodium atom and a sodium ion. Likewise, only 56% of senior students and 25% of junior students were able to state the difference between a chlorine atom and a chlorine ion. The most common misconception in the test was that there was no difference in the number of sub-atomic particles between elements and ions. While this particular alternative conception remains unreported in the literature reviewed on chemical bonding, Kind (2004) has noted that students do not draw a distinction between ionic substances such as NaCl and $MgCl_2$ and simple molecules such as CH_4 and H_2O.

Questions that focused on the card with the sub-microscopic representation of water molecules were answered satisfactorily by all but one student. This student thought water molecules contained hydrogen bonding within the molecule.

4. Properties of Ionic, Metallic and Covalent Substances

Interviewees answered questions about the properties of ionic substances with ease. Nonetheless, three participants stated that ionic substances are able to conduct electricity in the molten or aqueous states because this is when ionic substances have free moving electrons. This is a new alternative conception that was not reported in the literature reviewed on chemical bonding. Students may be confusing ionic bonding with metallic bonding with this alternative conception.

Discussion on the properties of metals showed that students had a good understanding of properties such as hardness, malleability, electrical conductivity and melting point. Students were able to give general statements about the properties of a metal and recognise exceptions. For example, many students gave responses similar to Thomas below.

Interviewer: Is a substance with this [metallic] type of bonding typically hard or soft? Why?

Thomas: Ignoring mercury, they [metals] tend to be very hard. Because the bonds between the positive [cations] and the sea of electrons can be very strong.

The dialogue about the differences between diamond and hydrochloric acid revealed that all of the interviewees were able to distinguish between the properties of a continuous covalent lattice and a small molecule. The only difficulty that interviewees had was in determining the type of intermolecular bonding that existed between hydrochloric acid molecules. Two participants concluded that the intermolecular bond type was a hydrogen

bond. Another participant believed single covalent bonds existed between hydrochloric acid molecules. The rest of the participants were able to discuss the bonding type accurately.

Summary of Chapter

In summary, 172 students participated in a chemical bonding diagnostic test. Year 11 students achieved the best test average (75%) while Year 9 students attained the lowest test average (42%). A significant difference was found between the test scores of students at different ages and year levels. Year 11 students achieved significantly better results than Year 9 or 10 students, and Year 12 students also achieved significantly better results than Year 9 or 10 students. 17-year-olds significantly out-performed 14, 15 and 16-year-olds. However, there was no significant difference to be found between the performance of males and females.

A number of alternative conceptions that appear to be quite persistent were discovered during this research project. Some of the alternative conceptions were uncovered by the diagnostic test, while other alternative conceptions were revealed during the interview process. A number of these alternative conceptions have been previously reported in the literature, while some of these alternative conceptions appear to be new. These alternative conceptions have been summarised in Table 10 below.

This table is not a list of every alternative conception presented by students during the course of the study. It is a list of the *common* alternative conceptions encountered in the

diagnostic test or interview. This means that at least 26 students (i.e. 15%) in the chemical bonding test must have believed the alternative idea. Or two out of the seven senior chemistry students (i.e. 29%) who were interviewed must have made particular mention of the same alternative conception before it was listed below.

Table 10 – Common Alternative Conceptions Featured During the Test and Interview

Concept	Common Alternative Conception	Prevalence
Metallic bonding	The positive charges in a metallic lattice are protons.	This is a very common alternative conception. 66% of students in the diagnostic test believed that the positive charges in a metallic lattice of copper were protons. Only 13% of students were able to correctly identify the positive charges in a metallic lattice as copper ions. One interviewee also reported this alternative conception. This alternative conception does not appear in the literature reviewed on chemical bonding.
	A metallic lattice consists of protons and electrons.	This is a very significant alternative conception. In the test 105 students (61%) thought that the positive particles in a copper metallic lattice were protons and the negative particles were electrons. In addition, one interviewee also reported this alternative conception. This alternative conception does not appear in the literature reviewed on chemical bonding.

Concept	Common Alternative Conception	Prevalence
	The negative charges in a copper metallic lattice are copper ions.	This alternative conception does not appear in the literature reviewed on chemical bonding. 16% of students (i.e. 27 participants) in the test stated that the negative charges in a metallic lattice of copper were copper ions. Of these 27 students, 14 of them believed that in a copper metallic lattice the positive charges are copper atoms and the negative charges are copper ions.
	The positive charges in a metallic lattice are held together by repulsive forces between positive particles.	15% of senior students (year eleven and twelve) believed this response about copper. However, considerably fewer junior students selected this answer in the test. This minor alternative conception does not appear in the literature reviewed on chemical bonding.
	The positive charges in a metallic lattice are held together by attractive forces between positive particles.	This alternative conception does not appear in the literature reviewed on chemical bonding. 15% of junior students (year nine and ten) and 14% of test respondents overall selected this statement. Further analysis revealed that the majority of these respondents went on to say that attractive forces between positive and negative particles hold together an ionic lattice (and also a molecule of water). This seems to indicate some inconsistent thinking. In addition to this, one interviewee stated that strong triple metallic bonds form between aluminium ions.
Ionic bonding	The negative charges in an ionic lattice are electrons.	This was a common alternative conception, with 30% of test respondents choosing this option in the test. This alternative conception does not appear in the literature reviewed on chemical bonding.

Concept	Common Alternative Conception	Prevalence
	The positive charges in an ionic lattice are protons.	This was a very common alternate conception. 38% of students in the test believed this was true. This alternative conception does not appear in the literature reviewed on chemical bonding.
	The negative charges in a sodium chloride lattice are sodium ions.	This alternative conception was shown by a small number of students. 19% of students selected this response in the diagnostic test.
	The positive charges in a sodium chloride lattice are sodium atoms.	This alternative conception was shown by a small number of students. 15% of students selected this response in the test.
	The positive charges in a sodium chloride lattice are chloride ions.	This alternative conception was shown by a small number of students. 15% of students selected this response in the test.
	An ionic lattice consists of protons and electrons.	From the test we can see that 26% of students believed this statement. 51 students stated that the negative charges were electrons, 66 students thought that the positive charges were protons. 45 students selected both of these responses. One interviewee also reiterated this alternative conception. This important alternative conception does not appear in the literature reviewed on chemical bonding.

Concept	Common Alternative Conception	Prevalence
	The number of sub-atomic particles in the sodium element is identical to the number of sub-atomic particles in the sodium of sodium chloride.	This is an important alternative conception that does not appear in the literature reviewed on chemical bonding. 31% of test respondents thought that there was no change in the number of sub-atomic particles between element and ion.
	The number of sub-atomic particles in the chlorine element is identical to the number of sub-atomic particles in the chlorine of sodium chloride.	This is an important alternative conception that does not appear in the literature reviewed on chemical bonding. 32% of participants in the chemical bonding test said there was no difference in the number of sub-atomic particles between these two species.
	There is no difference between particles in an ionic lattice and neutral elements.	In the test 26% of students indicated that sodium and chlorine have the same number of sub-atomic particles as the ions in sodium chloride. This alternative conception does not appear in the literature reviewed on chemical bonding.
	A sodium ion contains one more electron than the sodium element.	This alternative conception was shown by a small number of students. 15% of senior students chose this response. Fewer junior students made this mistake.
	A chloride ion contains one less electron than the neutral chlorine atom.	This alternative conception was shown by a small number of students. 15% of students selected this response in the diagnostic test.

Concept	Common Alternative Conception	Prevalence
	A chloride ion contains one more proton than the neutral chlorine atom.	This alternative conception was shown by a small number of students. 15% of students selected this response in the test.
	The cations and the anions in an ionic substance are neutral.	Three out of seven interviewees believed that ionic substances contained neutral particles. They explicitly stated that the particles in an ionic lattice were not charged. This alternative conception is related to one reported by Kind (2004), who found that students made no distinction between molecular species such as water or methane, and ionic species such as sodium chloride or magnesium chloride. One interviewee further added that ions are neutralised when they "mix together". A similar view was reported by Coll & Treagust (2002).
	Aqueous and molten ionic substances conduct electricity because they contain free moving electrons.	Three out of the seven interviewees used this explanation to describe why ionic substances conduct electricity. This alternative conception was not found in the literature reviewed on chemical bonding.
Covalent bonding	Water contains just one central hydrogen atom.	In the diagnostic test students were shown an unlabelled diagram of a water molecule containing three spheres. 26% of students thought the large central sphere was a hydrogen atom. This alternative conception was not found in the literature reviewed on chemical bonding.

Concept	Common Alternative Conception	Prevalence
	Water contains two oxygen atoms.	22% of students in the diagnostic test thought water molecules contain two oxygen atoms. This alternative conception was not found in the literature reviewed on chemical bonding.
	Bonding in water consists of an attraction between a positive atom and a negative atom.	This is a major alternative conception. 67% of students stated that a water molecule is held together by an ionic-type bond. Only 20% of students in the diagnostic test identified the correct definition of a covalent bond in water. 40% of students thought that a water molecule is held together because a positive hydrogen atom is attracted to a negative oxygen atom, and 27% of students thought that a negative hydrogen bonds to a positive oxygen atom. Researchers have also reported instances of students believing that molecular species contain ions. For example, Coll & Taylor (2001) wrote about students thinking that molecular iodine contains 1- ions.
	A water molecule is held together by a chemical bond consisting of one electron simultaneously attracted to the hydrogen and oxygen nuclei.	15% of junior students selected this response in the test. One interviewee described at length a covalent bond. However, in his description he explicitly stated that the bond consists of a single electron. Unal, Calk, Ayas, & Coll (2006) reported that some students believe that covalent bonding is the result of the sharing of one electron between two atoms.

Concept	Common Alternative Conception	Prevalence
	In a covalent bond between carbon and hydrogen, the hydrogen atom donates one electron and the carbon atom does not donate any electrons.	Two interviewees described a covalent bond consisting of a single electron. The one electron is donated by the least electronegative element. The alternative conception of one electron bonds has been previously reported by researchers such as Unal, Calk, Ayas, & Coll (2006).
	Hydrogen bonds exist between hydrochloric acid molecules.	Two interviewees explained that hydrochloric acid molecules have a lower boiling point than diamond because of the relatively weak hydrogen bonds between HCl molecules. This is a new alternative conception not previously reported in the literature reviewed on chemical bonding.
Bonding models	Students have difficulty distinguishing between ionic lattices and metallic lattices.	Students struggled in the test to differentiate between ionic and metallic lattices. For example, 48% of students thought the ionic bonding model depicted the sub-microscopic structure of copper. 36% thought an ionic bonding model was depicting metallic bonding. Similarly, 35% of students picked the metallic bonding model to show the sub-microscopic structure of salt.

Concept	Common Alternative Conception	Prevalence
	Students find it difficult to work with sub-microscopic representations.	Students were able to recognise photos of everyday substances but were confused by sub-microscopic representations of those same substances. For example, only 52% of students were able to identify the two hydrogen atoms in a simple sub-microscopic representation of water. Only about one-third of junior students could correctly distinguish between sub-microscopic representations of metallic, ionic or covalent bonding.
	Atoms bond in order to get a full shell of (eight) electrons.	This common alternative conception has been commented upon by many researchers, such as Taber (2002a), Taber & Coll (2002) and Horton (2004). Three senior chemistry students also reported this alternative conception during their interview.
	Atoms have human qualities, for example they 'like' to be bonded, are 'happier' when they are bonded, and they enthusiastically 'hug' each other as they initiate a bond.	This common alternative conception was displayed by two interviewees. Researchers have previously reported that students make wide use of anthropomorphic language and analogy when trying to understand chemical bonding concepts (Unal, Calk, Ayas, & Coll, 2006).

A number of alternative conceptions that do not appear in the literature reviewed on chemical bonding have been reported in this chapter. These will be further discussed in the conclusion. Furthermore, the conclusion will consider the implications of these findings and discuss recommendations for the pedagogical history. Finally the conclusion will include some suggestions for further research.

Chapter 5 - Conclusion

This study has successfully provided a foundation upon which to construct a pedagogical history of chemical bonding. A pedagogical history is a valuable teaching device that will help students gain a more comprehensive understanding of the concept of chemical bonding. This study is significant because it has traced the history of the development of chemical bonding and extended the research into students' alternative conceptions of chemical bonding; thereby providing the necessary information to write a pedagogical history.

The diagnostic test developed for this study showed that for the most part high school students struggle to explain chemical bonding. Diagnostic testing was conducted on 172 high school students. Additionally, seven of these students were interviewed. The notion that each class of students holds multiple persistent alternative conceptions of chemical bonding is strongly supported. This makes the diagnostic test written for this study a valuable research tool for chemistry teachers. The diagnostic test produced for this study could be gainfully utilised in many schools.

A number of themes emerged while analysing the data gained from the diagnostic test, interview and literature review. Consequently, the pedagogical history will include a discussion on:

- interpreting sub-microscopic representations of chemical bonding, including the purpose of models;

- describing particles, in particular the particles in ionic or metallic lattices, and the difference in atomic structure between elements and ions;
- understanding the range of bond types that exist;
- avoiding oversimplified chemical bonding descriptions, including anthropomorphic language, and replacing the use of the octet rule with electron pair concepts;
- interesting stories, incorporating the major personalities and conflicts involved in the development of chemical bonding ideas.

The students in this study struggled to *interpret sub-microscopic representations of substance*s. Students were unable to differentiate between sub-microscopic representations of metallic or ionic substances, and were even confused by relatively simple sub-microscopic representations of water, although they could readily work with macroscopic representations of substances.

Sub-microscopic representations require thinking at more than one level simultaneously. Johnstone (1991, 2006) found that students are presented with difficulties whenever more than one level of thinking at a time is required. Teachers tend to move between levels of thinking too rapidly; from sub-micro to macro level thinking, and then onto the representational level, all within the space of a few minutes. Students find multiple levels of thinking confusing, and often remain at the macro level of thinking long after the teacher has moved on to other levels of thinking (Johnstone, 2006).

This study has shown that sub-microscopic representations are not intuitive to students. Sub-microscopic, macroscopic and representational levels of thinking need to be amalgamated in the minds of students for them to understand chemical bonding. The pedagogical history will move slowly from one level of thinking to another before attempting to bring all of these conceptual levels together.

The purpose of models needs to be discussed in this pedagogical history. The construction of models is central to chemistry. However, models are sometimes believed to be an exact replica of the real-world substance (Treagust, Chittleborough & Mamiala, 2002). Some students believe there is only one correct model of the atom (Horton, 2004). Seemingly, students do not have an awareness of the limitations of models. The limitations of covalent, metallic and ionic bonding models should be discussed. Studying the development of chemical bonding ideas over time will be helpful in showing how models are proposed, developed, amended or replaced over time.

Students are not able to adequately *describe the particles involved in bonding.* For example, a large number of students did not see a difference between a neutral element and an ion. Some students also stated that cations and anions in ionic substances are neutral. Therefore, the pedagogical history of chemical bonding needs to expand upon the concepts of atoms, elements and ions. Emphasis needs to be placed on clarifying the importance of protons, neutrons and electrons in atomic structure. Further research is necessary to determine why students are seeing no difference between the structure of elements and ions.

Additionally, a common alternative conception was the notion that the positive spheres in sub-microscopic representations of metals or salts are protons. Most students believed that a metallic lattice was composed of protons surrounded by a sea of electrons. Furthermore, a significant number of students explained that an ionic lattice was composed of alternating protons and electrons. Similarly, a number of senior students thought ionic substances were great conductors of electricity in particular states because of the presence of free-moving electrons.

The idea that the positive spheres in a sub-microscopic representation of a metal or a salt are protons proved to be a very prevalent alternative conception. The difficulty with this idea is that these students are not completely incorrect. The cations within a metallic or ionic lattice are positive because of protons. One possible solution to this alternative conception would be to emphasise the notion of core charge when interpreting sub-microscopic representations of ionic and metallic substances. For example, it could be explained that in a metallic substance it is the core charge that is attracting the delocalised valence electrons.

The pedagogical history will aim to increase students' understanding as to the *range of bond types that exist*. This is a problem that has its origins in history. Lewis had to battle other scientists who did not want to recognise the covalent bond. It required a long time to get the idea of covalent bonding to be recognised alongside the existing ionic bonding concept (Niaz, 2009). Students still struggle in differentiating between the different bond types. Moreover, some students believe that all bonding needs to be explained in terms of the transfer of electrons or the sharing of electrons (Taber & Coll, 2002). Learners are inclined

to describe other types of bonds, such as metallic bonds, also in terms of electron transfer or electron sharing (Unal, Calk, Ayas, & Coll, 2006; Taber, 2002a). The range of bonding models is far more extensive than most students imagine.

Due to the powerful alternative conceptions that are known to form, it is better to separate the teaching of the concepts of electron transfer and ionic bonding. A number of students take on board the concept of electron transfer and apply it to other forms of bonding, for example, believing that covalent bonding is explained by the transfer of electrons (Coll & Treagust, 2002). Separately teaching electron transfer and ionic bonding is also designed to prevent students from explaining that electron transfer *is* ionic bonding, that an ionic bond only forms if an electron has been transferred between two atoms, or that an anion will only bond with the specific cation that donated it an electron (Taber, 2002a). In addition, most salts are not created by electron transfer from neutral elements as usually taught in text books, but from some other type of reaction, such as a neutralisation reaction.

The pedagogical history should explain ionic bonding by focusing on the attractive forces operating between particles in an ionic lattice, rather than linking ionic bonding with electron transfer. Ion formation should be taught separately. It may also be better that students shift towards an understanding that most bonds are intermediate between the extremes of covalent, metallic or ionic bonding. As Fernelius and Robey (1935) proposed with their bonding-type triangle, many ionic compounds will have some degree of covalency, or covalent bonds some degree of ionicity, and so forth.

Students fail to appreciate the range of bonds that are possible partly because they sometimes describe the chemical bond as some type of spring or solid link (Pabuccu & Geban, 2006; Taber & Coll, 2002). At times students have explained that metallic substances are held together just by forces and not bonds, or that intermolecular bonds are just forces rather than proper bonds (Taber, 2002a). In the past, Dalton rejected Newton's idea that a chemical bond was a type of force that operated over a distance. Dalton, amongst other chemists, imagined bonds formed when atoms were joined together with some type of physical hook (Myers, 2003). Many students today also see forces and bonds as being somewhat different.

The pedagogical history will encourage students to *avoid oversimplified chemical bonding descriptions*. For example, one of the common ways that students oversimplify bonding in molecules is to apply the octet rule to explain most bonding phenomena. However, it has been widely known, even as the octet rule was formulated, that there are numerous elements that do not conform to this 'rule' (Gillespie & Robinson, 2007). Nonetheless, students have applied the rule almost universally despite its limitations, and some are unable to explain bonding in atoms that contradict the octet rule (Taber, 2001a; Taber & Coll, 2002). The octet rule has proved to be a significant barrier to students developing a deeper understanding of chemical bonding (Taber, 1999).

A discussion of the origin of the octet rule in the pedagogical history can help students to appreciate the limitations of this rule. Ideas about the rule of eight had its origins in Lewis's model of the cubical atom (Lewis, 1916). His drawings showed a cubical atom with electrons positioned at the eight corners of a cube. A single bond formed when two atoms

shared an edge of the cube, and a double bond was formed when two atoms shared a face of the cube. Ionic bonds formed when one cube transferred electrons to another cube. To explain a triple bond, Lewis had to propose a tetrahedral arrangement of electrons around the nucleus, and then share a face of this new shape.

From the cubical atom Lewis developed the idea of electron pairs, the octet rule and Lewis structures. He explained that a covalent bond resulted from shared pairs of electrons (Lewis, 1916). He noted that electrons are usually found in pairs, and he termed a molecule with an unpaired electron 'odd', although today we use the term free radical. From the cubical atom Lewis also developed his idea about the 'rule of eight', which Langmuir further developed into the 'octet rule' (Gillespie & Robinson, 2007). Afterwards, quantum mechanics proved to be a better model for explaining bonding than the cubical atom. Although the cubical atom has now been abandoned, Lewis's ideas of electron pairs, the octet rule and Lewis structures are still used to a significant extent in high schools today.

The pedagogical history of chemical bonding needs to emphasise that Lewis's idea of electron pairs is more important than his idea about the rule of eight (Shaik, 2007), and that molecules far more frequently contain electrons in pairs than conform to the octet rule. Lewis's ideas about the electron pair were later extended and improved upon by Pauling and other workers. It is interesting to note that students use a rule that does not always work in preference to electron pairing concepts which are more significant.

An emphasis on electron pairs could help alleviate a number of alternative conceptions that were apparent in this study. For example, some believed that covalent substances

contained one-electron bonds. More importantly, most students did not believe that water contained shared pairs of electrons. Most students thought that water was held together because of the attraction between positive and negative hydrogen and oxygen atoms. This pedagogical history will accentuate the importance of electron pairs and downplay the significance of the octet rule in explaining chemical bonding.

Another oversimplification of chemical bonding concepts made by some students is to discard ideas that they cannot explain. For example, some students believe that Coulomb's law does not operate within the atom, or that the laws of physics do not operate within the realm of chemistry (Horton, 2004), amongst other physical impossibilities. This alternative conception was promulgated for a time by Lewis. In trying to explain the existence of electron pairs, he erroneously proposed that Coulomb's law must not operate at the distances experienced in a bonding situation. Fortunately quantum mechanics came to Lewis's rescue and explained how the electron pair could exist while Coulomb's law was still in operation (Gillespie & Popelier, 2001). However, Lewis has not been the last scholar to attempt to suspend the laws of physics. It appears that history does indeed repeat itself.

Students also oversimplify chemical bonding by using anthropomorphic language. Atoms 'like', 'need' or 'want' to bond, and are 'happier' and 'hug' each other when they bond. Students make wide use of anthropomorphic language and analogy when trying to understand chemical bonding concepts (Unal, Calk, Ayas, & Coll, 2006).

These examples indicate that *research questions* one and three; "do students in two Victorian high schools also communicate these alternative conceptions about chemical

bonding?"; and "can a diagnostic test which makes use of sub-microscopic representations of chemical bonding reveal new student conceptions not reported in the literature?"; can thus be answered in the affirmative.

The pedagogical history will narrate *interesting stories* of some of the most engaging personalities involved in the development of chemical bonding ideas. There are many interesting historical anecdotes surrounding characters such as Newton, Thomson, Lewis, Langmuir, and Pauling.

For instance, Lewis had a difficult task to convince other scientists of his new views on covalent bonding. It took many years of work to convince other workers in the field of the validity of the idea of a pair of electrons. Lewis made the intuitive discovery of the electron pair without much in the way of experimental evidence. It took some time after Lewis's original publications for the existence of an electron pair to be confirmed. Even though Lewis was absolutely correct in pushing forward the idea of the electron pair, his explanation for their existence was less than compelling. Lewis advanced the problematic idea that Coulomb's Law must not be operational at the bonding level.

Here may lie a valuable lesson for students on the nature of science, that new evidence is rarely embraced with open arms, but often builds up over time until it becomes overwhelming and a shift in thinking occurs. Furthermore, new scientific ideas are rarely final, and are typically modified over time. As Pauling summed it up, "when an old and distinguished person speaks to you, listen to him carefully and with respect — but do not believe him..." (Hager, Hughson, Anderson, Castaño, Blasen, Burriel et. al., 2008, p. 49).

Furthermore, some of the controversies between scientists will be some of the most compelling reading for helping students to understand the nature of chemical bonding. This can be illustrated by Newton, as his ideas on the nature of the chemical bond competed with those from Descartes. For a time, the view promoted by Descartes prevailed, as Boyle and later Dalton explained that atoms were held together with hooks and barbs. Although it took a number of generations of scientists, eventually researchers such as Boltzmann agreed with Newton and came to understand that atoms attract each other at a distance due to a force.

Historical accounts of rivalry between scientists are amongst some of the most useful stories for inclusion into a pedagogical history, particularly the rivalry involved in competing scientific theories or philosophies. The rivalry between the covalent and ionic models will help "facilitate conceptual understanding" (Niaz and Rodriguez, 2001, p. 162). It is interesting to note that scientists in Lewis's day resisted the idea that there was more than one model to explain bonding. They attempted to explain every bonding phenomenon in terms of ionic bonding. Students today like to limit themselves to a constrained number of bonding models. A study of history can help students learn that it is perfectly valid to use multiple models for a particular concept.

A personal rivalry existed between Lewis and Langmuir. This rivalry would be a valuable inclusion into any pedagogical history of chemical bonding. Lewis formulated the earliest ideas of covalent bonding. However, it was the gifted speaker with his silver tongue, Langmuir, who came up with the terms 'covalent' and 'octet rule'. He did much to promote

the theory. Langmuir was an influential presenter and a great champion of science when he was promoting valuable new theories, but quite an obstacle to the advancement of science if he took it upon himself to advance a flawed hypothesis.

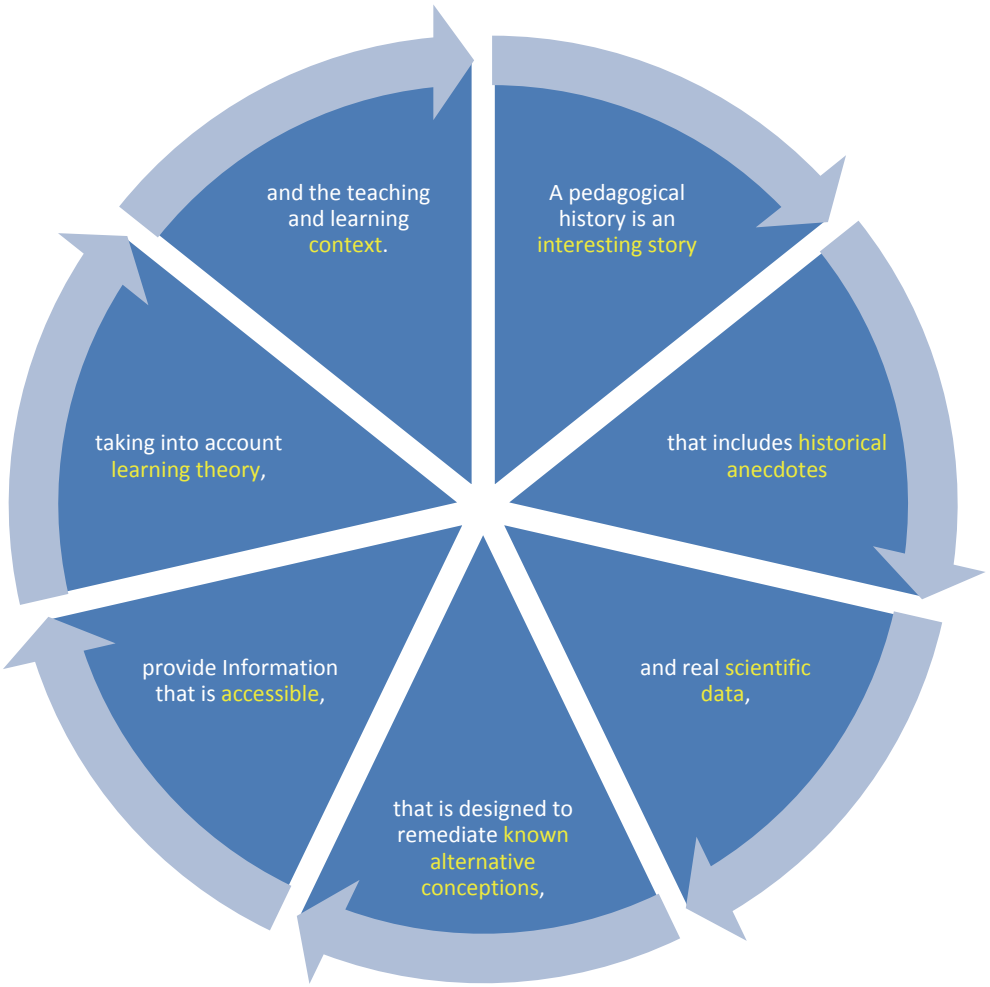
Lewis and Langmuir met for lunch on the day Lewis died. Their lives had taken quite different routes. Langmuir had made millions for his employer and was graced with a Nobel Prize. Lewis had built one of the greatest university departments, but his failure to net a Nobel Prize despite being nominated dozens of times almost certainly put a real dampener on his career and personal happiness. Lewis and Langmuir had both worked for and disliked Nernst. Reportedly, Nernst was responsible for making sure Lewis was never awarded the Nobel Prize. Interestingly, Nernst was also blocked for a long time from receiving his Nobel Prize by Arrhenius. It was only hours after Lewis and Langmuir dined together that Lewis was found dead on the floor of his laboratory. Did depression lead to suicide? Nobody can be sure, although some of his co-workers suspected he may have taken his own life. His life ended in a lab filled with deadly hydrogen cyanide (Coffey, 2008). The cause of death was officially reported as a heart attack, which certainly was more than possible considering his chain-smoking unhealthy lifestyle. Details such as these could be used to inject human interest value into the story of the development of chemical bonding.

Another historical example of competing paradigms can be seen in attempts to better explain the chemical bond. Mulliken promoted molecular orbital theory, and Pauling the valence bond approach. In this case, it was Pauling who was the eloquent teacher and persuasive writer, and his approach quickly took off. Over time it was seen that both approaches led to the same results.

These stories will help students develop a deeper understanding of chemical bonding, remediate alternative conceptions, and perhaps most significantly engage them in the study of chemical bonding. A pedagogical history illustrates the nature of science, as students witness scientists undertaking science as a highly social activity, trying to make sense of their world, having their ideas subject to change, and working hard to convince others of new ideas. Thus *research question* two; "can student conceptions be linked to historical conceptions of chemical bonding in a way that might inform student conceptions?"; can be answered in the affirmative.

In conclusion, students struggle to understand chemical bonding concepts and need assistance in overcoming alternative conceptions. In addition, teachers would appreciate resources that help make highly theoretical bonding constructs 'come alive'. A pedagogical history of chemical bonding can help with these problems and deliver some of the latest educational research into the classroom in an easy to use format. Figure 11 summarises the important elements that are woven into a pedagogical history.

Figure 11 – The Important Elements of a Pedagogical History



This research project has identified a number of areas where *further research* would prove most valuable. First and most important is the development of a pedagogical history of chemical bonding. The pedagogical history should be written in narrative form, with the elements of explanation woven into a story interspersed with questions, at a level readily understood by year eleven and twelve chemistry students. Once this has been written, it needs to be trialled, assessed, and modified where necessary. Then steps need to be taken to disseminate the pedagogical history to the wider chemical education community.

Another valuable research development would be to make changes to the diagnostic test written for this study in order to gain new insights. The scope of the test could be expanded, with new questions written. Alternatively, the focus of the test could be shifted to attempt to answer some of the questions raised by this study. It would be informative to write a two-tier test to further investigate some of the themes raised by this study. A two-tier test is designed to establish the reasoning behind the alternative conception.

Furthermore, philosophical ideas underpinning theories of chemical bonding could be explored. This would add another layer of depth to this study. Some of the most fundamental questions about chemical bonding remain difficult to explain. The pedagogical history could be expanded to include some of the important philosophical ideas that have impacted upon chemists' understanding of bonding.

Finally, it may prove valuable to investigate the significance of the notion of core charge in explaining chemical bonding. An analysis of text books could be conducted to determine how core charge concepts are presented, and if these concepts are linked to ideas about chemical bonding.

On a more *personal note*, I have experienced the benefits that a pedagogical history promises to deliver. I have read highly illuminating accounts of researchers such as Lewis, Pauling, Newton, and many others; accounts that have been extremely interesting. I have appreciated authors who have crafted narratives that are fascinating and highly educational. My students have shared my interest as I have retold some of these stories. And as I have

conducted this research I have developed a more thorough understanding of chemical bonding theories.

This project is part of our challenge to become more effective chemistry educators, to build upon the current body of research, and to develop novel solutions to age-old chemistry education problems.

Appendices

Appendix 1 – A List of Student Chemical Bonding Alternative Conceptions Found in the Literature

Concept	Students' Alternative Conceptions	Source
Ionic bonding	Oppositely charged ions will use up each others' force and lock together in a molecule.	Horton, 2004
	An atom will spontaneously emit an electron to become an ion.	Taber, 2002a
	An isolated cation is very stable.	Taber, 2002a
	A positive cation could not spontaneously attract a negative electron.	Taber, 2002a
	Only one electron can be removed from a sodium atom.	Taber, 2002a
	The sodium anion Na^{7-} is more stable than a neutral atom as it has a full outer shell of electrons.	Taber, 2000a
	Ionic bonding is defined as electron transfer.	Taber, 2002a
	The reason a bond is formed between chloride ions and sodium ions is because an electron has been transferred between them.	Taber, 2002a
	Ion-pairs are implied to act as molecules of an ionic substance. Ionic substances contain molecules.	Taber, 2002a
	Each ion has one ionic bond and five 'physical' bonds.	Taber & Coll, 2002
	Sodium chloride ion-pairs are internally ionically bonded but attracted to each other by weaker forces.	Taber, 2002b
	Ionic bonds form molecules.	Horton, 2004

Concept	Students' Alternative Conceptions	Source
	Ionic compounds form neutral molecules, such as $Na^{+}Cl^{-}$, in water.	Horton, 2004
	Ionic bonds are not real bonds in the sense of covalent bonds.	Unal, et. al., 2006
	The atomic electronic configuration determines the number of ionic bonds formed. For example, a sodium atom can only donate one electron so it can only form an ionic bond to one chlorine atom.	Taber, 2002a
	Bonds are only formed between atoms that donate and accept electrons. For example, a chloride ion bonds to a specific sodium ion that donated an electron to that particular anion. The chloride ion is only bonded to the sodium ion it accepted an electron from.	Taber, 2002a
	In sodium chloride a chloride ion is bonded to one sodium atom, and attracted to a further five sodium ions. This attraction is just by forces – not bonds.	Taber, 2002a
	Metals and non-metals form molecules.	Pabuccu & Geban, 2006
	Metals and non-metals form strong covalent bonds.	Unal, et. al., 2006
	Ionic substances such as sodium chloride possess	Taber & Coll,

Concept	Students' Alternative Conceptions	Source
	covalent bonds.	2002
	The structure of crystals was a mystery for most students entering university to study science.	Taber & Coll, 2002
	A '+' charge symbol represents a species which had one electron in its outermost shell which it would tend to donate to achieve a stable electronic configuration. Likewise, a '-' charge symbol implied an atom one electron short of a stable electronic configuration.	Taber, 1993
	A sodium ion could not possibly form six ionic bonds unless it had a 6+ charge.	Kind, 2004
	Ionic bonds cannot be broken by heating.	Kind, 2004
	Compounds with ionic bonds behave as simple molecules. There is no distinction between molecular formulas such as CH_4 and H_20 and ionic formulae such as NaCl and $MgCl_2$.	Kind, 2004
	H^+ and Cl^- ions form molecules in HCl solution.	Horton, 2004
	Ionic bonds are not seen as three-dimensional.	Horton, 2004
	Na^+Cl^- bonds are not broken in dissolving. Only intermolecular bonds are broken.	Horton, 2004
	The presence of ionic charge determines molecular polarity.	Coll & Taylor, 2001

Concept	Students' Alternative Conceptions	Source
	The bonding in ionic compounds involves intermolecular bonding.	Coll & Taylor, 2001
	The ionic radius of the sodium ion is greater than the chloride ion.	Coll & Taylor, 2001
	The ionic radius of the lithium ion is greater than the sodium ion.	Coll & Taylor, 2001
	Ionic bonding comprises sharing of electrons.	Coll & Taylor, 2001
	Ionic bonding contains an element of directionality.	Coll & Taylor, 2001
	Ionic shape and packing is influenced by pressure.	Coll & Taylor, 2001
	Bonding in ionic substances is weak.	Coll & Taylor, 2001
	Electrostatic forces in ionic substances are weak.	Coll & Taylor, 2001
Metallic bonding	Metallic bonds are like covalent bonds.	Taber, 2002a
	Metallic bonds are like ionic bonds.	Taber, 2002a
	There is no bonding in metals.	Taber, 2002a
	There is some form of bonding in metals, but not proper bonding.	Taber, 2002a

Concept	Students' Alternative Conceptions	Source
	Metals have covalent and/or ionic bonding.	Taber, 2002a
	Metals have metallic bonding, which is a sea of electrons.	Taber, 2002a
	The sea of electrons is a vast excess of electrons surrounding the cations.	Taber & Coll, 2002
	Metals are molecular.	Taber, 2002a
	Metallic substances are held together just by forces, rather than bonding.	Taber, 2002a
	All metals have the same electronic structure and obey a definite list of properties.	Nahum, et. al., 2006
	Metallic bonding is inferior to other forms of bonding.	Coll & Treagust, 2002
	Metallic bonding is weak bonding.	Coll & Taylor, 2001
	The bonding in metals involves intermolecular bonding.	Coll & Taylor, 2001
	The charged species in metallic lattices are nuclei rather than ions.	Coll & Taylor, 2001
	Metallic lattices contain neutral atoms.	Coll & Taylor, 2001
	Metallic bonding contains an element of directionality.	Coll & Taylor, 2001

Concept	Students' Alternative Conceptions	Source
	Metal to non-metal bonding in alloys is electrostatic in nature.	Coll & Taylor, 2001
	Electrons are shared.	Taber & Coll, 2002
	Electrons are being moved around so that the atoms take turns in having full shells.	Taber & Coll, 2002
Covalent bonding	Bonding electrons belong and are still part of the atom from which they originated. These atoms reclaim their own electrons when the bond breaks.	Taber, 2002a
	Bonding is about striving to obtain a full outer shell.	Taber, 2002a
	Atoms form covalent bonds to satisfy the octet rule.	Horton, 2004
	Atoms lend and borrow electrons to satisfy the octet rule.	Horton, 2004
	A shared electron pair holds atoms together because it enables them to have octets of electrons.	Taber & Coll, 2002
	The existence of bonding which does not lead to atoms having full electron shells is something of a mystery to many learners.	Taber & Coll, 2002
	Equal sharing of the electron pair occurs in all covalent bonds. All covalent bonds are non-polar.	Pabuccu & Geban, 2006
	The shape of a molecule is due to repulsion between bonding pairs of electrons.	Kind, 2004

Concept	Students' Alternative Conceptions	Source
	The shape of a molecule is due to repulsion between non-bonding pairs of electrons.	Horton, 2004
	Small molecules have low melting points and boiling points because covalent bonds are weaker than ionic bonds.	Kind, 2004
	Covalent bonds are not as strong as hydrogen bonds.	Unal, et. al., 2006
	Continuous covalent lattices contain molecular species.	Coll & Treagust, 2002
	Learners often do not understand the nature of giant covalent structures.	Taber & Coll, 2002
	Strong intermolecular forces exist in a continuous covalent network solid.	Unal, et. al., 2006
	Molecular solids consist of molecules with weak covalent bonding between the molecules.	Unal, et. al., 2006
	The number of valence electrons and the number of covalent bonds is one and the same.	Coll & Treagust, 2002
	Covalent bond formation involves the complete transfer of electrons.	Coll & Treagust, 2002
	Non-polar molecules are only formed between atoms of similar electronegativity.	Coll & Taylor, 2001
	The presence of lone pairs of electrons determines	Coll & Taylor,

Concept	Students' Alternative Conceptions	Source
	molecular polarity.	2001
	Polar covalent compounds contain charged species.	Coll & Taylor, 2001
	Molecular iodine contains 1- ions.	Coll & Taylor, 2001
	Molecular iodine is metallic in nature.	Coll & Taylor, 2001
	Glass is an ionic crystalline substance.	Coll & Taylor, 2001
	Covalent bonding is the result of the sharing of one electron between two atoms.	Unal, et. al., 2006
	Covalent bonding is the result of attractions between the negative and positives ends of an atom.	Unal, et. al., 2006
	Graphite conducts electricity because it has layers of carbon atoms which can slip over each other.	Unal, et. al., 2006
	Graphite conducts electricity because in graphite some carbon atoms are delocalised and they conduct electricity.	Tan & Treagust, 1999
	Covalent bonds are broken when a substance changes state.	Unal, et. al., 2006
	Students use the terms 'atom' and 'molecule' interchangeably and have difficulty differentiating	Nicoll, 2001

Concept	Students' Alternative Conceptions	Source
	between them.	
	Molecules form from isolated atoms.	Ozmen, 2004
	The largest atom exerts the greatest control over the shared electron pair.	Ozmen, 2004
	A grain of sugar is a single molecule. When it changes state the covalent bonds break. Therefore, covalent bonds must be relatively weak.	Taber & Coll, 2002
	Students see bond polarity as an additional secondary characteristic of covalent bonds, rather than as something between covalent and ionic bonds.	Taber & Coll, 2002
Intermolecular bonding	Students are readily confused about the differences between intermolecular and intramolecular forces, in part because of the linguistic similarity of the terms.	Unal, et. al., 2006
	Intermolecular bonds are just forces rather than proper bonding.	Taber, 2002a
	Polar bonding is a type of covalent bond.	Taber, 2002a
	Hydrogen bonds are a type of covalent bond.	Taber, 2002a
	Hydrogen bonds are simply bonds to hydrogen. They are a type of covalent bond.	Taber, 2002a
	Hydrogen bonds between water molecules are liquid or weak bonds.	Horton, 2004
	Hydrogen bonds are just a type of force, they are not	Taber, 2002a

Concept	Students' Alternative Conceptions	Source
	real bonds.	
	Hydrogen bonds are an attractive force, not a bond.	Horton, 2004
	Hydrogen bonds are one of the strongest type of bonds.	Unal, et. al., 2006
	Van der Waals forces are too weak to be considered proper bonds.	Taber, 2002a
	Ionic charges determine the polarity of the bond.	Pabuccu & Geban, 2006
	Polar molecules form when it has polar bonds.	Pabuccu & Geban, 2006
	Intermolecular forces are forces within a molecule.	Pabuccu & Geban, 2006
	Strong intermolecular forces exist in a continuous covalent network.	Kind, 2004
	Intermolecular forces are a type of energy.	Talanquer, 2004
	The strengths of covalent bonds and intermolecular forces are similar.	Horton, 2004
	The strength of intermolecular forces is determined by the strength of the covalent bonds in the molecules.	Tan & Treagust, 1999
	Oil and water do not mix because oil and water molecules repel each other.	Horton, 2004

Concept	Students' Alternative Conceptions	Source
	Intermolecular bonding is stronger than intramolecular bonding.	Coll & Treagust, 2002
	Students are unaware of the differences in strength of covalent bonds compared with intermolecular forces.	Unal, et. al., 2006
	Intermolecular bonding is absent in polar molecular substances such as water.	Coll & Treagust, 2002
	Intermolecular forces are influenced by gravity.	Coll & Taylor, 2001
Models	Students do not understand that models are only models, serving the development and testing of ideas, and are not the depiction of reality.	Horton, 2004
	The study showed that 43% of students agreed that a model was an exact replica.	Treagust, 2002
	Students make wide use of anthropomorphic language and analogy when trying to understand chemical bonding concepts.	Unal, et. al., 2006
	There are only four types of structures: ionic, metallic, covalent and molecular.	Nahum, et. al., 2006
	There are only two types of bonds. Everything has to be either covalent or ionic.	Nahum, et. al., 2006
	Students mistakenly use the properties of the element to describe the properties of a compound.	Taber, 1993

Concept	Students' Alternative Conceptions	Source
	For example, sodium is very reactive, therefore sodium chloride will also be very reactive.	
	Students transfer macroscopic properties to the molecular species. For example, atoms in a metal are hard, while atoms in liquids are softer. Copper is malleable because it has malleable atoms.	Taber & Coll, 2002
	There should be a one-to-one correspondence between models and reality. All models should be correct. The model is simply a representation of reality. The model may be an incomplete copy of reality.	Robinson, 2000
	The main purpose of models is the communication of ideas. However, models are real-world objects as opposed to the representation of ideas.	Robinson, 2000
	Models presented by experts are "true".	Robinson, 2000
	Atoms and molecules have macroscopic properties: they expand and lose weight when heated, have uniform densities and well-defined colours, are malleable, change their shape under pressure, etc.	Talanquer, 2004
	Different models of the same thing show literally different aspects of real things.	Smith, et. al., 2001
	There is only one correct model of an atom.	Horton, 2004

Concept	Students' Alternative Conceptions	Source
	Atoms are like cells with a membrane and a nucleus.	Horton, 2004
	Atoms can reproduce after the nuclei divide.	Horton, 2004
	The size of an atom depends on the number of protons it has.	Horton, 2004
	The electron shell is a matrix of some kind of stuff with electrons embedded in it.	Horton, 2004
	Coulomb's law does not work inside the atom. It works in physics but not in chemistry.	Horton, 2004
	Electrons are kept in orbit by gravity.	Horton, 2004
	The octet rule drives the chemical reaction.	Horton, 2004
	Every element wants to obey the octet rule.	Horton, 2004
	Students use octet thinking despite knowing about a large number of examples where the octet rule does not work.	Taber, 2001a
	Atoms need a certain number of bonds.	Horton, 2004
	Students could not indicate the specific particles that make up matter.	Frailich, Kesner & Hofstein, 2009
	Students have many difficulties in understanding the type of bond that was between the particles of various structures.	Frailich, Kesner & Hofstein, 2009
	Students invoke a solar system model of the atom.	Nicoll, 2001
	Students discount any type of bonding that does not	Taber & Coll,

Concept	Students' Alternative Conceptions	Source
	fit the description of electron sharing or electron transfer.	2002
	Students do not always understand that bonding may be intermediate between covalent and ionic.	Taber & Coll, 2002
	Students do not always understand that not all chemical bonds are ionic or covalent.	Taber & Coll, 2002
	Students do not always understand that bonding need not imply molecules.	Taber & Coll, 2002
	Students do not always understand that the chemical bond is due to electrical forces.	Taber & Coll, 2002
	Learners tend to think of the starting materials of chemical processes as being single unbound atoms, even though this is hardly ever the case.	Taber & Coll, 2002
Bonds and energy	Students have no clear understanding of the nature of the chemical bonds and energetics involved. Students struggle to relate thermodynamic ideas to bond formation.	Unal, et. al., 2006
	Breaking chemical bonds releases energy.	Horton, 2004
	Bond breaking releases energy and bond making involves energy input.	Taber & Coll, 2002
	Chemical bonds are some type of energy containers.	Talanquer, 2004
	Reactions are caused by atoms trying to fill shells.	Horton, 2004

Concept	Students' Alternative Conceptions	Source
	Bonds store energy.	Horton, 2004
	An atom may want to bond because it 'desires' to lose energy.	Unal, et. al., 2006
	Bond breaking is both exothermic and endothermic because energy is needed to break bonds initially, but once broken, energy is released.	Unal, et. al., 2006
Nature of bonds	Bonds are material connections rather than forces.	Pabuccu & Geban, 2006
	Chemical bonds are actually solid links between atoms.	Talanquer, 2004
	Learners imagine bonds to be very small springs or lengths of string.	Taber & Coll, 2002
	Students confuse intramolecular bonds and intermolecular bonds.	Nahum, et. al., 2006
	Students tend to overgeneralise and use rote memorisation instead of scientific explanations.	Nahum, et. al., 2006
	Students use the right terms and concepts but do not understand their meaning or their conceptual relevance.	Nahum, et. al., 2006
	The positive nuclear charge is used up on core electrons.	Taber, 1993
	The central element is responsible for bond	Kind, 2004

Concept	Students' Alternative Conceptions	Source
	formation. Or similarly, the first element written in a formula is responsible for bond formation. For example, carbon in CH_4 is the more powerful element and needs four bonds. Hydrogen is the weaker partner and only needs one bond.	
	Atoms want or need to form bonds.	Kind, 2004
	Bond polarity determines molecular shape.	Talanquer, 2004
	Electron clouds are structures in which electrons are embedded.	Smith, et. al., 2001
	Atoms own their electrons.	Horton, 2004
	Electrons know which atom they came from.	Horton, 2004
	Atoms know who owes them an electron.	Horton, 2004
	Nuclear force gets spread over a number of electrons. None is left over to attract another electron.	Horton, 2004
	The nucleus attracts all electrons around it equally.	Horton, 2004
	Atoms are glued together to make molecules.	Horton, 2004
	The attraction between two oppositely charged species results in neutralisation.	Coll & Treagust, 2002
	Electronegativity is the attraction for a single electron.	Coll & Taylor, 2001
	Electrons are ions and bonding occurs between them.	Unal, et. al., 2006

Concept	Students' Alternative Conceptions	Source
	Bonding electrons do not have any motion.	Unal, et. al., 2006
	Bonding electrons sit between the nuclei.	Unal, et. al., 2006
	Electrons are attracted to one another when they bond.	Nicoll, 2001
	Shells and orbitals are the same thing.	Nicoll, 2001
	Electrons move in a figure eight pattern.	Nicoll, 2001
	Eight electrons in the third or higher shells gives a full shell.	Taber & Coll, 2002

Appendix 2 – Diagnostic Chemical Bonding Test

Participant Number: ☐

Chemical Bonding Test

This test is designed to find out what you know about *chemical bonding*. Please answer the following questions *carefully* so that we can know what you *think* about this topic. You will be pleased to know that this test is not going to affect your grade in any way. In addition, participating will help you to better understand this topic.

Gender: ☐ M ☐ F (tick appropriate box)

Age: ☐ (insert age in box)

Year level at school: ☐ 9 ☐ 10 ☐ 11 ☐ 12 (tick appropriate box)

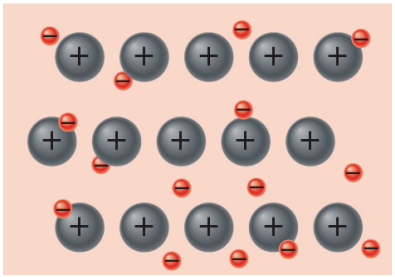
Instructions:

- This test has three parts, Parts A, B and C. Part A will be collected before handing out Part B. Part B will be collected before handing out Part C.
- Parts A and B should take about five minutes to complete. Part C should take no longer than ten minutes to complete.
- You will be given a participant number. You should use this number on all three parts.
- Please answer the questions to the best of your ability.

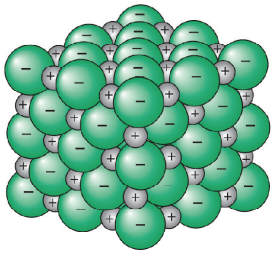
Chemical Bonding Test – Part A

Here are three models, A, B and C, representing three different types of substances. One model illustrates covalent bonding, another ionic bonding and another metallic bonding.

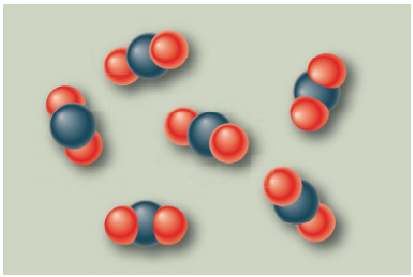
Model A



Model B



Model C



Question 1

Select, by ticking the appropriate box, which one of the above models represents:

	Model A	Model B	Model C
covalent bonding	☐	☐	☐
ionic bonding	☐	☐	☐
metallic bonding	☐	☐	☐

Choose only one model for each type of bonding.

Please submit your test.

Chemical Bonding Test – Part B **Participant Number:** ☐

Here are three photos, A, B and C, representing three different substances. One photo illustrates water, another copper and another sodium chloride (salt).

Photo A



Photo B



Photo C



Question 1

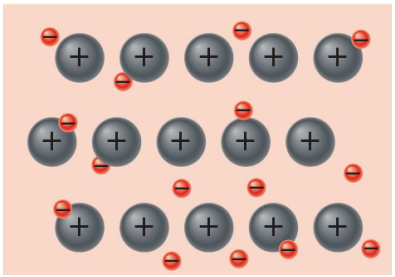
Select, by ticking the appropriate box, which one of the above photos represents:

	Photo A	Photo B	Photo C
water	☐	☐	☐
copper	☐	☐	☐
salt	☐	☐	☐

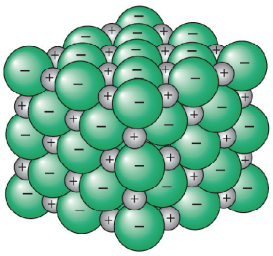
Please turn over.

Here are three models, A, B and C, representing three different substances. One model illustrates water, another copper and another sodium chloride (salt).

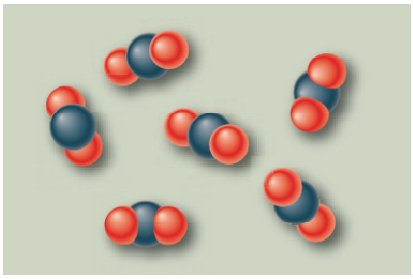
Model A



Model B



Model C



Question 2

Select, by ticking the appropriate box, which one of the above models represents:

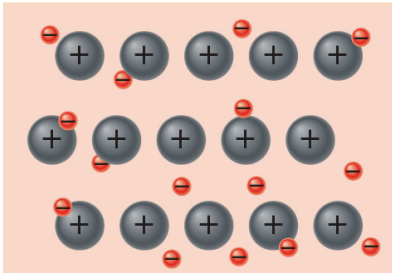
	Model A	Model B	Model C
water	☐	☐	☐
copper	☐	☐	☐
salt	☐	☐	☐

Choose only one model for each substance.

Please submit your test.

Chemical Bonding Test – Part C **Participant Number:** ☐

Choose the one correct answer by ticking the appropriate box for Questions 1-3.



This is a model that represents copper.

Question 1

The negative charges represent:

- ☐ copper atoms
- ☐ copper ions
- ☐ electrons
- ☐ protons

Question 2

The positive charges represent:

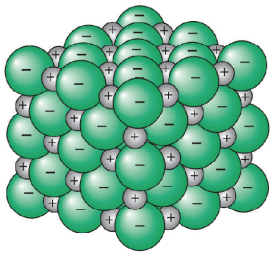
- ☐ copper atoms
- ☐ copper ions
- ☐ electrons
- ☐ protons

Question 3

The positive charges are held together by:

- ☐ attractive forces between positive particles
- ☐ attractive forces between positive and negative particles
- ☐ repulsive forces between positive particles
- ☐ repulsive forces between positive and negative particles

Choose the one correct answer by ticking the appropriate box for Questions 4-8.



This is a model that represents common table salt, sodium chloride.

Question 4

The negative charges represent:

- ☐ electrons
- ☐ sodium ions
- ☐ sodium atoms
- ☐ chloride ions
- ☐ chlorine atoms

Question 5

The positive charges represent:

- ☐ protons
- ☐ sodium ions
- ☐ sodium atoms
- ☐ chloride ions
- ☐ chlorine atoms

Question 6

The positive and negative charges are held together by:

- ☐ attractive forces between positive particles
- ☐ attractive forces between positive and negative particles
- ☐ repulsive forces between positive particles
- ☐ repulsive forces between positive and negative particles

Question 7

An atom of the element sodium has 11 protons, 12 neutrons and 11 electrons in the neutral atom. The number of protons, neutrons and electrons in the sodium of sodium chloride is:

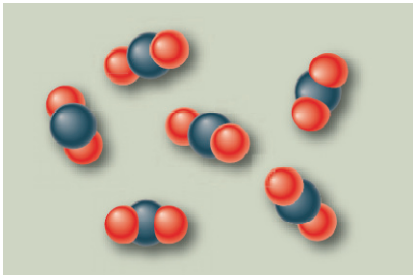
- ☐ 11 protons, 12 neutrons and 11 electrons
- ☐ 11 protons, 12 neutrons and 12 electrons
- ☐ 11 protons, 12 neutrons and 10 electrons
- ☐ 10 protons, 12 neutrons and 11 electrons
- ☐ 12 protons, 12 neutrons and 11 electrons

Question 8

An atom of the element chlorine has 17 protons, 18 neutrons and 17 electrons in the neutral atom. The number of protons, neutrons and electrons in the chlorine of sodium chloride is:

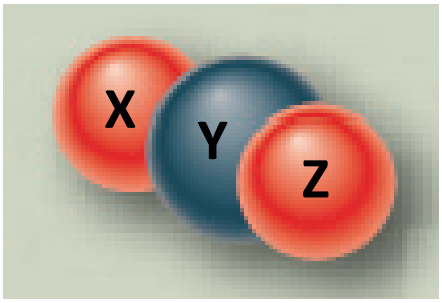
- ☐ 17 protons, 18 neutrons and 17 electrons
- ☐ 17 protons, 18 neutrons and 18 electrons
- ☐ 17 protons, 18 neutrons and 16 electrons
- ☐ 18 protons, 18 neutrons and 17 electrons
- ☐ 16 protons, 18 neutrons and 17 electrons

Please turn over for the final page of questions.



This is a model that represents six water molecules.

Consider just one of the water molecules:



Choose the one correct answer by ticking the appropriate box for Questions 9-11.

Question 9

The sphere or spheres above which represent a hydrogen atom:

- ☐ sphere X
- ☐ sphere Y
- ☐ sphere Z
- ☐ spheres X and Y
- ☐ spheres X and Z

Question 10

The sphere or spheres above which represent an oxygen atom:

- ☐ sphere X
- ☐ sphere Y
- ☐ sphere Z
- ☐ spheres X and Y
- ☐ spheres X and Z

Question 11

The hydrogen and oxygen atoms are held together by a chemical bond consisting of:

- ☐ the positive hydrogen atom being attracted to the negative oxygen atom
- ☐ the negative hydrogen atom being attracted to the positive oxygen atom
- ☐ one electron simultaneously attracted to the hydrogen and oxygen nuclei
- ☐ two electrons simultaneously attracted to the hydrogen and oxygen nuclei

Appendix 3 – Interview Questions

Interview Protocol to Determine Student Conceptions of Chemical Bonding

The interview protocol used in this study was a semi-structured open-ended protocol. This is similar to studies done by the researchers Nicoll (2001), Coll & Treagust (2000, 2002), Coll & Taylor (2001), Taber (1993, 2001b), Peterson & Treagust (1989) and a significant number of other researchers as listed by Unal, Calk, Ayas, & Coll (2006). The students were guided through the questions in order, but the interviewer asked follow-up questions where necessary to probe more deeply.

Directions for interviewees:

This interview is not going to affect your grade in anyway. I just want to understand what you think and believe about chemical bonding. This will help me and other teachers to teach your class and other students more effectively.

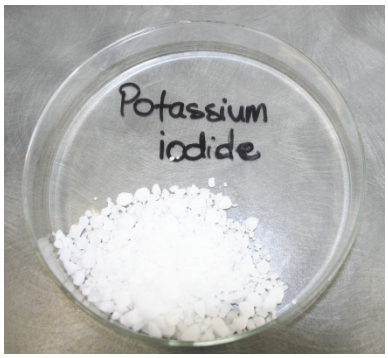
This interview will be anonymous and your name will not be associated with your answers in any way. This interview is purely voluntary and so you may stop at any time. However, your answers will be very helpful. I will record your answers as an mp3 file to make sure that I fully understand your response.

I want to understand what you are thinking as you answer the interview questions, and for that reason I would like you to talk as much as possible and tell me what you are thinking. When you get questions wrong, I will also help you to understand the correct answer so that you will benefit from this interview process.

Questions:

1. What does the term 'chemical bond' mean to you?
2. Why do atoms form chemical bonds?
3. How many different ways can atoms bond together? In other words, how many different types of bonds are there for holding together atoms in molecules?

How substances bond together



4. This is a sample of potassium iodide.
   (a) In what form do the potassium atoms and iodine atoms exist in potassium iodide?
   (b) What is holding the potassium and iodide ions together in this substance?
   (c) What type of bonding do we call this?
   (d) What does a potassium atom have to do with its atomic structure to become a potassium ion?
   (e) What does an iodine atom have to do with its atomic structure to become an iodine ion?

5. This is a sample of *aluminium*.



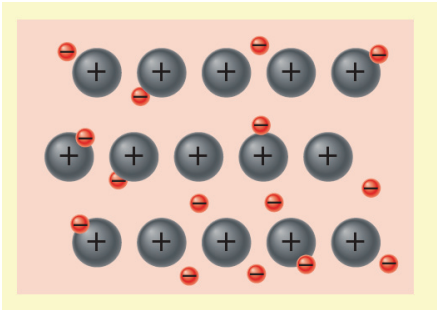
   (a) In what form do the aluminium atoms exist in aluminium metal?
   (b) What is holding the aluminium ions together in this substance?
   (c) What type of bonding do we call this?
   (d) What does an aluminium atom have to do to become an aluminium ion?

6. This is a sample of *hexane*.



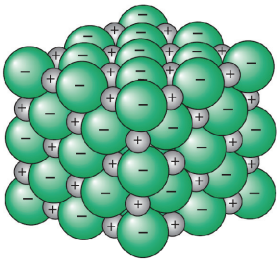
   (a) What is holding the carbon and hydrogen atoms together in a molecule of this substance?
   (b) What type of bonding do we call this?

7. Have a look at this diagram:



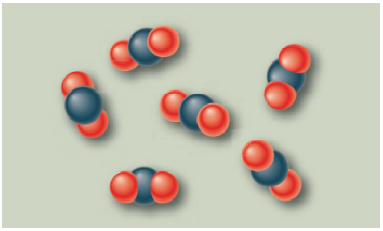
   (a) What type of bonding is depicted by this diagram?
   (b) What do the positive particles represent? Also, what do the negative particles represent?
   (c) What type of elements use this type of bonding?

8. Have a look at this diagram:



   (a) What type of bonding is depicted by this diagram?
   (b) What do the positive particles represent? Also, what do the negative particles represent?
   (c) What type of elements use this type of bonding?
   (d) The small grey spheres could represent sodium ions. Is there are difference in the number of protons, neutrons or electrons between sodium ions and the sodium element?
   (e) The larger green spheres could represent chloride ions. Is there are difference in the number of protons, neutrons or electrons between chloride ions and the chlorine element?

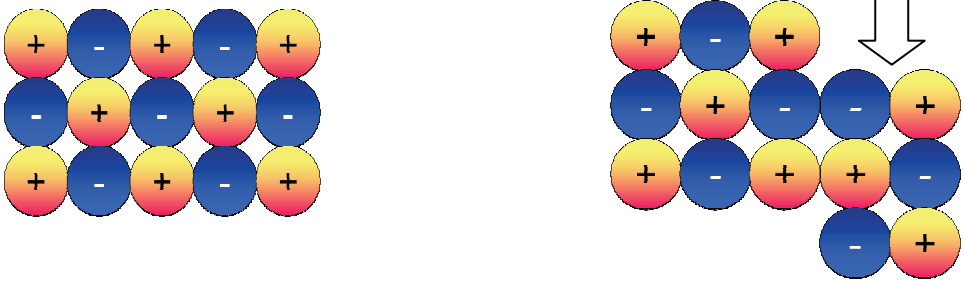
9. Have a look at this diagram:



(a) What type of bonding between atoms in a molecule is depicted by this diagram?
(b) What type of elements use this type of bonding?

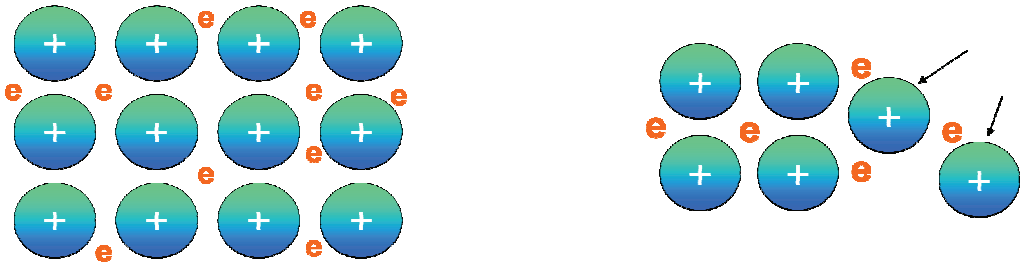
Explaining and predicting the properties of a substance

10. Have a look at this diagram. This substance uses ionic bonding. Here is where I have moved some of the ions of a crystal around.



(a) What is going to happen to the crystal as a result of moving these ions around?
(b) Is a substance with this type of bonding typically hard or soft?
Why is this substance typically {hard/soft... }?
(c) Does a substance with this type of bonding typically have a high or low melting point?
Why does this substance typically have a {high/low...} melting point?
(d) Will a substance with this type of bonding typically be able to conduct electricity?
Why is this substance typically {able to conduct electricity/not able to conduct electricity/able to conduct electricity in the molten and aqueous states but not the solid state...}?

11. Have a look at this diagram. This substance uses metallic bonding. Here is where I have moved some of the ions of a metal around.

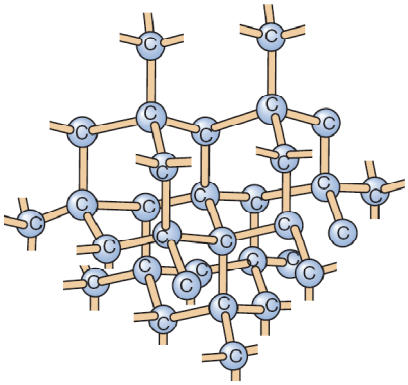


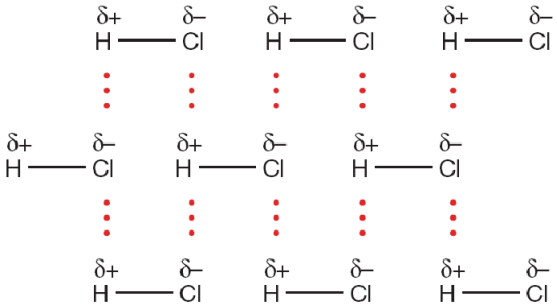
(a) What is going to be the effect on the substance as a result of moving around these ions?
(b) Is a substance with this type of bonding typically hard or soft?
Why is this substance typically {hard/soft...}?

(c) Does a substance with this type of bonding typically have a high or low melting point?
Why does this substance typically have a {high/low...} melting point?

(d) Will a substance with this type of bonding typically conduct electricity?
Why is this substance typically {able to/not able to...} conduct electricity?

12. Both of these two substances use covalent bonding. Which of these following two substances will have the highest boiling point?
Why does this substance have the highest boiling point?
Why is the boiling point of the other substance lower?





13. Further individualised questions may be asked. For example, regarding whether the information given in the interview is consistent with their test answers.

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