DEVELOPMENT OF A TWO-TIER MULTIPLE CHOICE DIAGNOSTIC INSTRUMENT TO DETERMINE A-LEVEL STUDENTS' UNDERSTANDING OF IONISATION ENERGY

Daniel Tan, Goh Ngoh Khang & Chia Lian Sai, *National Institute of Education*
Keith S. Taber, *University of Cambridge*

ISBN: 981 - 05 - 2995 – 3

Acknowledgement

This research was funded by the Academic Research Fund, National Institute of Education, Nanyang Technological University, Singapore (RP 8/00 TKC)

February, 2005

ABSTRACT

Previous research has shown that A-level students in the United Kingdom had difficulty understanding the concepts involved in ionisation energy. This report describes the development and administration of a two-tier multiple choice diagnostic instrument on ionisation energy to determine if A-level students (16 to 19 years old) in Singapore had similar alternative conceptions as their counterparts in the United Kingdom, as well as explore their understanding of the trend of ionisation energy across Period 3. The results showed that students in Singapore applied the same octet rule framework and conservation of force thinking to explain the factors influencing ionisation energy as the students in the United Kingdom. In addition to the above alternative frameworks, many students in Singapore also resorted to relation-based reasoning to explain the trend of ionisation energy across Period 3 elements. The authors believed that the way ionisation energy was taught by teachers and presented in textbooks could be the cause of students' difficulties in understanding ionisation energy. Teachers and textbooks need to focus explicitly on the effects of nuclear charge, the distance of the electron from the nucleus, the repulsion/screening effect of the other electrons present, and the interplay between these factors to explain the factors influencing ionisation energy and the trend in ionisation energy across period 3.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

THE STUDY

This study addressed the problem of how to determine Singapore A-level (Grade 11 and 12) students' understanding of the topic, ionisation energy, using semi-structured interviews, multiple-choice questions in which students have to justify their answers, and two-tier multiple-choice questions.

CONTEXT OF THE STUDY

Educational psychology suggests that the teaching and learning of scientific content are greatly enhanced if the students' pre-existing conceptual framework is considered when pedagogic strategy is planned (Ausubel, 1968, 2000). This is because the new content has to be subsumed into the existing cognitive structure of the student. Studies have revealed that students bring with them to science lessons certain ideas, notions and explanations of natural phenomena that are inconsistent with the ideas accepted by the scientific community (Osborne, Bell, & Gilbert, 1983). These existing ideas are often strongly held, resistant to traditional teaching and form coherent though mistaken conceptual structures (Driver & Easley, 1978). Students may undergo instruction in a particular science topic, do reasonably well in a test on the topic, and yet, do not change their original ideas pertaining to the topic even if these ideas are in conflict with the scientific concepts they were taught (Fetherstonhaugh & Treagust, 1992). Thus, students' alternative conceptions have to be identified so that measures can be taken to help students replace them with more scientifically acceptable concepts (Taber, 1998a). Studies in which students' alternative conceptions are described cover a wide range of subject areas including physics (Gardner, 1986; Shipstone, 1984; Watts, 1983), biology (Fisher, 1985; Haslam, & Treagust, 1987) earth science (Nussbaum & Novak, 1976) and chemistry (Barker & Millar, 2000; Harrison & Treagust, 2000; Pedrosa & Dias, 2000; Schmidt, 2000; Taber, 2001; Taber & Watts, 2000). A useful review of alternative conceptions at secondary school level was provided by Driver et al (1994). Besides exploring and identifying students’ alternative conceptions, most of these studies provide implications for the teaching and learning of the concepts examined.

PURPOSE OF THE STUDY

The objectives of this study were to:

1. identify the concepts and propositional knowledge necessary for A-level (Grade 11 and 12) chemistry students to understand the topic of ionisation energy,
2. develop a two-tier multiple-choice diagnostic instrument consistent with the identified concepts, propositional knowledge and known student alternative conceptions related to ionisation energy,
3. measure the understanding of the concepts and propositional knowledge related to ionisation energy of A-level chemistry students in Singapore through the use of the two-tier multiple-choice diagnostic instrument developed.

SIGNIFICANCE OF THE STUDY

The topic of ionisation energy is important as the concepts involved also provide the foundation for the understanding of atomic structure, periodic trends and energetics of reactions (Taber, 2003a). Research in the United Kingdom has shown that Grade 11 and 12 students have difficulty in understanding concepts related to ionisation energy (Taber 1999a, 2000a, 2003a), and this present study seeks to determine if students in Singapore have similar difficulties. The development of a diagnostic instrument, the Ionisation Energy Diagnostic Instrument (IEDI) provides teachers with a tool to diagnose students’ understanding of ionisation energy. By knowing their students’ alternative conceptions of ionisation energy, teachers can gain a greater insight into the subject matter of the topic, their teaching, and the learning processes of their students. They are also likely to be more receptive and willing to try or develop alternative teaching strategies if they find that their present methods are inadequate in addressing students' difficulties.

RESEARCH QUESTIONS

Three research questions were considered in this study of the understanding and conceptions of ionisation energy of A-level students:

1. What are the concepts and propositional knowledge necessary for A-level chemistry students to understand the topic of ionisation energy?
2. How can a two-tier multiple-choice diagnostic instrument which is consistent with the identified concepts, propositional knowledge and known student alternative conceptions related to ionisation energy be developed?
3. What do A-level chemistry students in Singapore understand about the concepts and propositional knowledge related to ionisation energy?

LIMITATIONS OF THE STUDY

The results and conclusions generated in this study refer specifically to the sample groups involved in the study. Generalisation of the findings to all A-level chemistry students in Singapore must be considered with caution due to the nature and the limited size of the sample. Potential effects of the students' learning styles, the attitudes of the students towards the learning of chemistry, the classroom climate, as well as the effects of the different teachers who taught the students, their teaching and management styles were not explored in this research. In view of the large number of Singapore A-level students involved in the development and administration of the IEDI, the authors are confident that the findings presented here, if not strictly speaking from a representative sample, are none-the-less relevant to all teachers of A-level chemistry in Singapore.

METHODOLOGY

The study took place in four stages:

1. Definition and validation of the content framework defined through concept mapping and a list of propositional knowledge statements (June 2001 – December 2001)

2. Interviews with students to determine and/or clarify their conceptual difficulties and alternative conceptions of ions and ionisation energy (January 2002 – November 2003).
3. Development of the diagnostic instrument (July 2002 – November 2003)
    a. Preparation of diagnostic items on areas of conceptual difficulty, and students' alternative conceptions and misunderstanding identified in the literature, interviews and free response tests.
    b. Pilot studies to develop, test and refine the diagnostic items.
    c. Validation and administration of the finalised diagnostic instrument.
4. Analysis of data and writing of report (August 2003 – August 2004).

SUMMARY

The main purpose of this study was to develop a written diagnostic instrument that could be used to determine A-level students' understanding as well as identify alternative conceptions of ionisation energy following instruction in the topic. This is to enable teachers and curriculum writers to be aware of students' alternative conceptions so that they can develop appropriate teaching strategies and materials to help students better understand ionisation energy.

CHAPTER TWO

LITERATURE REVIEW

INTRODUCTION

The literature review serves to provide a theoretical and methodological framework for this study on A-level students' understanding and alternative conceptions of ionisation energy. There are three main sections in this literature review. The first section describes the nature of alternative conceptions, while the second section discusses previous research in students' understanding of ionisation energy. The final section discusses several methods of determining alternative conceptions.

NATURE OF ALTERNATIVE CONCEPTIONS

> Science instruction, from the elementary school to the university level, is frequently disappointing as far as promoting students' understanding of science is concerned. Students are often in full command of science terminology and, for example, might be able to provide the names of animals and plants, to write down the Schrödinger equation without any difficulties, or to provide key examples when presented with formulas. However, there very often is no deep understanding behind the facade of knowledge.
>
> (Duit & Treagust, 1995, p. 46)

Many researchers agree that the most important significant things that students bring to class are their conceptions (Ausubel, 1968, 2000; Driver & Oldham, 1986). Duit and Treagust (1995) define conceptions as "the individual's idiosyncratic mental representations", while concepts are "something firmly defined or widely accepted" (p. 47). Children develop ideas and beliefs about the natural world through their everyday life experiences. These include sensual experiences, language experiences, cultural background, peer groups, mass media as well as formal instruction (Duit & Treagust, 1995). Some of these ideas and beliefs, such as those about light and sight

(Driver, 1995) may be similar across cultures as children have very similar personal experience with phenomena.

Students' conceptions are critical to subsequent learning in formal lessons because there is interaction between the new knowledge that the students encounter in class and their existing knowledge. Johnstone (2000) states that when a person tries to store material in long term memory and cannot find existing knowledge with which to link it, he/she may try to 'bend' the knowledge to fit somewhere, and this gives rise to erroneous ideas (cf. Gilbert, Osborne & Fensham, 1982). When students' existing conceptions differs from those commonly accepted in the disciplines, they are termed as alternative frameworks (Driver & Easley, 1978), misconceptions (Cho, Kahle, & Nordland, 1985; Driver & Easley, 1978), student conceptions (Duit & Treagust, 1995), alternative conceptions (Abimbola, 1988; Hewson, 1981), intuitive beliefs (McCloskey, 1983), intuitive conceptions (Duit, 1995), naive beliefs (Caramazza, McCloskey, & Green, 1981), or children's science (Osborne, Bell & Gilbert, 1983). The particular terms used may depend on the author's views of science (Abimbola, 1988) and of the nature of knowledge (Duit & Treagust, 1995). For example, Duit and Treagust state that the term alternative frameworks suggests that the students' conceptions are effective in daily life and hence valuable to them, while children's science indicates that students' conceptions are to be taken seriously as they formulate their ideas in a way that is similar to scientists. Abimbola (1988) prefers the use of the term alternative conceptions to describe the student's ideas and alternative frameworks for the organisation of ideas, while Gilbert and Watts (1983) describe alternative frameworks as "thematic interpretations of data, stylised, mild caricatures of responses made by students" (p. 69). Vosniadou (1994) regards misconceptions to be spontaneous constructions which are often generated on the spot, and not deeply held specific theories. These misconceptions arise as "individuals' attempts to assimilate new information into existing conceptual structures that contain information contrary to the scientific view" (Vosniadou, 1994, p. 45).

In this study, the term 'alternative conceptions' is used to describe student conceptions which differ from scientific concepts. The authors agree with Wandersee, Mintzes and Novak (1994) that the term "confers intellectual respect on the learner who holds those ideas – because it implies that alternative conceptions are contextually valid and rational and can lead to even more fruitful conceptions (e.g., scientific conceptions)" (p. 178). The term 'alternative framework' is also used in this study to describe significant ‘theory-like’ sets of ideas which are “carefully thought through and well integrated with other knowledge” (Taber, 1999b). Interest in student conceptions surged with the emergence of constructivism (Osborne, 1996; Solomon, 1994), which brought along with it “a language with new descriptive power” (Solomon, 1994, p. 6). This language, Solomon argues, transmuted the study of common student mistakes, previously of little appeal to anyone, to something exciting and of great interest.

Students’ existing ideas are often strongly held, resistant to traditional teaching and form coherent though mistaken conceptual structures (Driver & Easley, 1978). Students may undergo instruction in a particular science topic, do reasonably well in a test on the topic, and yet, do not change their original ideas pertaining to the topic even if these ideas are in conflict with the scientific concepts they were taught (Fetherstonhaugh & Treagust, 1992). Duit and Treagust (1995) attribute this to students being satisfied with their own conceptions and therefore seeing little value in the new concepts. Another reason they proposed was that students look at the new learning material “through the lenses of their preinstructional conceptions” (p. 47) and may find it incomprehensible. Osborne et al. (1983) state that students often misinterpret, modify or reject scientific viewpoints based upon the way they really think about how and why things behave, so it is not surprising that research shows that students may persist almost totally with their existing views (Treagust, Duit, & Fraser, 1996). When the students' existing knowledge prevails, the science concepts are rejected or there may be misinterpretation of the science concepts to fit or even support their existing knowledge. If the science concepts are accepted, it may be that they are accepted as special cases, exceptions to the rule (Hashweh, 1986), or in isolation from the students' existing knowledge, only to be used in the science classroom (de Posada, 1997; Osborne & Wittrock, 1985) and regurgitated during examinations. Additional years of study can result in students acquiring more technical language but still leave the alternative conceptions unchanged (de Posada, 1997). However, cognitive development over time is important for learning as development of scientific reasoning ability and conceptual change during adolescence has been shown to be linked to brain growth (Kwon & Lawson, 2000).

Thus, teachers must be aware that they “cannot assume that what is taught is what is learned” (Driver & Scott, 1996, p. 106). Alternative conceptions may arise when students are presented with concepts in too few contexts or when concepts presented are beyond their developmental level (Gabel, 1989). Another source of confusion is the different meaning of common words in different subjects and in everyday use. Harrison and Treagust (1996) reported that students were confused between the nucleus of an atom and the nucleus of a cell, and that one student actually drew a cell for an atom. They also found students having alternative conceptions about electron clouds, and cautioned that teachers need to qualify the sense in which they transfer the attributes of the analog to the target. Many scientifically associated words are used differently in the vernacular (Gilbert & Watts, 1983), for example, energy has a cluster of ‘life-world’ associations that do not match its technical use (Solomon, 1992). Schmidt has pointed out how linguistic cues in scientific terminology may lead to inappropriate inferences being drawn (Schmidt, 1991). McDermott (1988) suggests that some alternative conceptions may arise from failure to integrate knowledge from different topics and from concept interference that comprises “situations where the correct application of a conception by students is hindered by their misuse of another concept that they have learned” (p. 539). This occurs when students do not have an adequate conceptual framework to know which concept to apply in a situation. Concept interference may also be due to set effects (Hashweh, 1986) where certain knowledge or conceptions are brought to mind due to strong ties with certain features of a given situation through previous experience. Taber (in press) has suggested that these effects may be compounded in chemistry by the rate at which learners meet new ideas that are then used as the basis for further learning: from a consideration of A-level students’ learning difficulties relating to orbital ideas he has suggested that learners may need time to consolidate new learning before it is robust enough to act as the foundations of further knowledge construction.

Teachers need to be aware that they also can be the sources of alternative conceptions. Teachers can unwittingly pass their own alternative conceptions to their students, and the way they teach, for instance, using imprecise terminology, can also cause confusion (Chang, 1999; De Jong, Acampo, & Verdonk, 1995; Gilbert, Osborne, & Fensham, 1982; Lee, 1999; Lenton & Turner, 1999; Lin, Cheng, & Lawrenz, 2000; Quilez & Solaz, 1995; Taylor & Coll, 1997; Wandersee et al., 1994; Willson & Williams, 1996). When teachers have the same alternative conceptions as their students (Wandersee et al., 1994), they think that there is nothing wrong with their students’ conceptions. Given the number of students taught over a teaching career, the generation of alternative conceptions can be quite significant. Teachers should realise that textbooks also can contain errors and misleading or conflicting illustrations and statements which can give rise to alternative conceptions (Boo, 1998; Cox, 1996; de Posada, 1999; Garnett, Garnett, & Treagust, 1990; Griffiths & Preston, 1992; Sanger & Greenbowe, 1999; Wandersee et al., 1994); hence, textbooks should not be regarded as infallible.

Teachers need to know their students' alternative conceptions in order to help them lower the status of these conceptions in favour of the accepted science concepts. Unfortunately teachers are often unaware of their students' alternative conceptions (Treagust et al., 1996), which is why Posner et al. (1982) maintain that teachers "should spend a substantial portion of their time diagnosing errors in thinking and identifying moves used by students to resist accommodation" (p. 226). However, Wandersee et al. (1994) contend that the large quantity of research on alternative conceptions, the format in which the studies have been reported, and the lack of access to the published studies make them virtually inaccessible to classroom teachers. In this context, Driver et al.'s 1994 book reviewing the literature for teachers, despite being 10 years old and limited to secondary level topics, remains a useful introduction to this area of work for classroom practitioners.

Scott et al. (1994), Wittrock (1994) and Ebenezer and Erickson (1996) believe that identifying and understanding student conceptions will advance the design of science teaching. Scott et al. (1994) argue that if the central focus of planning lessons was the comparison of students' conceptions with the accepted views of science, insights into the intellectual demands made on students would be more evident. They propose the useful notion of 'learning demand' as the difference between current conceptions and target understanding (Leach & Scott, 1995; Leach & Scott, 2002). The information obtained could be used to develop strategies to induce students' dissatisfaction with their alternative conceptions, and give them access to newer and better ideas which are intelligible, plausible and fruitful in offering new interpretations (Hewson, 1981; Posner et al., 1982).

ALTERNATIVE CONCEPTIONS OF IONISATION ENERGY

Chemistry is a difficult subject for most students because it involves "abstract and formal explanations of invisible interactions between particles at a molecular level" (Carr, 1984, p. 97). Studies have shown that students have alternative conceptions in many chemistry topics (e.g. Barker, 2000; Garnett, Garnett, & Hackling, 1995; Nakhleh, 1992). Taber (1999a) found that students had difficulty in understanding the principles determining the magnitude of ionisation energy. He administered his 'Truth about Ionisation Energy diagnostic instrument' to 110 first year A-level students in the UK to determine their understanding of ionisation energy. The instrument comprised thirty statements that were to be judged in terms of their veracity. Items were selected to reflect student comments in interviews, as well as target curricular principles. Several alternative conceptions he determined from the results were:

1. The sodium atom would be more stable if its 3s electron is removed.
2. If 3s electron of sodium is removed, it will not return because the sodium ion achieves a stable electronic configuration.
3. Only one electron can be removed from sodium because of the stable configuration of the sodium ion.
4. Sodium 7- ion (Na^{7-}) is more stable than the sodium atom.
5. Each proton attracts only one electron.
6. The attractive force available is shared between the electrons.
7. Once an electron is removed, the remaining electrons receive an extra share of the attraction from the nucleus.

Taber believes that the first four alternative conceptions arose because the students based their explanations on the octet rule/full shell framework (Taber, 1998b) – atoms try to gain full outermost shells or octets of electrons in the outermost shell, and only give them up, if at all, under extreme circumstances. He also argues that the students did not or could not apply basic electrostatic principles that they learned in physics to explain the interactions between the nucleus and electrons in an atom (alternative conceptions 5 to 7). In addition, students also adopted an alternative explanatory principle, the 'conservation of force' conception – that a charged body gave rise to a certain amount of force, which was available to be shared amongst oppositely charged bodies. They thought that an atom's electrons shared-out the attraction from its nuclear charge, so successive ionisations resulted in a greater share of the nuclear charge acting on each of the remaining electrons, resulting in increasing successive ionisation energies (alternative conceptions 6 and 7). Students also made use of the ‘conservation of force’ conception to explain why an anion has a greater size than its corresponding atom, and why the atom is larger than its cation (Taber, 1998a).

A-level students in Singapore need to explain the trend of ionisation energy across Periods 2 and 3, and down a group, in line with requirements of the A-level chemistry syllabus section on ionisation energy (Appendix A). For the first twenty elements, ionisation energy tends to decrease down a group and increase across a period. Down a group, although the nuclear charge is increasing, the amount of shielding of the ionising electron from the nuclear charge by the inner shell electrons is also increasing – so that the ‘core charge’ (Taber, 2002a) remains constant. In addition, the distance between the ionising electron and the nucleus is greater down a group, resulting in the decrease in the overall attraction of the nucleus for the ionising electron. Across a period, the increasing nuclear charge is accompanied only by a small increase in shielding as the number of inner shells is constant and the electrons in the same shell as the ionising electron are not effective in their shielding. The model usually presented at this level treats the electrons as if they are in concentric shells, so that shielding is only considered to occur due to electrons in the shells ‘nearer’ the nucleus. Thus, the net attraction between the ionising electron and the nucleus increases. Cann (2000) further explains that the shielding potential of the inner shells actually increases slight across the period because the increasing nuclear charge pulls inner shells closer to the nucleus, so the penetration by outer shell electrons is less effective. However, the increasing nuclear charge also pulls the outer shell inwards, bringing the electron to be removed in ionisation closer to the nucleus, and this outweighs the weaker penetration effect. It is usual at the level being considered, just to consider the latter point – that the electrons get closer to the nucleus across a period.

The increase in ionisation energy across a period is not a regular trend. Discontinuities occur between Groups II and III, and between Groups V and VI. The former is associated with the start of the occupancy of the np orbitals. The nodal plane of a p orbital passes through the nucleus, so there is zero probability of finding a p electron there. Hence electrons in the np orbital are more effectively shielded from the nuclear charge than are electrons in the ns orbitals, which have a significant positive electron density surrounding the nucleus (Cann, 2000). Three main explanations for the discontinuity between Groups V and VI found in textbooks (Cann, 2000) are, firstly, in a shell having more than half its complement of electrons, one (or more) orbitals will accommodate two electrons. These two electrons, sharing the same region of space, will experience an extra repulsion from each other over and above that experienced by electrons in separate orbitals. Secondly, because of the Pauli exclusion principle, electrons with parallel spins tend to avoid each other, thus decreasing the electrostatic repulsion between them. When electrons are forced to doubly occupy orbitals (pair up with opposite spins) in the second half, the electrostatic repulsion increases. This explanation is similar to the first explanation but involves a spin factor as well as a distance factor. The third reason given in books (e.g., Lee, 1977) is that half-filled (and also completely-filled) sub-shells of electrons have an intrinsic stability – an explanation that mirrors the popular, but ultimately impotent, arguments about full shells being inherently stable (Taber, 1998b) Cann (2000) argues that this reason offers no explanation in terms of electrostatic or quantum mechanical interactions within the atom. It is misleading in that it suggests that the interaction between electrons of the same spin stabilizes a system. Cann believes that pre-university students should be taught the first model (two electrons, sharing the same region of space, will experience an extra repulsion from each other over and above that experienced by electrons in separate orbitals) because it is easier for the students to understand, and for pre-university chemistry, its predictions are no less accurate than those of more sophisticated theories.

METHODOLOGIES FOR INVESTIGATING STUDENT CONCEPTIONS

This section discusses selected methodologies used in this study to define the content framework and investigate students’ conceptions in ionisation energy. Concept mapping was used to define the content framework of ionisation energy as an A-level topic. To investigate students’ conceptions of ionisation energy in this study, interviews and written tests were used. Interviews were used to collect data that were used to develop a two-tier multiple diagnostic instrument on ionisation energy. The diagnostic instrument was administered to A-level students to determine their understanding of ionisation energy.

Yarroch (1985), and Gabel and Bunce (1994) believe that the ability of a student to choose the correct answer or solve a problem does not indicate that the student has understood the concepts involved; more information is required to determine the nature of the knowledge that a student possesses. A variety of methods have been used to investigate students' understanding of concepts. These methods include clinical interviews, multiple-choice tests, concept mapping, sorting tasks, student drawings, and open-ended questions. The nature and uses of clinical interviews, multiple-choice tests and concept mapping are discussed in the following sections. Duit (1995), Duit, Treagust and Mansfield (1996), and Johnson and Gott (1996) warn that what researchers call students’ conceptions are actually their own conceptions about the students’ conceptions. As Gilbert and Watts (1983) have suggested, an ‘alternative conceptual framework’ is something presented in the public domain that is constructed by the researcher on the basis of data collected from a sample of learners. Thus, the researcher has to be aware of the pitfalls of investigating students’ conceptions. For example, students’ responses can be misinterpreted as their perspectives may be different from the researchers. Another danger is that researchers may read too much into the students’ responses and come up with interpretations which are far from the students’ own ideas. Thirdly, the students’ conceptions may be created by the study and not brought to light, that is, the students may never have thought about the concepts or phenomena before but had to invent something to answer the question or perform the task required by the researcher (cf. Piaget, 1973{1929}). Fourthly, students might give responses that they think the researcher expects and which are not their actual ideas. In addition, any data collected cannot be considered as “students’ unchanging views” (Duit et al., 1996, p. 21), but only as instances of conceptions at a given moment in time as construction and reconstruction of conceptions are ever on-going. Johnson and Gott (1996) propose the creation of a “neutral ground [in which] a largely (but never completely) undistorted communication takes place between the child and researcher” (p. 565). They believe that to develop a neutral ground, the tasks given must be neutral, interpretation must proceed in the neutral ground and that triangulation must be a priority.

The level of understanding of a given concept and the range of contexts in which the concept is expected to be used also must be specified in a study and agreed upon by the researchers and the teachers of the students involved (Hashweh, 1986). These specifications prevent the testing of any concept if it was not taught to the students, or if it was not the aim of the course to foster understanding of the concept at the level tested.

Concept mapping

Concept maps are intended to represent meaningful relationships between concepts in the form of propositions (Novak & Gowin, 1984). Propositions are two or more concepts linked by words describing the relationships between the concepts. Thus a concept map is a kind of visual map showing the relationships between the meanings of concepts in proposition. Novak and Gowin (1984) suggest that concept maps should be hierarchical, that is, the more general, more inclusive concepts should be at the top of the map with progressively more specific and less inclusive concepts arranged below. Related concepts are then linked by words describing their relationships.

Concepts maps have many uses – for example, in the planning of teaching or pedagogic research, or as revision and study aids. One use of concept maps, when students are asked to draw them for a topic, is to assess the extent and accuracy of student understanding of that topic. The number of valid concepts and propositions will indicate the amount of scientifically acceptable knowledge that a student has, the number of branching and hierarchies indicate the degree of conceptual differentiation and subsumption, while the number of cross-links suggest conceptual integration or cohesion (Markham & Mintzes, 1994).

Concept mapping is a process which has to be learned. Novak and Gowin (1984) give procedures for teaching students of various ages concept mapping. Students can be taught how to extract specific concepts from printed or oral material and identify relationships among the concepts before writing them down in the form of concept maps. This is just one approach as concept mapping can be introduced in a variety of ways (see Taber, 2002b). Students’ language ability is important for concept mapping, as without the appropriate vocabulary, the students may not be able to express their ideas logically (Kinchin, 2000). The maps must then be evaluated and redrawn, a few times if necessary, to correct errors, increase their meaningfulness and tidy them up. Thus a considerable amount of time will be taken up before the students are able to submit reasonable concept maps. However, students may not be willing to spend the time and effort necessary to produce well-constructed concept maps, especially if they are not worth the credit given (Markow & Lonning, 1998). The analysis of the students' concept maps if the maps are extensive, will also be time consuming as one has to look out for all the important concepts to determine if any are missing, and examine all the links and linking words to determine if they are valid.

Interviews

Interview methods, for example, interview-about-instances and interview-about-events (Carr, 1996; Osborne & Gilbert, 1980; White & Gunstone, 1992), are very useful for exposing the nature of students' understanding and possible alternative conceptions. An interview about an instance is a deep probe of the student's understanding of a single concept (White & Gunstone, 1992). It is a conversation that an expert has with one student, focused by initial questions about situations represented in a series of line diagrams that checks not only whether the student can recognise the presence of the concept in specific instances, but also whether the student can explain his or her decision. The quality of the student's understanding can be determined by his or her explanation. Interviews-about-events are similar probes though the emphasis is now on the student's interpretation of a natural phenomenon or social occurrence and his or her ability to explain it (White & Gunstone, 1992). Interviews also can involve the manipulation of concrete objects (Lazarowitz & Tamir, 1994; White & Gunstone, 1992), and students can be asked to explain the outcomes of their manipulations, for example, the results obtained when two chemical reagents are mixed.

Interviews can be structured, semi-structured or unstructured. In a structured interview, a series of questions, called a protocol, is prepared prior to the interview, and the interviewer has to follow rigidly the series of questions. In a semi-structured interview, the interviewer also follows a sequence of questions prepared beforehand, but he or she is allowed to probe the interviewee's answers with additional questions. In an unstructured interview, the interviewer asks open-ended questions, and based on the response given by the interviewee, more specific follow-up questions are asked to probe any point of interest. Carr (1996) believes that unstructured interviews are difficult to sustain and are confrontational for interviewees, so the interviewer must have a set of questions in mind for use when necessary.

Interviews are highly flexible because they allow the interviewer to change his or her mode of questioning when required; the interviewer can rephrase the questions if the interviewee does not understand the questions, and he or she can probe any response to obtain clarification and elaboration from the interviewee. Thus, the interview allows the interviewer to probe the interviewee's ideas in as much detail as desired (Taber, 1998a). The interview situation also allows the interviewee to ask questions, for example, to clarify perceived or actual ambiguities before attempting to answer a question (Osborne & Gilbert, 1980). An advantage that interviews have over written answers is that students "cannot easily ignore a question and give no answer, or omit to give a reason for an answer, or simply produce an answer by guessing" (Osborne & Gilbert, 1980, p. 318). However, as Duit et al. (1996) point out, much experience is needed to carry out interviews effectively and much background knowledge is needed to make valid interpretations of students' responses. Thus, classroom teachers are not likely to conduct interviews, especially when they have limited time and high enrolments (Treagust, 1995). In addition, many teachers are not trained to prepare for and conduct interviews, record and transcribe interview data, or to interpret findings (Fensham, Garrard & West, 1981). Teachers also may have difficulty in "moving from Socratic teaching, where they helped individuals understand the ideas being probed, to non-cuing, probing interviewing" (Novak & Musonda, 1991, p. 124), and may turn interviews into an oral examination instead of encouraging dialogue (Osborne & Gilbert, 1980), or may have difficulty in refraining from comment or teaching when the student says something wrong (White & Gunstone, 1992). In addition, if the interviewer is also the teacher of the interviewee, the interviewee may be reluctant to voice negative opinions (Markow & Lonning, 1998). Thus, the interviewer has an ethical responsibility to ensure the interview is beneficial to the student, or - at least - not abusing the teacher-student power relationship (Taber, 2002c).

Multiple-choice tests

Multiple-choice tests have been used for measuring students' understanding of concepts as they enable a large number of students to be sampled in a given amount of time as compared to time-consuming interviews. These tests are also easy to administer and score, and the results obtained are also easily processed and analysed (Peterson, Treagust, & Garnett, 1989; Taber, 1999a; Tan & Treagust, 1999). Researchers such as Doran (1972), Halloun and Hestenes (1985), Peterson et al., (1989), Tamir (1971), Taber (1997a,b, 1999a), and Voska and Heikkinen (2000) have used multiple-choice tests to determine students' conceptions in science. However, there are problems associated with the pencil-and-paper tests. For example, multiple-choice tests "make some demands on the reading/comprehension skills of the respondents" (Taber, 1999a, p. 99), and students do not "always perceive and interpret test statements in the way that test designers intend" (Hodson, 1993, p. 97). Since they have little recourse for clarification, misunderstandings do occur and this affects the validity and reliability of the tests. Bar and Travis (1991) warned that students could be induced to choose distractors that appear 'scientific'; they conducted a study of phase changes using three formats, an oral test, multiple-choice questions and open-ended written questions, and found that the apparently more scientific alternative conceptions detected in the multiple-choice questions were rarely brought up in the two other test formats. Taber (1999a) cautioned that only the most common alternatives were likely to be diagnosed as the test writer would have to leave out the less common ones (as suggested by previous research) to avoid too many distractors.

Students' test-wiseness skills may affect the validity and reliability of the test (Towns & Robinson, 1993). Strategies such as time-management, error avoidance, checking responses and elimination of incorrect answers do not damage the validity and reliability of a test, while strategies that take "advantage of consistent idiosyncrasies of the test constructor such as grammatical agreement, length of response, location of response, and previous emphases of the test constructor" (Towns & Robinson, 1993, p. 710) do. Guessing, when students do not know the answer, is also a problem in multiple-choice tests. However, Tamir (1990) expressed his opinion that if a test consisted of cognitively high level items, students should be advised to attempt all items, making educated guesses where necessary, for example, by narrowing down the possible choices through the elimination of incorrect or absurd responses (Towns & Robinson, 1993).

Treagust (1986, 1988, 1995) and Tamir (1990) state that the development of multiple-choice tests on student conceptions has the potential to make a valuable contribution to the body of work in the area of students' conceptions, and to enable classroom teachers to more readily use the findings of research in their lessons. Ben-Zvi and Hofstein (1996) believe that research in student conceptions has had only limited impact on teaching and learning in schools, one of the reasons being teachers' unawareness of the learning difficulties and alternative conceptions that exist among their students. Thus, teachers could use such tests as a tool to diagnose student conceptions, and steps could then be taken to help students see that the science concepts make more sense than their conceptions, hence increasing the status of the science concepts (Hewson, 1996). Classroom discussion of the items in such diagnostic tests provides a means of challenging alternative conceptions as “students are often well-motivated to know the ‘right’ answers after they have completed such an activity” (Taber, 1999a, p. 97).

Tamir (1971) pioneered the use of tests derived from a specified and limited content area, as well as the use of distracters which were based on students' answers to essay questions and other open-ended questions, in the multiple-choice items. He believes that normal multiple-choice items tend to overestimate students’ knowledge as students may not be able to explain adequately their choices (Tamir, 1990). He suggests that students should be made to justify their choices in the multiple-choice items so that more information can be obtained on the students’ knowledge. Incorrect justifications could also provide “a rich source of students’ misconceptions” (Tamir, 1990, p. 572) and justification analysis could provide “raw material for the construction of effective diagnostic two-tier multiple-choice items” (p. 573).

Treagust (1995) describes how two-tier multiple-choice diagnostic instruments can identify and be used to evaluate student conceptions in specific content areas; the first-tier choices examine factual knowledge while the second-tier choices examine the reasons behind the first-tier ones. To ensure the validity of the diagnostic instrument, the propositional knowledge is to be specified clearly. The items in the instrument are to be developed based on known student conceptions, student-drawn concept maps and responses from students to interviews and free response items. This methodology has been used to develop diagnostic tests on photosynthesis and respiration (Haslam & Treagust, 1987), and diffusion and osmosis (Odom & Barrow, 1995) in biology; in chemistry, diagnostic instruments were developed for covalent bonding (Peterson & Treagust, 1989; Peterson et al., 1989), chemical bonding (Tan & Treagust, 1999), chemical equilibrium (Tyson, Treagust, & Bucat, 1999), and qualitative analysis (Tan et al., 2002).

Voska and Heikkinen (2000) noted that two-tier tests had the disadvantage of detecting far fewer conceptions than students might actually possess within a content domain and that a multiple-choice test in which students had to supply their reasons for their choices could detect more alternative conceptions. They, however, did also acknowledge that the use of such approach within large classes was not feasible, and that the teacher's analysis and interpretation of results might be fraught with errors unless supported by formal training and complemented by the benefit of information from student interviews. Thus, the selection of a multiple-choice test with free response justification or a two-tier multiple-choice test depends on the goal of the researcher or teacher in using the test.

SUMMARY

In the literature review, the nature of alternative conceptions, studies of students' conceptions in ionisation energy, and methodologies for investigating students' conceptions have been described. These provided the theoretical and methodological framework for this study on A-level students' understanding of ionisation energy. All findings pertaining to this study are discussed in Chapters Three, Four, Five and Six.

CHAPTER THREE

IDENTIFICATION OF CONCEPTS AND PROPOSITIONAL STATEMENTS

INTRODUCTION

This chapter describes the development of the content framework in response to research question 1 (i.e., what are the concepts and propositional knowledge necessary for A-level chemistry students to understand the topic of ionisation energy). A sound starting point for the teaching and learning of a difficult chemistry topic such as ionisation energy would be the clarification of the content framework that is required for the topic (Taber, 2002b; Tan, 2002).

Taber (2003a) argues that a teacher needs to undertake a content analysis when preparing to teach a complex subject in order to determine the relationship between the relevant concepts and so the logical order in which the concepts should be presented. Content analysis helps teachers not to underestimate the complexity a topic may seem to have to the learner – "assuming too much prior learning, or not allowing enough time to process the complexity of the new information" (Taber, 2003a, p. 153). It is useful to start the process of translating a scheme of work or examination specification into lesson plans (or assessment objectives) by undertaking a thorough 'content analysis' that involves both breaking each idea down to see how it is explained in terms of other more fundamental ideas (the analytical aspect), and then identifying all the links between aspects of the topic (the synthetic aspect) (Taber, 2002b; Kind & Taber, in press).

A concept map and a list of propositional knowledge statements were prepared at a level of sophistication appropriate to the understanding required by Grade 11 and 12 students for the A-Level chemistry examinations. The assessment of the mastery of the content would then be administered in accordance to this framework and this would ensure the content validity of the assessment. The list of propositional knowledge statements (i.e. the analytical aspect of the analysis) helps to make explicit the pre-requisite knowledge that students had encountered during previous learning (for example, from less advanced levels of chemistry, previous topics or even other subjects), and highlights the essential concepts of the topic; and the concept map (i.e. the synthetic part of the analysis) shows how these concepts are linked to each other.

IDENTIFICATION OF SUBJECT CONTENT

Three procedures were used to limit and specify the subject content related to the topic, ionisation energy. The steps were:

1. identify the propositional knowledge,
2. develop a concept map,
3. relate the propositional knowledge to the concept map.

The three steps were necessary to ensure that the content and hence the determination of students' understanding of the content knowledge was based on the concepts and propositional knowledge which were required for the A-level chemistry examinations. The list of propositional knowledge statements (Figure 3.1) written and concept map (Figure 3.2) drawn for the content and concepts relevant to the topic of ionisation energy taught in Singapore schools were based on the Taber's (1997b, 1999a) work, an extract of the sections of the A-level chemistry syllabus relevant to ionisation energy (Appendix A), and two chemistry textbooks. The concept map and propositional knowledge were reviewed by 13 experienced A-level chemistry teachers and two tertiary chemistry educators. The reviewers agreed that the concept map and propositional knowledge statements met the requirements of A-level chemistry syllabus on ionisation energy (Appendix A) in terms of accuracy and relevance.

To ensure the list of propositional knowledge statements and the concept map were internally consistent, a matching of the propositional knowledge statements to the concept map was carried out. The matching is shown in Figure 3.3.

Figure 3.1: Propositional knowledge statements for ionisation energy

1. Electrical charge exists in two forms called positive and negative.
2. Oppositely charged particles attract each other.
3. Similarly charged particles repel each other.
4. An atom consists of a nucleus and one or more electrons.
5. An electron has a negative charge.
6. The magnitude of charge on any electron is the same.
7. The nucleus contains one or more protons.
8. A proton has a positive charge.
9. The magnitude of charge on any proton is the same.
10. The magnitude of charge on a proton and an electron is the same.
11. The force between two charged particles acts (with equal magnitude) on both charged particles.
12. The force between two charged particles increases with the magnitudes of the charged particles.
13. The force between two charged particles decreases as the distance between the charged particles increases.
14. The nucleus may contain none, one or more neutrons.
15. A neutron has no charge (is neutral).
16. An atom has a zero net charge (is neutral).
17. An atom contains equal numbers of protons and electrons.
18. An ion contains unequal numbers of protons and electrons
19. If an atom loses electrons, it becomes a positively charged ion.
20. If an atom gains electrons, it becomes a negatively charged ion.
21. The nucleus is located at the centre of the atom.
22. The electrons occupy one or more shells surrounding the nucleus.
23. Electron shells are filled starting with the first quantum shell, then the second quantum shell, third and so forth.
24. The sub-shells of each electron shell are filled starting with the s (lowest energy), p and then d orbitals.
25. The first quantum shell has only an s orbital, the second quantum shell has only s and p orbitals, and the third shell has s, p and d orbitals.

Figure 3.1 (continued): Propositional knowledge statements for ionisation energy

26. Each s sub-shell consists of 1 orbital, each p sub-shell consists of 3 orbitals, and each d sub-shell consists of 5 orbitals.
27. Each orbital can accommodate a maximum of 2 electrons which must be in opposite spin.
28. Electrons will fill orbitals within the same sub-shell, singly first with parallel spins, then will they form electron pairs with opposite spins.
29. Electrons go to the 4s orbitals of the nineteenth and twentieth elements, potassium and calcium, after the 3p orbitals are filled as their 4s orbitals are of lower energy than their 3d orbitals.
30. The periodic table is related to the electronic structure of elements as follows.

30a. The atoms of the elements in Period 1 only have electrons in the first shell.

30b. The atoms of the elements in Period 2 have electrons in the first two shells.

30c. The atoms of the elements in Period 3 have electrons in the first three shells.

30d. The atoms of the elements in Group I have one electron in the outermost (occupied) shell.

30e. The atoms of the elements in Group II have two electrons in the outermost (occupied) shell.

30f. The atoms of the elements in Group III have three electrons in the outermost (occupied) shell.

30g. The atoms of the elements in Group IV have four electrons in the outermost (occupied) shell.

30h. The atoms of the elements in Group V have five electrons in the outermost (occupied) shell.

30i. The atoms of the elements in Group VI have six electrons in the outermost (occupied) shell.

30j. The atoms of the elements in Group VII have seven electrons in the outermost (occupied) shell.

30k. The atoms of the elements in Group 0 have eight electrons in the outermost (occupied) shell, except helium which has a completely filled shell of two electrons only.

Figure 3.1 (continued): Propositional knowledge statements for ionisation energy

31. The ionisation energy is the energy required to remove electrons from an isolated gaseous atom/ion.

31a. The first ionisation energy is the energy required to remove the first electron in the outermost shell of each atom in 1 mole of isolated gaseous atoms.

32. The ionisation energy depends mainly on the nuclear charge, the distance of the electrons from the nucleus, and the screening effect of the inner shell electrons.

33. The number of valence electrons that an atom has can be determined by the trend in successive ionisation energies of the atom.

34. The first ionisation energy generally increases across the first three periods due to increasing nuclear charge of the elements in the period. The exceptions are:

34a. The first ionisation energy of beryllium is higher than that of boron. This is because the 2p electron has a lower penetrating power than the 2s electrons and therefore is more shielded from the nucleus than the 2s electrons, outweighing the increase in nuclear charge. A similar reason explains the higher first ionisation energy of magnesium compared to that of aluminium.

34b. The first ionisation energy of nitrogen is higher than that of oxygen. This is because mutual repulsion between the paired electrons in one of the 2p orbitals of oxygen outweighs the increase in nuclear charge. A similar reason explains the higher first ionisation energy of phosphorus compared to that of sulphur.

35. The first ionisation energy decreases down a group as the effect of increasing distance of the outermost electrons from the nucleus and shielding effect of the inner shells of electrons are greater than the effect of increasing nuclear charge.

36. An isolated atom will not spontaneously lose electron(s) unless energy is supplied to it. For example, a sodium atom will not spontaneously lose an electron to form the sodium ion Na^+ unless energy is supplied to it.

Figure 3.2. Concept map of ionisation energy

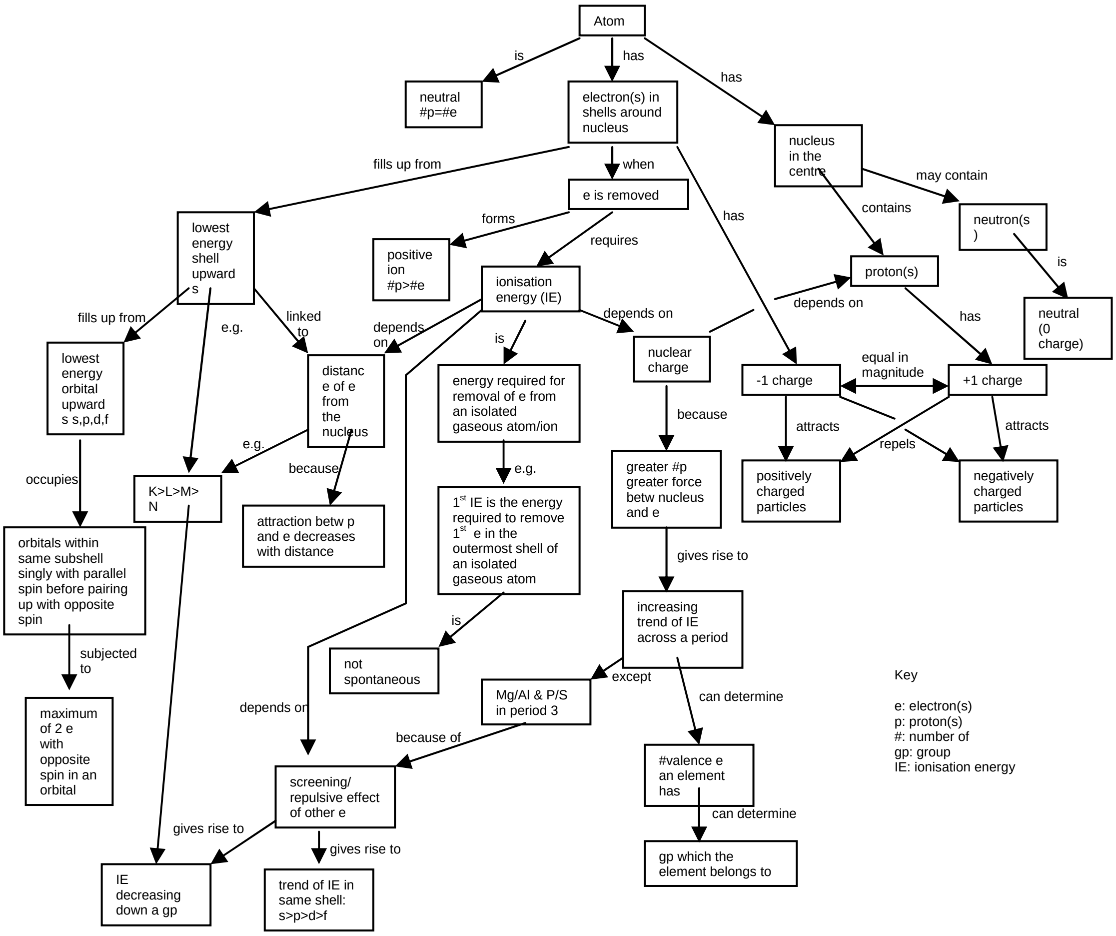
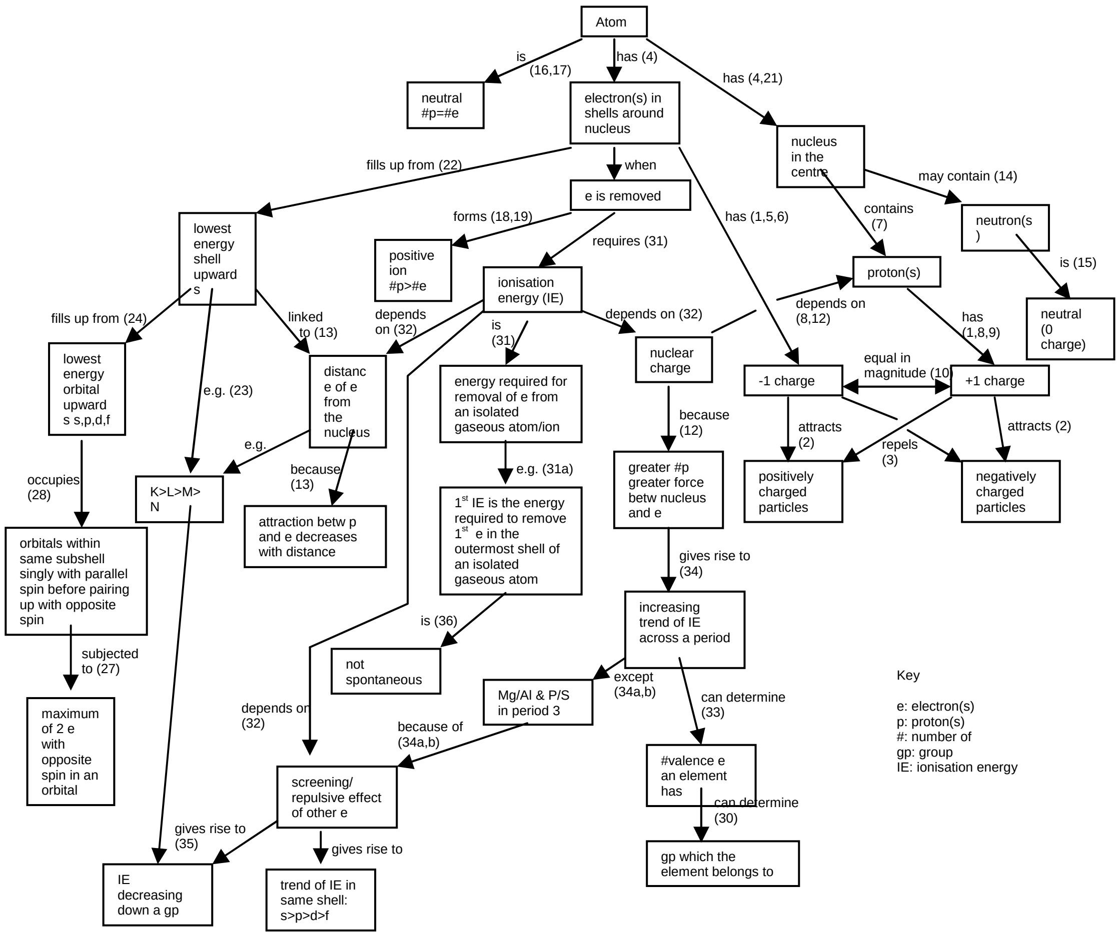


Figure 3.3 Matching of propositional knowledge statements with concept map



SUMMARY

In this chapter, the concepts and propositional knowledge statements that A-level students need in order to develop an understanding of the topic, ionisation energy, were described by a concept map and a list of propositional knowledge statements. A matching of the propositional knowledge statements to the concept map also was carried out to ensure that they were internally consistent. Thus, the chapter has defined the conceptual boundaries of the A-Level requirements of the topic, ionisation energy, and this addressed Research Question 1. Chapters Four and Five document the identification of the various alternative conceptions within the defined conceptual boundaries.

CHAPTER FOUR

PHASE ONE: DEVELOPMENT AND ADMINISTRATION OF A FREE RESPONSE INSTRUMENT ON IONISATION ENERGY

INTRODUCTION

A review of the literature (as reported in Chapter Two) was conducted to determine known student knowledge, alternative conceptions and difficulties relevant to ionisation energy. The concept map and propositional knowledge statements presented in Chapter Three provided the framework for the development of a written test instrument to diagnose A-level students' understanding and alternative conceptions of ionisation energy. This chapter addresses Research Questions 2 and 3 which focus on the development of a diagnostic instrument on ionisation energy and what students understand about the concepts and propositional knowledge related to ionisation energy:

2. How can a two-tier multiple-choice diagnostic instrument which is consistent with the identified concepts, propositional knowledge and known student alternative conceptions related to ionisation energy be developed?
3. What do A-level chemistry students in Singapore understand about the concepts and propositional knowledge related to ionisation energy?

Phase One was carried out in three stages. In Stage 1, a justification multiple-choice instrument, in which students had to supply reasons for their choice of options, was developed based on the propositional knowledge statements on ionisation energy and the findings of Taber's (1999a, 2000a) research. The items in the instrument tested students' understanding of the factors influencing ionisation energy as well as the trend of ionisation energy across a period. This instrument was administered to 18 Grade 11 students after they were taught ionisation energy. Another six Grade 11 students were interviewed in pairs using the instrument as the interview protocol. The results obtained led to the development of the second version of the justification multiple-choice instrument which was administered to 146 Grade 11 and 12 students from four schools in Stage 2 of the study. The results obtained from the Stage 2 study guided the development of the third version of the justification multiple-choice instrument (Appendix B). Four A-level chemistry teachers reviewed this version of the justification multiple-choice instrument and agreed that the items were consistent with the requirements of the A-level syllabus in terms of ionisation energy.

In Stage 3, the third version justification multiple-choice instrument (Appendix B) was administered to 130 Grade 12 students from three schools. Eleven Grade 12 students who took the test were interviewed using the instrument as the interview protocol to determine whether any item was ambiguous and to probe the reasons for their answers. Six of them were interviewed in groups of three, four in pairs and one individually to cater to their availability for the interviews. The interviews lasted between 30 to 60 minutes, were semi-structured and transcribed verbatim. Data obtained in the Stage 3 study and from the interviews in Stage 1 are discussed in the following section.

RESULTS AND DISCUSSION

Student responses to the multiple-choice component of the items are given in Table 4.1. The number and percentage of students who provided a reason for their choices in each item are given in Table 2. It can be seen from Table 4.2 that not all students supported their choices with reason – more than 20% of the students did not give reasons to their answers for items 2, 3, 7, 8, 9 10 and 11. The students were told, quite explicitly, by their teachers that they should give reasons for their answers, and this was also made obvious by the space given for each item in the instrument. As items 2 and 3 appeared early in the instrument, it seemed likely that students left the justification part blank because they did not know or could not verbalise their reasons rather than not having enough time to finish writing their answers. However, the percentage of students not providing reasons increased steadily for the last six items, and it was not certain whether it was due to the lack of understanding of the trend of ionisation energy across Period 3 or to time constraints; the teachers were advised to allow students 45 to 60 minutes to complete the instrument. It is also possible that there was an issue of student fatigue – the original 30-item version of Taber's (1999a) original probe (with more items, but no requirement for justifying answers) was republished in diagnostic materials disseminated to UK schools (Taber, 2002b) as a 20-item version after feedback from teachers, who felt that student found answering many similar items tiresome. Voska and Heikkinen (2000) also used justification multiple-choice items in their study of students' conceptions of chemical equilibrium, but did not report any problem with students not supplying reasons for their answers. Students' conceptions of ionisation energy are discussed under three main headings, octet rule framework, conservation of force thinking and relational based thinking (Driver et al., 1996).

Octet rule framework

Thirty-nine students (30% - figure in normal print indicates percentage students who chose a given option out of 130 students, i.e. 39/130) in item 2 indicated that a sodium ion (Na^+) would not combine with an electron to reform the sodium atom, with 21 students (*62%* - figure in italics indicates percentage of students who actually stated reasons for choosing a particular option over those who chose the option, i.e. 21/34) giving reasons to the effect that the sodium ion was already in a stable octet configuration and would not want to gain an electron to form the relatively unstable sodium atom. Given below is an example of the justification given by students:

> Sodium ion has a noble gas electronic configuration, so it has no tendency to gain an electron and lose its stability.

The removal of an electron from the sodium atom leaves an electronic configuration which is isoelectronic with neon, but it requires energy to ionise the atom as the isolated negative electron and the positive cation formed would be attracted back together. Thus, the system of gaseous sodium ion and separated electron would be in a higher energy state compared to the gaseous sodium atom. However, in item 4, 101 students (78%) indicated that the gaseous sodium ion is more stable than the gaseous sodium atom, with 85 students (*93%*) stating to the effect that the sodium ion had an octet/noble gas/full valence shell configuration so it was more stable than the sodium atom. An example of a student's justification is as follows:

> This is because Na^+ has obtained noble gas configuration. The Na atom is an active, unstable metal. It has one lone valence electron in its outer shell, ready to donate it away.

Table 4.1: Students' responses to the multiple-choice components of the items (n=130)

Item	A	B	C	D	Sub-total	No response
	Option					
1	1	**128***	1	-	130	0
2	39	**80***	10	-	129	1
3	79	**34***	15	-	128	2
4	101	**24***	4	-	129	1
5	**118***	4	7	1	130	0
6	59	**66***	4	1	130	0
7	**101***	22	1	5	129	1
8	79	**43***	1	5	128	2
9	40	**80***	5	4	129	1
10	**85***	37	3	5	130	0
11	54	**60***	6	10	130	0

Note: Figures in bold and with an asterix represent the number of students choosing the correct answer for each question

Table 4.2: Number and percentage of students who provided a reason for the option chosen for each item

	Option			Number of
Item	A	B	C	students
1	1 (*100*)[1]	120 (*94*)	-	121 (*93*)[2]
2	34 (*87*)	52 (*65*)	-	86 (*72*)
3	54 (*68*)	19 (*56*)	-	73 (*64*)
4	91 (*90*)	20 (*83*)	-	111 (*89*)
5	102 (*86*)	2 (*50*)	2 (*29*)	106 (*82*)
6	46 (*78*)	55 (*83*)	4 (*100*)	105 (*81*)
7	81(*80*)	15 (*68*)	1 (*100*)	97 (*78*)
8	60 (*76*)	27 (*63*)	1 (*100*)	87 (*70*)
9	22 (*55*)	57 (*71*)	4 (*80*)	83 (*66*)
10	60 (*71*)	19 (*51*)	2 (*67*)	81 (*65*)
11	30 (*56*)	35 (*58*)	2 (*33*)	67 (*56*)

Notes:

1: The total number of students used in the calculation of percentage is the number of students who chose a given option in an item (obtained from the corresponding position in Table 1). This number excludes students who did not respond to an item and those who indicated that they did not know the answer.

2: The total number of students used in the calculation of the percentage is the number of students who chose an option for the item. This number excludes students who did not respond to an item and those who indicated that they did not know the answer.

Students also gave similar reasons during interviews, as illustrated below:

I: Why do you say it's more stable?
S17: Because Na^+ has…
S16: Octet structure.
S17: Yes…we learn that if it is completely filled, it's more stable.
I denotes the interviewer; S16 and S17 denote students 16 and 17.

In item 5, 16 students (*16%*) stated that a larger amount of energy is required to remove the second electron of sodium because this would disrupt the stable octet/noble gas configuration of the sodium ion. These students, though they had chosen the correct option, supported it with an incorrect reason. In item 6, seven students (*13%*) who correctly stated that magnesium would have a higher first ionisation energy than sodium gave the reason that the sodium atom had only one electron in the outermost shell, so the electron could be easily removed for the sodium ion would then attain a stable octet configuration. Four students (*15%*) who responded that sodium would have a lower first ionisation energy compared to aluminium in item 8 gave a similar reason.

The findings above reflect the results obtained by Taber (1999a). In his study, Taber found that 53 out of 110 A-level students (16 to 19 years old) believed that the "sodium atom would not be considered as stable as it does not have a full outer shell" (p. 101). He also found that a third of the students indicated that only one electron could be removed from the sodium atom as it then had a stable configuration. This was despite the fact that the students had studied patterns in successive ionisation energy. Taber (1997a, 1999a, 2000a) further investigated the octet rule framework by asking different groups of students to judge which was the more stable species, the sodium anion (Na^{7-}) or the sodium atom. The majority of the students responded that the sodium anion was more stable than the atom - a result later replicated, and extended to other examples such as the ions C^{4+} and C^{4-} which were judged more stable than a neutral carbon atom (Taber, 2002b). When a group of 38 UK post-graduate trainee science teachers undertook the probe most (26/38, i.e. 68%) thought that the sodium cation (Na^+) was more stable than the atom, and a noteworthy minority (15/38, i.e. 39%) believed that the anion (Na^{7-}) was more stable than the neutral atom (Taber, 2000b). A group of 114 trainee chemistry teachers in Singapore were asked the same question and it was found that about 50% of them ranked the sodium cation, followed by the sodium anion and finally the sodium atom in order of decreasing stability. Thus, the octet rule framework seemed to be common among students and even among trainee-teachers.

Fully-filled and half-filled sub-shells

An alternative conception that is related to the octet rule framework is that species with fully-filled or half-filled sub-shells are more stable than those without such electronic configurations. For example, in item 6, 11 students (*20%*) indicated that the first ionisation energy of magnesium was greater than that of sodium because magnesium has a stable fully-filled 3s sub-shell. In the curriculum model, the reason for the higher first ionisation energy of magnesium is that the increase in nuclear charge in the magnesium atom (12 protons in magnesium compared to 11 in sodium) outweighs the repulsion between the two electrons in the 3s sub-shell. However, these students seemed to believe that the higher ionisation energy was solely due to stability resulting from the filling of the 3s sub-shell; to disrupt the stable fully-filled 3s sub-shell configuration would require additional energy. Six students (*7%*) invoked the same reasoning to explain why the first ionisation energy of magnesium was higher than that of aluminium. One student looked at it in another way and said that aluminium would have a lower first ionisation energy because it would achieve a stable fully-filled 3s sub-shell if it loses its 3p electron. The students did not realize that the screening of the 3p electron of aluminium or the diffuse character of the 3p orbital outweighs the increase in nuclear charge of aluminium compared to magnesium resulting in the lower first ionisation energy of aluminium.

A number of students exhibited ‘stable half-filled sub-shell’ thinking in items 9, 10 and 11. For example, 12 students (*21%*) in item 9 and 5 students (*10%*) in item 10 stated that phosphorus has a higher first ionisation energy than silicon or sulphur because the 3p sub-shell of phosphorus was half-filled, hence more stable. They did not consider the higher nuclear charge of phosphorus compared to silicon, or the effect of the repulsion of paired electrons in one of the 3p orbitals of sulphur. Examples of the reasons given by the students include:

> Removal of an electron from a partially filled sub-shell is easier than the removal from a half-filled sub-shell because of its increased stability for half-filled sub-shells.
>
> Though sulphur has greater proton number, but because the electron to be removed from phosphorus is part of the half-filled sub-shell. Hence more difficult to be removed than sulphur.

An extract of an interview provided a similar reason:

> S17: I think silicon and phosphorus I will agree that the IE (ionisation energy) for silicon is lower…in other words the IE for phosphorus is higher because if you remove electrons from the $3p^3$ you are disturbing the…I think first you are disturbing the stable structure of the half-filled [sub-shells] and also second because of the nuclear charge of phosphorus is higher than that of silicon so should be phosphorus higher silicon lower.

Student 17 knew that the nuclear charge of phosphorus was greater than silicon but she also placed importance on 'disturbing the stable structure of the half-filled (sub-shell)'.

On the other hand, a small number of students (2 in item 10 and 1 in item 11) stated that sulphur had a lower first ionisation energy than phosphorus or silicon because it would readily lose one electron to attain a half-filled 3p sub-shell.

Conservation of force thinking

In item 3, 79 students (61%) agreed with the statement that the attraction of the nucleus for the 'lost' electron would be redistributed among the remaining electrons in the sodium ion. This result is similar to that obtained by Taber (1999a). A reason given by 29 of them (*54%*) was that since the same number of protons was attracting one less electron, the remaining electrons in the sodium ion would experience a greater attraction from the nucleus. An example of a student' written reason and an extract of an interview illustrating the conservation of force thinking are given below:

> Initially, the number of electrons and protons are equal. When one electron is removed, there is one more proton than electron. Thus, the attraction of the nucleus will be more and it will be redistributed.

> S4: Because the number of protons remain the same but the number of electrons has decreased…so it's like there is a greater charge, a greater positive charge…attracting a less…I mean a smaller negative charge…so it would attract it even closer.
> I: Yes…
> S4: Yes it would attract it even closer so it…it redistribute like…the total amount of…positive charge will attract the total amount of negative charge left after one electron has been removed.

In item 5, 21 students (*21%*) who agreed that the second ionisation energy of sodium was greater than the first, gave the reason that force of attraction per electron has increased with the earlier loss of an electron. This is illustrated by the following comments by students:

> The ratio of nuclear charge per electron will have increased, hence more energy is needed to remove the consecutive electrons from the Na^+ ion.

> The same amount of protons is pulling a lesser amount of electrons so the attraction on the remaining electrons is stronger.

Thus, in addition to the octet rule framework, students also use the conservation of force thinking to explain, in item 5, why the second ionisation energy of sodium is greater than the first.

A variation of the conservation of force thinking was seen in item 6 where eight students (*17%*) stated that the attraction of the 3s electron by the nucleus in sodium was stronger than the attraction of the two 3s electrons by the magnesium nucleus. This is illustrated by the following justification:

> In the sodium atom, it has only 1 valence electron compared to the 2 in magnesium atom. Hence, the average force of attraction exerted on the 2 valence electrons of magnesium is less than that of the one electron of sodium. Thus the electron of sodium is more difficult to remove.

The students seemed to ignore the increase in nuclear charge in magnesium compared to sodium. This overlooking of the effect of nuclear charge will be further discussed in the following section.

Relation-based reasoning

In the curriculum model, factors influencing ionisation energy include the nuclear charge, the distance of the electron from the nucleus and the repulsion/screening effect of the other electrons present. The results from items on the trend of the first ionisation energy across Period 3 showed that students did not consider all the three factors simultaneously, but based their reasons exclusively on one or two factors. Driver et al. (1996) describe this type of thinking as relation-based reasoning. For example, in item 6, 29 students (*63%*) stated that the first ionisation energy of sodium was greater than magnesium because the 3s electrons in magnesium were paired up and experience inter-electronic repulsion – this was opposite to the stable fully-filled sub-shell conception. It is true that there is repulsion between the 3s electrons of magnesium, but in this situation, the effect of an increase in nuclear charge in magnesium outweighs the repulsion between the two 3s electrons. In addition, the spherical nature of the 3s orbital also allows the electrons to penetrate the screening effect of the inner shell electrons.

Many students also neglected the effect of nuclear charge when they gave the reason for ionisation energy decreasing across a period. These students believed that the more electrons an atom has, the further away the electrons are from the nucleus, or the greater the repulsion between the electrons. For example, 34 students (*57%*) stated in item 8 that sodium had a higher first ionisation energy than aluminium because the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium. Similar reasons were cited by students in items 6, 7, 9, 10 and 11 to justify why the first ionisation energy of the element with the smaller number of electrons was higher than that of the element with the larger number of electrons. The following extract of an interview further illustrates the thinking on ‘the more electrons an atom has, the further away the outermost electrons are’:

> S2: I don’t know…because…they contain more electron then they will be bigger then…and then if it’s further away then attraction forces will be smaller…for the outside electrons…so the ionisation energy…in order to move the…electron will be…smaller…because this bigger…size.

A smaller number of students focused only on the nuclear charge and ignored the repulsion/screening effects of the other electrons in an atom. For example, four students (*27%*) stated that aluminium had a higher first ionisation energy than magnesium because it had a higher nuclear charge – they neglected the shielding of the 3p electron of aluminium by the 3s electrons. A similar reason was given by eight students (*42%*) in item 10 to explain why they believed that sulphur had a higher first ionisation energy than phosphorus. Again, the students neglected the repulsion between the paired 3p electrons in sulphur.

Students holding manifold conceptions

Students’ alternative conceptions were not mutually exclusive; often their explanations contained two or more alternative conceptions (cf. Taber, 2000c). Their explanations could also include the correct conceptions as well as alternative conceptions. These are illustrated by the following student’s written justification and two extracts of interviews:

> The 1st electron removed from Al is in 3p orbital, which is furthest from the nucleus, so IE is least. There is a repulsion force in 3s orbital in Mg, so 1st IE of Mg is less than that of Na.

> S13: I’ll start with aluminium…first IE the electron is in the 3p orbital…further away from the nucleus…better shielding effect…and…yah further away from nucleus so less attraction plus better shielding effect from the inner electrons…so first IE the lowest…secondly magnesium…from 3s orbital…I mean the first

IE…so the…the first IE for magnesium lower than sodium because the electron in the 3s orbital is paired…so creates more inter-electronic repulsion…so first IE is lower…sodium is highest…higher than the rest.

S16: First ionisation of sodium is less than that of aluminium…I think two things come into play, the nuclear charge…the attraction from the nuclear charge to the electron…aluminium has got more protons…so there is a stronger attraction for aluminium but when you …ok again if you remove the outermost electrons from sodium you result in that noble gas structure thing.

I: Ok…so two factors explain why aluminium has a higher ionisation energy than sodium.

S16: Yes…aluminium even though you have $3s^2$ (after it loses an electron), it's fully-filled but it's not as stable as getting a noble gas structure.

In the second version of the justification multiple-choice instrument, students were asked to compare the first ionisation energy of sodium, magnesium and aluminium in one question, and that of silicon, phosphorus and sulphur in another question. Therefore, students had to provide three explanations, for example, why magnesium had a higher first ionisation energy than sodium and aluminium, and why aluminium had a higher first ionisation energy than sodium. It was found that many students, who provided justifications, only explained one or two of the comparisons. Thus, in the third version, the comparisons were each spread over three items, 6, 7 and 8, and 9, 10 and 11. However, students were still instructed to compare the two sets of three elements during interviews (as in the interview extract above), as the interviewer could ask them to explain further if they left out any comparison.

SUMMARY

The results from the administration of the justification multiple-choice instrument on ionisation energy and the interviews with students described in this chapter agreed with many of the research findings on ionisation energy by Taber (1999a, 2000a) in the United Kingdom. It seemed that the A-level students in Singapore and the United

Kingdom had very similar alternative conceptions. The Phase One study also highlighted another area of student difficulty in ionisation energy, that is, the anomaly in the trend of ionisation energy across Period 3. The results from the Phase One study contributed to the development of a two-tier multiple-choice diagnostic instrument on ionisation energy in Phase Two, which is described in the Chapter Five.

CHAPTER FIVE

PHASE TWO: DEVELOPMENT AND ADMINISTRATION OF A TWO-TIER MULTIPLE-CHOICE DIAGNOSTIC INSTRUMENT ON IONISATION ENERGY

INTRODUCTION

The aims of Phase Two of the study were to develop a two-tier multiple-choice diagnostic instrument on ionisation energy and to administer it to A-level students. The data obtained in Phase One, described in Chapter Four, were used to design the first version of the diagnostic instrument. Further trials and refinement led to the development of the second version, and subsequently, the final version of the diagnostic instrument, the Ionisation Energy Diagnostic Instrument (IEDI), presented in Appendix C. The development and administration of the IEDI, the results obtained, the analysis, interpretation and discussion of the results are described in this chapter.

DEVELOPMENT AND ADMINSTRATION OF THE IEDI

The results from the administration of the justification multiple-choice instruments on ionisation energy and the interviews with students described in the previous chapter contributed to the development of the first version of the two-tier multiple-choice instrument in Phase Two. Further refinement involving 283 Grade 11 and 12 students led to the development of the second version, and subsequently, the final version of the diagnostic instrument, the IEDI. The IEDI was validated by five experienced A-level chemistry teachers and two tertiary chemistry educators for accuracy and relevance. The specification of each of the 10 items in the instrument is given in Table 5.1 which shows the items, the propositions assessed, and the areas of alternative conception involved. The IEDI was administered to 777 Grade 11 and 202 Grade 12 students from eight out of a total of 17 A-level institutions in Singapore, in June and July 2003 (see Tables 5.2 and 5.3). The schools were selected on the basis of the willingness of the teachers in the schools to participate in the study. From

Table 5.2, it can be seen that there were more females than males in the sample, and from Table 5.3, it can be seen that about equal number of students were selected from the three different rungs of A-level institutions.

Table 5.1: Specifications of the items in the Ionisation Energy Diagnostic Instrument

No	The items, specific alternative conceptions and their sources	Propositional knowledge statements	Areas of alternative conception
	For Questions 1 to 5, please refer to the statement below. **Sodium atoms are ionised to form sodium ions as follows:** **$Na(g) \rightarrow Na^+(g) + e$**		
1	Once the outermost electron is removed from the sodium atom forming the sodium ion (Na^+), the sodium ion will not combine with an electron to reform the sodium atom. A True. B False. C I do not know the answer. *Reason:* (1) Sodium is strongly electropositive, so it only loses electrons. (2) The Na^+ ion has a stable/noble gas configuration, so it will not gain an electron to lose its stability. (3) The positively-charged Na^+ ion can attract a negatively-charged electron.	2,5,7,8,19,36	Octet rule framework. Meaning of electropositivity.
2	When an electron is removed from the sodium atom, the attraction of the nucleus for the 'lost' electron will be redistributed among the remaining electrons in the sodium ion (Na^+). A True. B False. C I do not know the answer. *Reason:* (1) The amount of attraction between an electron and the nucleus depends on the number of protons present in the nucleus and the distance of the electron from the nucleus. It does not depend on how many other electrons are present, although electrons do repel each other (and can shield one another from the nucleus). (2) The electron which is removed will take away the attraction of the nucleus with it when it leaves the atom. (3) The number of protons in the nucleus is the same but there is one less electron to attract, so the remaining 10 electrons will experience greater attraction by the nucleus.	2,5,7,8,12,13,19	Conservation of force thinking. Nuclear attraction for an electron

Table 5.1 (continued): Specifications of the items in the Ionisation Energy Diagnostic Instrument

No	The items, specific alternative conceptions and their sources	Propositional knowledge statements	Areas of alternative conception
3	The Na(g) atom is a more stable system than the $Na^+(g)$ ion and a free electron. A True. B False. C I do not know the answer. *Reason:* (1) The Na(g) atom is neutral and energy is required to ionise the Na(g) atom to form the Na^+ (g) ion. (2) Average force of attraction by the nucleus on each electron of Na^+ (g) ion is greater than that of Na(g) atom. (3) The $Na^+(g)$ ion has a vacant shell which can be filled by electrons from other atoms to form a compound. (4) The outermost shell of $Na^+(g)$ ion has achieved a stable octet/noble gas configuration.	2,5,7,8,16,17, 18,19,31,36	Conservation of force thinking. Octet rule framework.
4	After the sodium atom is ionised (i.e. forms Na^+ ion), more energy is required to remove a second electron (i.e. the second ionisation energy is greater than the first ionisation energy) from the Na^+ ion. A True. B False. C This should not happen as the Na^+ ion will not lose any more electrons. D I do not know the answer. *Reason:* (1) Removal of the second electron disrupts the stable octet structure of Na^+ ion. (2) The same number of protons in Na^+ attract one less electron, so the attraction for the remaining electrons is stronger. (3) The second electron is located in a shell which is closer to the nucleus. (4) The second electron is removed from a paired 2p orbital and it experiences repulsion from the other electron in the same orbital.	2,5,7,8,12,13, 19,30c,30d, 31a,32	Conservation of force thinking. Octet rule framework. Relation-based thinking – focussing on electronic repulsion and ignoring nuclear charge.

Table 5.1 (continued): Specifications of the items in the Ionisation Energy Diagnostic Instrument

No	The items, specific alternative conceptions and their sources	Propositional knowledge statements	Areas of alternative conception
5	Sodium, magnesium and aluminium are in Period 3. How would you expect the first ionisation energy of sodium ($1s^2\ 2s^2\ 2p^6\ 3s^1$) to compare to that of magnesium ($1s^2\ 2s^2\ 2p^6\ 3s^2$)? A. The first ionisation energy of sodium is greater than that of magnesium. B. The first ionisation energy of sodium is less than that of magnesium. C. I do not know the answer. *Reason:* (1) Magnesium has a fully-filled 3s orbital which gives it stability. (2) Sodium will achieve a stable octet configuration if an electron is removed. (3) In this situation, the effect of an increase in nuclear charge in magnesium is greater than the repulsion between its paired electrons in the 3s orbital. (4) The paired electrons in the 3s orbital of magnesium experience repulsion from each other, and this effect is greater than the increase in the nuclear charge in magnesium. (5) The 3s electrons of magnesium are further from the nucleus compared to those of sodium.	2,5,7,8,12,13, 23,24,25,26, 27,28,30c, 30d,30e,31a, 32,34	Octet rule framework. Stable fully-filled sub-shell. Relation-based thinking – the more electrons, the further away they are/filling of electrons in orbitals and ignoring nuclear charge.
6	How do you expect the first ionisation energy of magnesium ($1s^2\ 2s^2\ 2p^6\ 3s^2$) to compare to that of aluminium ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$)? A. The first ionisation energy of magnesium is greater than that of aluminium. B. The first ionisation energy of magnesium is less than that of aluminium. C. I do not know the answer. *Reason* (1) Removal of an electron will disrupt the stable completely-filled 3s orbital of magnesium. (2) The 3p electron of aluminium is further from the nucleus compared to the 3s electrons of magnesium. (3) In this situation, the effect of an increase in nuclear charge in aluminium is greater than the repulsion between the electrons in its outermost shell. (4) In this situation, the effect of an increase in nuclear charge in aluminium is less than the repulsion between the electrons in its outermost shell. (5) The paired electrons in the 3s orbital of magnesium experience repulsion from each other, whereas the 3p electron of aluminium is unpaired.	2,5,7,8,12,13, 23,24,25,26, 27,28,30c, 30e,30f,31a, 32,34,34a	Stable fully-filled sub-shell. Relation-based thinking – the more electrons, the further away they are/filling of electrons in orbitals and ignoring nuclear charge. Relation-based thinking – focussing on electronic repulsion and ignoring nuclear charge.

Table 5.1 (continued): Specifications of the items in the Ionisation Energy Diagnostic Instrument

No	The items, specific alternative conceptions and their sources	Propositional knowledge statements	Areas of alternative conception
7	How do you expect the first ionisation energy of sodium ($1s^2\ 2s^2\ 2p^6\ 3s^1$) to compare to that of aluminium ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$)? A. The first ionisation energy of sodium is greater than that of aluminium. B. The first ionisation energy of sodium is less than that of aluminium. C. I do not know the answer. *Reason* (1) Aluminium will attain a fully-filled 3s orbital if an electron is removed. (2) Sodium will achieve a stable octet configuration if an electron is removed. (3) The 3p electron of aluminium experiences greater shielding from the nucleus compared to the 3s electron of sodium. (4) The 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium. (5) In this situation, the effect of an increase in nuclear charge in aluminium is greater than the shielding of the 3p electron by the 3s electrons.	2,5,7,8,12,13, 23,24,25,26, 27,28,30c, 30d,30f,31a, 32,34	Octet rule framework. Stable fully-filled sub-shell. Relation-based thinking – the more electrons, the further away they are/filling of electrons in orbitals and ignoring nuclear charge. Relation-based thinking – focussing on electronic repulsion/ shielding and ignoring nuclear charge.
8	Silicon, phosphorus and sulphur are in Period 3. How would you expect the first ionisation energy of silicon ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$) to compare to that of phosphorus ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^3$)? A The first ionisation energy of silicon is greater than that of phosphorus. B The first ionisation energy of silicon is less than that of phosphorus. C I do not know the answer. *Reason:* (1) Silicon has less electrons than phosphorus, thus its 3p electrons face less shielding. (2) The 3p orbitals of phosphorus are half-filled, hence they are stable. (3) The 3p electrons of phosphorus are further away from the nucleus compared to that of silicon. (4) In this situation, the effect of an increase in nuclear charge in phosphorus is greater than the repulsion between its 3p electrons.	2,5,7,8,12,13, 23,24,25,26, 27,28,30c, 30g,30h,31a, 32,34	Stable half-filled sub-shell. Relation-based thinking – the more electrons, the further away they are/filling of electrons in orbitals and ignoring nuclear charge. Relation-based thinking – focussing on electronic repulsion/shielding and ignoring nuclear charge.

Table 5.1 (continued): Specifications of the items in the Ionisation Energy Diagnostic Instrument

No	The items, specific alternative conceptions and their sources	Propositional knowledge statements	Areas of alternative conception
9	How would you expect the first ionisation energy of phosphorus ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^3$) to compare to that of sulphur ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^4$)? A The first ionisation energy of phosphorus is greater than that of sulphur. B The first ionisation energy of phosphorus is less than that of sulphur. C I do not know the answer. *Reason* (1) More energy is required to overcome the attraction between the paired 3p electrons in sulphur. (2) 3p electrons of sulphur are further away from the nucleus compared to that of phosphorus. (3) The 3p orbitals of phosphorus are half-filled, hence they are stable. (4) In this situation, the effect of an increase in nuclear charge in sulphur is greater than the repulsion between its 3p electrons. (5) In this situation, the effect of an increase in nuclear charge in sulphur is less than the repulsion between its 3p electrons.	2,5,7,8,12,13, 23,24,25,26, 27,28,30c, 30h,30i,31a, 32,34,34b	Stable half-filled sub-shell. Relation-based thinking – the more electrons, the further away they are/filling of electrons in orbitals and ignoring nuclear charge. Paired electrons in an orbital attract each other strongly.
10	How would you expect the first ionisation energy of silicon ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$) to compare to that of sulphur ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^4$)? A The first ionisation energy of silicon is greater than that of sulphur. B The first ionisation energy of silicon is less than that of sulphur. C I do not know the answer. *Reason* (1) Sulphur will have its 3p orbitals half-filled if an electron is removed. (2) The 3p electrons of sulphur are further away from the nucleus compared to that of silicon. (3) In this situation, the effect of an increase in nuclear charge in sulphur is greater than the repulsion between its 3p electrons. (4) In this situation, the effect of an increase in nuclear charge in sulphur is less than the repulsion between its 3p electrons.	2,5,7,8,12,13, 23,24,25,26, 27,28,30c, 30g,30i,31a, 32,34	Stable half-filled sub-shell. Relation-based thinking – the more electrons, the further away they are/filling of electrons in orbitals and ignoring nuclear charge.

Table 5.2: Distribution of students over schools

School	Grade	Female	Male	Total
81	12	76	71	147
82	11	72	57	129
83	11	35	40	75
84	11	81	66	147
85	11	77	80	157
86	12	31	22	53
87	11	110	75	185
88	11	17	29	46
Total		499 (53.1%)	440 (46.9%)	939 (100%)

Note: 40 students did not state their gender

Table 5.3: Types of schools involved in the study

Type of school	School	Total number of students (%)
Top rung	81, 83, 86, 88	325 (33.2)
Middle rung	84, 85	319 (32.6)
Lower rung	82, 87	335 (34.2)

Thirty-two Grade 11 and 12 students were interviewed, either in pairs or in groups of four, using the IEDI as the protocol to determine if there was any ambiguity in the items and to further probe the thinking behind their answers. These students were chosen by their teachers. Each interview lasted between 40 minutes to an hour. Table 5.4 describes the composition of the various groups interviewed and the school from which they came.

Table 5.4: Students interviewed using the IEDI as the interview protocol

School	Students	Number of students (%)
82 (lower rung)	(1,2), (3,4), (5,6), (7,8)	8 (25)
83 (top rung)	(9,10,11,12), (13,14,15,16)	8 (25)
84 (middle rung)	(25,26,27,28), (29,30,31,32)	8 (25)
85 (middle rung)	(17,18,19,20), (21,22,23,24)	8 (25)

Note: The numbers in a bracket in the 'Students' column denote the students in each interview group, for example, (1,2) denotes that Students 1 and 2, from School 82, were interviewed together.

RESULTS AND DISCUSSION

The answer sheets of the students were optically scanned, and SPSS version 11 was used to analyse the results. Following the procedure in Peterson (1986), each item was considered to be correctly answered if a student correctly responded to both parts of the item.

Test statistics

Some test statistics are given in Table 5.5, and the distribution of the students' scores is shown in Figure 5.1. It can be seen from both that a great majority of the Grade 11 and 12 students had low scores (79.7% of them scored 4 marks or less) with the mean score being 2.91 out of 10. The reliability of the instrument (Cronbach coefficient alpha) is a low .52, but consistent with the criterion-referenced nature of the test as each item tests different aspects of the concepts (Ross & Munby, 1991). The intention of the study was to determine the A-level (i.e. Grade 11 and 12) students' performance on the IEDI as a group, so the sex of the students, the different sample sizes of the two year groups of students as well as the schools these two groups of students came from were not important variables.

Table 5.5: Test statistics for the Grade 11 and 12 students

Variable	Statistic
No. of cases	979
No. of items	10
Alpha	.52
Mean	2.91
Standard Deviation	1.91
Median	3.00
Mode	2
Minimum	0
Maximum	9

Figure 5.1: Distribution of the Grade 11 and 12 students' scores on the IEDI

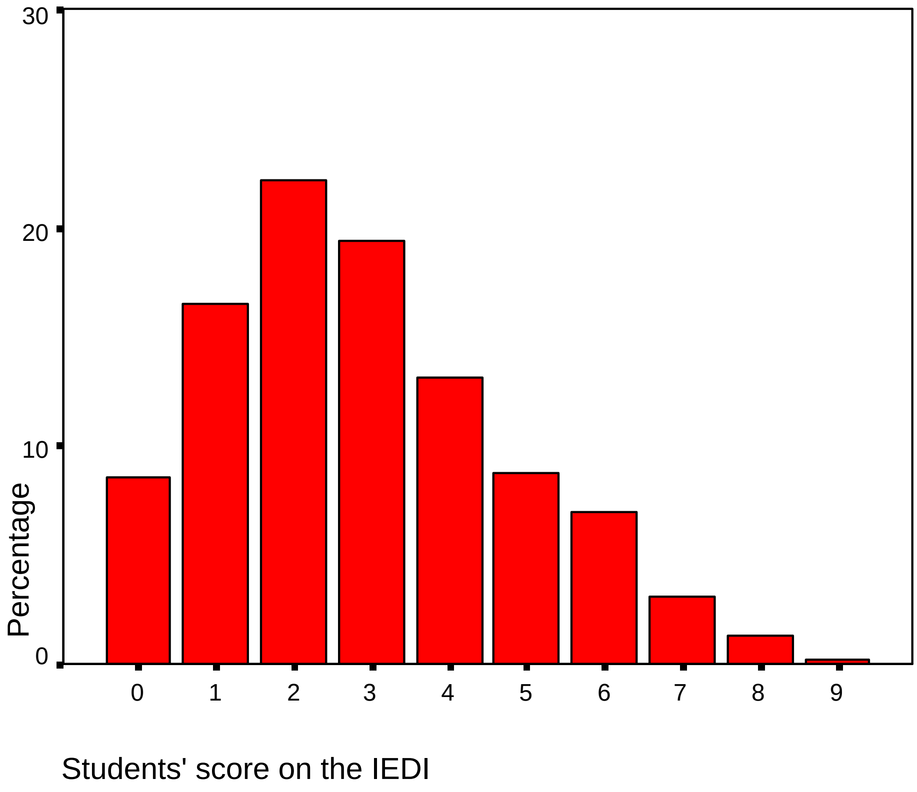


Table 5.6 describes the percentage of the Grade 11 and 12 students selecting each response combination for each item in the IEDI. The results for an item will not add up to 100% if there were students who did not select a response to both parts of the item, selected an answer combination which was beyond the options given in the item, or selected more than one answer combination. Thirty-one students chose more than one option in an item, especially in items 4 and 7. However, apart from (A1,A3 – 6 students) and (A2, A3 – 6 students) in item 4, and (A3, A4 – 5 students) in item 7, the various combinations of answers were the choice of only one to three students. The students were also allowed to write their answers at the back of the answer sheet if they believed that none of the reasons given in an item was appropriate. Forty-two written reasons were given by the students, and these form about 0.4% of the total possible item responses (10x979), that is, students gave their own alternative reasons for only about 0.4% of total item responses. Examples of these written responses are given in Table 5.7.

Table 5.8 gives the percentage of the students correctly answering both the content and reason parts of each item, and the discrimination index for each item (in brackets). The percentage of those correctly answering only the content part of the items was also included to highlight the situation that students' were getting the right content answers without knowing/recognising the valid reasons. The facility indices (FI) ranged between .05 to .48, with one very difficult question (FI<.10), four difficult questions (FI between 0.10 to 0.30) and five moderately difficult questions (FI between 0.30 to 0.70), showing that the diagnostic test was difficult for the secondary students. A comparison of the percentage of students who correctly answered the content part of the questions with that of those who correctly answered both parts of the questions suggested that many students may have learned facts without an adequate understanding of the propositions and concepts involved (Peterson et al., 1989). The discrimination indices (DI) ranged between .11 to .67, with eight items showing good discrimination (DI>.30).

Table 5.6: The percentage of Grade 11 and 12 students (n=979) selecting each response combination for each item in the IEDI

Item	Content option	Reason option					Total
		(1)	(2)	(3)	(4)	(5)	
1	A	4.8	*43.6*	3.3	-	-	51.7
	B	1.0	5.3	**38.2***	-	-	44.5
	C	0	.2	.2	-	-	0.4
2	A	6.5	.7	*49.7*	-	-	56.9
	B	**30.0***	1.4	3.7	-	-	35.1
	C	.4	.2	.4	-	-	1.0
3	A	**16.8***	.9	4.5	3.8	-	26.0
	B	1.7	1.3	2.2	*63.6*	-	68.8
	C	.1	0	.1	.4	-	0.6
4	A	*15.6*	*18.0*	**48.1***	3.6	-	85.3
	B	.1	.3	.7	1.6	-	2.7
	C	5.3	.3	.1	0	-	5.7
	D	.1	.1	0	0	-	0.2
5	A	1.2	2.2	2.9	*22.0*	4.2	32.5
	B	*13.1*	9.1	**29.2***	9.3	2.2	62.9
	C	.1	.1	.2	0	0	0.4
6	A	6.2	*48.1*	2.9	**5.4***	5.5	68.1
	B	.9	7.2	8.5	1.8	8.3	26.7
	C	.1	.1	.1	.1	.1	0.5
7	A	.5	1.8	*20.7*	*24.4*	1.5	48.9
	B	.7	5.6	7.4	6.8	**23.9***	44.4
	C	.1	0	.2	.1	.2	0.6
8	A	3.9	4.5	7.6	5.8	-	21.8
	B	5.5	*24.9*	4.6	**34.0***	-	69.0
	C	.3	.1	.1	.2	-	0.7
9	A	2.7	3.9	*19.6*	7.4	**32.1***	65.7
	B	6.8	1.6	3.5	*10.4*	4.3	26.6
	C	.2	.1	.3	.4	0	1.0
10	A	6.8	6.8	6.3	*19.0*	-	38.9
	B	3.6	3.5	**33.1***	9.0	-	49.2
	C	.3	.1	.6	.3	-	1.3

Note: Figure in bold and with an asterisk indicates the correct answer.

Figure in italics indicate a major alternative conception (>10%)

Table 5.7: Examples of written reasons given by students

Item 1

- A: Na^+ is unstable. There Na^+ must gain an e to be electrically neutral.
- B: By electrolysis, sodium atom can be still obtained. This must be done when the sodium ion is in molten state.

Item 2

No written reason.

Item 3

- C: Na is a very reactive metal.

Item 4

- A: The same number of protons in Na^+ attract one less electron, so the attraction for the remaining electron is stronger, moreover the second electron is located nearer to the nucleus.

Item 5

- B: Mg has a larger nuclear charge, therefore stronger attraction, hence more energy required to remove an electron from it.
- B: The outermost electron of Mg is nearer to the nucleus as there is more nuclear charge compared to sodium. It has a smaller atomic radius than Na and there is about the same shielding effect. Therefore, lesser energy is required to remove the outermost electron of Na than to remove the outermost electron of Mg.
- B: IE increases across the period.
- A: The paired electrons in the 3s orbital experience inter-electron repulsion and hence requires lesser energy for removal of the outermost electron than sodium.

Item 6

- A: 3p is of a higher energy level than 3s, therefore lower amount of energy is required to remove the valence e, resulting in a lower I.E.
- A: Mg will have a higher first IE than Al because Al has a lone electron in the 3p shell which is easier to remove than paired electrons. This electron is shielded by the inner shells, and this is enough to overcome the increase in nuclear charge.
- A: The 3p1 electron experiences a larger shielding effect by the 3s2 electrons and that the increase in shielding effect overcome the increase in nuclear charge. Thus, the effective nuclear charge of aluminium is lower than that of magnesium, therefore first IE of aluminium is lower than that of magnesium.

Item 7

- B: As the number of protons increases, the size of the atom decreases and so there is greater forces of attraction. Therefore sodium is easier to ionize.

Item 8

- B: The outermost electron of phosphorus is nearer to the nucleus having a smaller atomic radius compared to silicon. This is because phosphorus has more nuclear charge than silicon and the shielding effect is about the same. Therefore, lesser energy is required to remove the outermost electron of silicon than that of phosphorus.
- B: No repulsion between electrons in 3p orbital of phosphorus as they are singly filled into orbitals.

Item 9

- A: The pair electron in the 3p sub-shell of sulphur experience a repulsion thus need less energy to remove the electrons whereas phosphorus does not experience such repulsion.

Item 10

- A: In sulphur, the inter electron repulsion is greater than in silicon. Hence less energy would be required to remove an electron from sulphur.
- B: More protons thus greater nucleus attraction. So sulphur has a greater ionisation energy.

Others

- Actually I don’t understand majority of the questions. Most of them are almost similar questions, which makes it complex/complicated to choose which answer. I also forgot some of the concepts.

Table 5.8: The percentage of Grade 11 and 12 students (n=979) correctly answering the first part only and both parts of the items in the IEDI

Item	Percentage of students correctly answering	
	first part	both parts
1	45	38 (.35)
2	36	30 (.32)
3	27	17 (.21)
4	89	48 (.42)
5	65	29 (.59)
6	70	5 (.11)
7	46	24 (.56)
8	72	34 (.67)
9	68	32 (.51)
10	51	33 (.61)

Alternative conceptions

Alternative conceptions are considered significant and common if they existed in at least 10% of the student sample (Peterson, 1986). If a higher minimum value, say 25%, was chosen, this would mean not discussing alternative conceptions that seemed likely to be found among students in many classes. Tables 5.9 and 5.10 summarise the significant common alternative conceptions determined from the administration of the IEDI to the 979 Grade 11 and 12 students. Eleven significant common alternative conceptions were identified and grouped under the headings of ‘Octet rule framework’, ‘Stable fully-filled or half-filled sub-shells’, ‘Conservation of force thinking’ and ‘Relation-based reasoning’ in Table 5.10. These are the categories used in the discussion of the data obtained from interviews and free-response questions in Chapter Four.

Table 5.9: The percentage of Grade 11 and 12 students (n=979) with significant alternative conceptions in each item of the IEDI

Item	Option	Alternative conception	Percentage of Grade 11 and 12 students
1	A2	The sodium ion will not recombine with an electron to reform the sodium atom because the sodium ion has a stable/noble gas configuration, so it will not gain an electron to lose its stability.	44
2	A3	When an electron is removed from the sodium atom, the attraction of the nucleus for the 'lost' electron will be redistributed among the remaining electrons in the sodium ion because the number of protons in the nucleus is the same but there is one less electron to attract, so the remaining 10 electrons will experience greater attraction by the nucleus.	50
3	B4	The Na(g) atom is a less stable system than the $Na^+(g)$ and a free electron because the outermost shell of the $Na^+(g)$ ion has achieved a stable octet/noble gas configuration.	64
4	A1	The second ionisation energy of sodium is greater than its first ionisation energy because removal of the second electron disrupts the stable octet structure of the Na^+ ion.	16
	A2	The second ionisation energy of sodium is greater than its first ionisation energy because the same number of protons in the Na^+ ion attracts one less electron, so the attraction for the remaining electrons is stronger.	18
5	B1	The first ionisation energy of sodium is less than that of magnesium because magnesium has a fully-filled 3s sub-shell which gives it stability.	13
6	A2	The first ionisation energy of magnesium is greater than that of aluminium because the 3p electron of aluminium is further from the nucleus compared to the 3s electrons of magnesium.	48
7	A3	The first ionisation energy of sodium is greater than that of aluminium because the 3p electron of aluminium experiences greater shielding from the nucleus compared to the 3s electron of sodium.	21
	A4	The first ionisation energy of sodium is greater than that of aluminium because the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium.	24
8	B2	The first ionisation energy of silicon is less than that of phosphorus because the 3p sub-shell of phosphorus is half-filled, hence it is stable.	25
9	A3	The first ionisation energy of phosphorus is greater than that of sulphur because the 3p sub-shell of phosphorus is half-filled, hence it is stable.	20

Table 5.10: Alternative conceptions determined from the administration of the IEDI

Alternative conception	Choice combination	Percentage of students with the alternative conception
Octet rule framework		
The sodium ion will not recombine with an electron to reform the sodium atom as its stable octet configuration would be disrupted.	Q1 (A2)	44
The Na(g) atom is a less stable system than the $Na^+(g)$ and a free electron because the $Na^+(g)$ has a stable octet configuration.	Q3 (B4)	64
The second ionisation energy of sodium is higher than its first because the stable octet would be disrupted.	Q4 (A1)	16
Stable fully-filled or half-filled sub-shells		
The first ionisation energy of sodium is less than that of magnesium because magnesium has a fully-filled 3s sub-shell.	Q5 (B1)	13
The first ionisation energy of silicon is less than that of phosphorus because the 3p sub-shell of phosphorus is half-filled.	Q8 (B2)	25
The first ionisation energy of phosphorus is greater than that of sulphur because the 3p sub-shell of phosphorus is half-filled, hence it is stable.	Q9 (A3)	20
Conservation of force thinking		
When an electron is removed from the sodium atom, the attraction of the nucleus for the ‘lost’ electron will be redistributed among the remaining electrons in the sodium ion.	Q2 (A3)	50
The second ionisation energy of sodium is greater than its first ionisation energy because the same number of protons in the Na^+ ion attracts one less electron, so the attraction for the remaining electrons is stronger.	Q4 (A2)	18
Relation-based reasoning		
The first ionisation energy of magnesium is greater than that of aluminium because the 3p electron of aluminium is further from the nucleus compared to the 3s electrons of magnesium.	Q6 (A2)	48
The first ionisation energy of sodium is greater than that of aluminium because the 3p electron of aluminium experiences greater shielding from the nucleus compared to the 3s electron of sodium.	Q7 (A3)	21
The first ionisation energy of sodium is greater than that of aluminium because the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium.	Q7 (A4)	24

Options A4 of item 5 (22%), B4 of item 9 (10%) and A4 of item 10 (19%) (see Table 5.11) were not considered as alternative conceptions even though they were incorrect. These questions dealt with the trend of ionisation energy across Period 3. In the items, students had to consider which important factors were in play, as well as to decide which factor outweighed the other (nuclear attraction versus shielding/repulsion) in the specific instance. If a student chose one of the stated options, it could indicate that he/she knew which two factors were in play, but decided wrongly the more important factor in that specific situation. Thus, it was difficult to determine if the student had an alternative conception, or if he/she forgot or could not decide which factor outweighed the other in that specific situation. In other words, these errors are better considered failures of recall than lack of understanding of the concepts involved.

Table 5.11: Significant errors of students (10% or greater) which were not considered as alternative conceptions

Item	Option	Errors	Percentage of Grade 11 and 12 students
5	A4	The first ionisation energy of sodium is greater than that of magnesium because the paired electrons in the 3s orbital of magnesium experience repulsion from each other and this effect is greater than the increase in the nuclear charge in magnesium.	22
9	B4	The first ionisation energy of phosphorus is less than that of sulphur because the effect of an increase in nuclear charge in sulphur is greater than the repulsion between its 3p electrons.	10
10	A4	The first ionisation energy of silicon is greater than that of sulphur because the effect of an increase in nuclear charge in sulphur is less than the repulsion between its 3p electrons.	19

Octet rule framework

Many students (44%) thought that the sodium ion would not recombine with an electron to reform the sodium atom because the sodium ion had already achieved a noble gas configuration, and gaining an electron would cause the ion to lose its stability (Item 1, A2). In item 3, 64% agreed that the ‘sodium ion and a free electron’ system was more stable than the sodium atom because the outermost shell of the ion had achieved a stable octet/noble gas configuration (B4). When asked during interviews why an octet configuration gave the sodium ion “stability”, several students either stated that they were taught so, or that it was because the outermost shell of the sodium ion was filled so it could not gain or lose any electrons.

P6: Because it is already stable…I mean you know…the outermost shell…it’s like eight electrons…so…if it attracts another electron…then it will become unstable…so…it’s more likely to stay stable then form [the atom].

I: Why do you say that the octet structure gives it stability?

P6: That’s what we are taught right…octet structure is supposed to be stable.

P15: I put B4 (item 3)…because with sodium [ion] right … you have the…octet configuration so it will be more stable…whereas sodium as an atom…only has…is not fully filled in the outermost shell…so it is not so stable.

I: Ok…can you explain why the fully filled outermost shell is stable?

P15: Because the teacher taught so.

P1: I feel that for the arrangement of 2,8 right…since there is eight electrons it fills every single empty spaces for electron to come in…so the structure is more extensive…so it will be stronger since it will not lose one electron or take in one electron…it will remain in the stable state.

I: Why will the ion be more stable?

P14: Because octet…stable octet configuration.

I: Why is an octet configuration stable?

P14: Because it has eight electrons in the outermost shell already…so no electrons will go in no electrons will go out…then it is very stable…to achieve a stable configuration…stable octet structure you need to have all your…shells filled… outermost shell filled.

Cross-tabulation was used to study the consistency of the students' answers (Tan et al., 2002). Cross-tabulation of items 1 and 3 showed that only 90 students (9%) had both items correct, and 323 students (34%) consistently used the octet rule framework in both items (item 1: A2, 44%; item 3: B4, 64%). In addition, 211 students who had item 1 correct used the octet rule framework in item 3. This indicated that students could have and use both the correct concepts and the octet rule framework, even if they resulted in conflicting answers in different items. The explicit comparison of the stability of sodium atom with the system consisting of the sodium ion and free electron could have influenced the students' use of the octet rule framework in item 3.

Students also used the octet rule framework to justify why the second ionisation energy of sodium was greater than its first ionisation energy (Item 4, A1, 16%). This differs from the curriculum model, which states that the removal of the second electron from sodium involves removing an electron from an inner (second) shell. The electrons in the second shell are more strongly attracted to the nucleus as they are closer to the nucleus and experience shielding/screening from only two electrons in the first shell, so the second ionisation energy of sodium is higher than its first ionisation energy. Alternatively, this last factor may be described in terms of the core charge (Taber, 2002; 2003a) having increased from +1 (attracted by 11 protons but repelled by 10 inner shell electrons) to +9 (attracted by 11 protons but now repelled by only two inner shell electrons). Six students indicated on their answer sheets that they had two reasons (1 – octet rule framework and 3 – inner shell) to support their answer that the second ionisation energy of sodium was greater than its first ionisation energy; there was no conflict this time as both reasons supported the same answer. This is also illustrated by an excerpt of an interview:

P17: A3 and 1 (item 4).

I: Two reasons…why 1?

P17: True…the first…sodium has one…one electron in the s orbital…the outermost shell…so there's higher tendency for it to lose this electron…therefore a lower energy required…but after it…when it

> forms the sodium ion…it has achieved the stable structure…so it is unlikely for it to…very hard to remove the next electron…and 3 because the electron is closer to the nucleus…so is…the attractive force between the protons and electron is stronger…due to it being closer.

Cross-tabulation of items 1, 3 and 4 showed that only 62 students (6%) consistently adopted the octet rule framework in all three items (item 1: A2, 44%; item 3: B4, 64%; item 4: A1, 16%). One hundred and sixty-one students (16%) who had item 4 correct used the octet rule framework in items 1 (A2, 44%) and 3 (B4, 64%), and 52 students (5%) who adopted the octet framework in items 1 and 3 used the conservation of force thinking (to be discussed in a later section) in item 4 (A2, 18%). The lack of consistency of alternative conceptions held by the students could point to students having more than one conception for a particular concept and "different conceptions can be brought into play in response to different problem contexts" (Palmer, 1999, p. 639). Palmer believes that the student has a collection of scientific concepts and alternative conceptions and that the student's knowledge structures or personal propositions guide the student on which to use in any given situation. He contends that there is no inconsistency from the viewpoint of the student because the responses will be "a true reflection of the 'if…then' nature of their understanding" (p. 650). Taber (1999a) also found that "apparently related items do not always receive a consistent level of support from the students" (p. 103). He agrees with Palmer that students "may have several alternative explanatory schemes that can be applied to a particular context" (p. 103). One interpretation is that students may be in the process of transition, for example, between only holding an alternative conception and adopting the approved curriculum model (Taber, 2000c). Caravita & Halldén (1994) talk about the 'meta-level' of cognitive structure where metacognitive and epistemological beliefs may influence the conceptions that are accessed and applied. The study by Voska and Heikkinen (2000) on student conceptions in chemical equilibrium also revealed that only a small proportion of students showed consistency in their thinking. Finally, the lack of consistency could also be due to students not having adequate understanding of the topic and resorting to guessing.

Stable fully-filled or half-filled sub-shells

In item 5, 13% stated that magnesium had a higher first ionisation energy than sodium because magnesium had a fully-filled 3s orbital/sub-shell which gave it stability (B1), while in items 8 and 9, 25% (B2) and 20% (A3), respectively, indicated that phosphorus had a higher first ionisation energy compared to silicon and sulphur because the 3p sub-shell of phosphorus was half-filled, hence it was stable. Three excerpts of interviews illustrate this 'stable fully-filled or half-filled sub-shell' thinking:

P14: I put B1 (item 5)…because the magnesium…the last orbital…the 3s orbital is fully filled so it will tend to be more stable…and when an orbital is either half or fully filled it will be more stable…so since sodium has only one electron in the…so when fully filled will be more stable…sodium has only one electron in the s orbital…so to be more stable it will tend…it will be easier to remove…that electron and so the ionisation energy will be lower than that of magnesium.

I: So you are saying that the first ionisation energy of magnesium is higher?

P14: It is more stable.

I: Because of the…

P14: It's fully filled orbital.

I: So why is this fully filled orbital stable…the $3s^2$?

P14: Just like in the shell…I mean…to achieve the octet structure…must have eight electrons…so when you have eight electrons in the outer shell…will be more stable… so when the orbital is fully filled then… more stable… because there's…like…more stable.

I: So stability comes with filled orbitals?

P14: Fully filled and half filled…but fully filled will have higher stability.

I: And the reason for the stability is?

P14: Reason for the stability…I not so sure.

P23: A3 (item 9).

I: A and 3…oh, half filled therefore they are more stable…why?

P23: Octet…should be the same concept with the octet structure.

I: Ok, what about you, P30?
P30: I choose B2 (item 8).
I: Why B2?
P30: Because it's like…phosphorous is $3p^3$ so that means there's the last…they are half-filled so they are more stable.
I: Why is half-filled more stable?
P30: Half-filled because they are all filled singly throughout, that's why it is more stable.
I: How does singly filled throughout gives it more stability?
P30: Because…at least…there's no repulsion…at least no repulsion.
I: No repulsion between the three…
P30: Between the…between the three…I mean…maybe if it is paired up right, they might experience repulsion, so…yah…at least half-filled is more stable.
I: Ok, but…silicon is only…has two…that is not stable compared to phosphorus?
P30: I mean its…3p3 is fully-filled (all three orbitals contain one electron each)…it's all filled up.

P14 and P23 believed that a fully-filled or half-filled sub-shell was stable because both were analogous to a 'stable octet' – there was no conflict between the octet rule framework and the 'stable fully-filled or half-filled sub-shell' thinking, in fact, the former seemed to lead 'naturally' to the latter, from shell to sub-shell. In the curriculum model, magnesium has a higher first ionisation energy than sodium because its greater nuclear charge outweighs the repulsion between its 3s electrons. A similar reason accounts for the higher first ionisation energy of phosphorus compared to silicon. However, sulphur has lower first ionisation energy than phosphorus even though sulphur has a greater nuclear charge. This is because the repulsion between the paired 3p electrons in sulphur outweighs its greater nuclear charge. The greater shielding of the 3p electron by the inner shell electrons as well as the 3s electrons explains why aluminium has a lower first ionisation energy compared to magnesium. It has to be noted that students will have great difficulty answering questions on ionisation energy trends if they cannot *either* remember whether increased nuclear charge or increased repulsion/shielding between electrons is more important in specific cases *or* recall the shape of the trend graph, and so work out which factors must be more important in each case. Thus, as mentioned earlier, it is not a matter of grave concern if students cannot decide between, for example, A4 or B3 in item 5, or A5 or B4 in item 9. However, it is problematic when students think that a fully-filled 3s sub-shell gives magnesium its stability, and hence higher first ionisation energy compared to aluminum, while phosphorus, with its 3p sub-shell half-filled, is more stable than sulphur and hence has higher first ionisation energy than sulphur.

Unfortunately, teachers often use ‘stable fully-filled or half-filled sub-shell’ as a rule-of-thumb to explain the anomaly in the ionisation energy trend across Periods 2 and 3 of the Period Table, and to help students remember the anomaly. A textbook on introductory tertiary chemistry (Lee, 1977) also uses the octet rule framework and stable fully-filled or half-filled sub-shells to explain the anomaly.

> “The values for Ne and Ar are the highest in their periods because it requires a great deal of energy to break *a stable filled shell of electrons*. There are several irregularities. The high values for Be and Mg are attributed to the *stability of a filled s shell*. The high values of N and P indicate that *a half-filled p level is also particularly stable*. The values for B and Al are lower because removal of one electron leaves *a stable filled s shell*, and similarly with O and S *a stable half-filled p shell* is left” (Lee, 1977, p.96, *present authors’ emphasis*)

Cann (2000) also commented that this ‘half-filled (and also completely-filled) shells having intrinsic stability’ reason was common and could be found in textbooks, but it offered “no explanation in terms of electrostatic or quantum mechanical interactions within the atom” (p. 1056). In summary, it was not surprising that students readily accepted the ‘stable fully-filled or half-filled sub-shell’ thinking as it was a ‘natural progression’ from the octet rule framework, in addition to being given credence by teachers’ and textbooks’ use of it.

Though item 6 was related to item 5, only 61 students (6%) chose the ‘stable fully-filled 3s sub-shell of magnesium’ reason (A1) in item 6. Cross-tabulation showed that only 25 (3%) students who chose the ‘stable fully-filled s sub-shell of magnesium' reason in item 5 (B1, 13%) chose the same reason in item 6 compared to 127 students (13%) who consistently adopted the 'stable half-filled 3p sub-shell of phosphorus' thinking in items 8 (B2, 25%) and 9 (A3, 20%). The option 'the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of magnesium' was the major alternative conception in item 6 (48%), and it attracted 67 (7%) students who chose the 'stable fully-filled s sub-shell of magnesium' option in item 5 (B1, 13%). Item 7 also had a 'stable fully-filled 3s sub-shell' option (A1, 1%) but from a different perspective – aluminium would achieve a stable fully-filled 3s sub-shell if an electron was removed. However, it proved equally unpopular as only one student consistently exhibited this alternative conception in items 5 and 7. Thirty-five students (4%) who chose the 'stable fully-filled s sub-shell of magnesium' reason in item 5 (B1, 13%) chose the option 'the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium' (A4, 24%) option and another 36 students (4%) chose the "3p electron of aluminium experiences greater shielding from the nucleus compared to the 3s electron of sodium" (A3, 21%) option in item 7. The data showed that students could have manifold alternative conceptions and were inconsistent in their application of their conceptions (Palmer, 1999; Taber, 1999a, 2000c). Similarly, item 10 had a 'stable half-filled 3p sub-shell' option (A1) with a different perspective – sulphur would have a stable half-filled 3p sub-shell if an electron was removed. This time, 67 students (7%) chose this option. Only one student showed the "stable fully-filled 3s sub-shell" thinking throughout items 5 (B1, 13%), 6 (A1, 6%) and 7 (A1, 1%), but 31 students (3%) showed the 'stable half-filled 3p sub-shell' thinking throughout items 8 (B2, 25%), 9 (A3, 20%) and 10 (A1, 7%). The numbers of students who correctly answered items 5 to 7 and items 8 to 10 were 16 (2%) and 94 (10%), respectively. The lower level of consistency in items 5, 6 and 7 was most probably due to other alternative conceptions, for example, 'the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium/magnesium' in items 6 (A2, 48%) and 7 (A4, 25%) being more attractive to the students. This alternative conception is discussed in greater detail in the section on relation-based thinking.

Conservation of force thinking

Students indicated in item 2 (A3, 50%) that the nuclear attraction would be redistributed among the remaining 10 electrons when an atom of sodium loses an electron because the number of protons was the same but there was one less electron to attract. The curriculum model states that the attraction for an electron by the nucleus depends on the number of protons in the nucleus, the distance of the electron from the nucleus and the shielding effect of other electrons in the atom. Removal of one electron from the sodium atom may reduce some repulsion between electrons causing the remaining 10 electrons to move closer to the nucleus, but the nuclear attraction for the electron which was removed is not redistributed to the remaining 10 electrons. Though conceptually incorrect, the conservation of force thinking "does often allow correct predictions to be made (successive ionisation energies do increase) and seems to have an intuitive attraction to many students" (Taber, 2003a, p. 156). This was shown in item 4 (A2) where 18% thought that the second ionisation energy of sodium was greater than its first because the same number of protons in sodium was attracting 10 electrons now instead of 11. Three excerpts of interviews illustrate the conservation of force thinking:

P4: Ok…I think it is true (item 2) because…like one electron is lost…the atom has one electron less, right…so…the attraction will just remain the same…so the other electrons have …greater attraction.

I: So you believe the electron…

P4: The attraction stays the same…when the electron goes out, the attraction doesn't go with the electron…so the other electrons experience greater attraction.

I: So it experiences the attraction left behind by the electron…ok P3 what is your reason?

P3: It's the same…since one electron is removed right…so the proton number is the same…so the protons has lesser electrons to attract…so the attraction force is greater …it will pull [the electrons] closer.

P13: A3 (item 2)…because I'm taught this.

I: What do you understand about this?

P13: When you remove an electron, the remaining protons…the effective nuclear charge remains the same but then…it is distributed over less electrons, so each electron receive more attraction from the nucleus...so will be harder to pull them away.

I: Ok…what about you P14?

P14: A3.

I: A3 also…your reasoning?

P14: Because it is like…it's like what P13 said…the effective nuclear charge… what I think is simpler…I think that proton is positive, electron negative…positive attracts negative…now one less negative to attract, so the remaining negative will experience a greater attraction by the positive.

P10: A and number 2 (item 4)…because they say that the same number of protons attracts one less electron because the electron is gone…so the attraction…is stronger which is true…because the effective nuclear charge increases.

I: What do you mean by effective nuclear charge?

P10: As in the nuclear charge that attracts the electrons after subtracting the screening effect.

Cross-tabulation showed that 134 students (14%) consistently exhibited the conservation of force thinking in items 2 (A3, 50%) and 4 (A2, 18%). This indicated that students who chose the conservation of force option in item 4 were also likely to choose the similar option in item 2. Students can hold both the correct concept and alternative conception as shown by 215 students (22%) who had item 4 correct (A3, 48%) but chose the conservation of force option in item 2 (A3, 50%), and the written answer of one student, "The same number of protons in Na^+ attracts one less electron, so the attraction for the remaining electron is stronger, moreover the second electron is located nearer to the nucleus". There will be no cognitive conflict deriving from holding alternative conceptions like these where the conservation of force thinking and the curriculum model (as discussed above) lead to the same outcomes – in this case a greater value for the ionization energy. Students could also hold more than one alternative framework – 52 students (5%) who adopted the octet rule framework options in items 1 (A2, 44%) and 3 (B4, 64%) used the conservation of force thinking in item 4 (A2, 18%), while 67 students (7%) who chose the conservation of force option in item 2 (A3, 50%) selected the octet rule framework option in item 4 (A1, 16%).

Relation-based reasoning

Factors influencing ionisation energy include the nuclear charge, the distance of the electron from the nucleus and the repulsion/screening effect of the other electrons present. The results from items 5 to 10 on the trend of the first ionisation energy across Period 3 showed that many students did not consider all the three factors but based their reasons exclusively on one or two factors. As mentioned in Chapter Four, Driver et al. (1996) describe this type of thinking as relation-based reasoning, where "students tend to consider only one factor as possibly influencing the situation – the one which they see as the 'cause'. As a consequence, other possible influential factors are overlooked" (p. 115). For example, many students indicated the first ionisation energies of magnesium and sodium were greater than that of aluminum because the 3p electron of aluminum was further away from the nucleus compared to the 3s electron(s) of magnesium (item 6: A2, 50%) and sodium (item 7, A4, 26%), respectively. However, in the curriculum model, atomic radii decrease from sodium to sulphur in Period 3 because of increasing nuclear charge which outweighs the increase in repulsion between increasing number of electrons in the same shell.

P15: I put A2 (item 6)…because the 3p electron of aluminium is further, right…so they will be further from the nucleus…because they experience…the attraction won't be so strong.
I: What made you say that the 3p electron of aluminium is further from the nucleus compared to the 3s of magnesium?
P13: We were taught that way.
P15: It's further…is taught it's further…it's taught during lectures.
P14: 1s, 2s, 2p, 3s, further, further, further.
P15: Further away.
P14: The 3p is further away.

Note that here students are remembering a comparison presented in the context of a single atomic system (e.g. 3s of sodium compared with 3p of sodium), and expecting the same pattern when the comparison is made between different systems (e.g. 3s of magnesium compared with 3p of aluminium).

P22: A2 (item 6).

I: Why A2?

P22: Because…the 3p orbital is further away from the nucleus…so…the distance…the greater the distance, the attraction is…smaller…energy used to take away the electron…the outermost electron will be smaller.

I: How do you know that the 3p electron is further away?

P22: 3p orbital.

I: How do you know it is further away?

P22: Using the Aufbau principle.

I: And how does that help you to decide it is further away?

P22: The triangle…you know, where the 1s, 2s, 2p, 3s, 3p, and then arrow…I don't know why…the way you write $1s^2$, $2s^2$, then $2p^3$, $3s^2$, $3p^1$.

I: So you equate that as distance away.

P22: Yes.

I: Ok what about you P23?

P23: A2.

I: A2…ok why A2?

P23: Same reason as P22…but how I say the distance is different…I assume the distance by seeing the energy diagram.

I: What energy diagram?

P23: The energy diagram…that show us the position…from…

I: Ok…the energy diagram tells you the distance away from the…

P23: Some sort…something like that.

I: So the…s^2 of magnesium is nearer than the p^1.

P23: Yah.

I: Let's look at question six…P25, what's your answer for six.

P25: I put A2…because the…3p electrons are further…so they contain more energy than the s electrons, so it's easier to remove them.

I: How do you decide that the 3p electron of aluminium is further than the 3s electrons of magnesium?

P25: Because usually you always fill up the…s orbitals first before you fill up the p orbitals.

I: Because of the filling up…you said that the…p is further away.

P25: Not so sure.

I: Ok…P26, what do you think?

P26: A2

I: A2, same answer as P25…what's your reason?

P26: It's further.

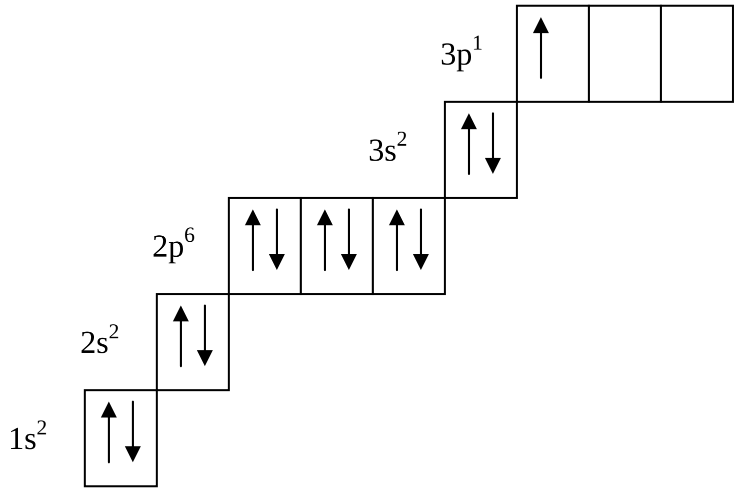
I: How do you know it's further away?

P26: Because there is this diagram…that's says 3p is further than 3s

I: Where you fill up the electrons in the orbitals…the diagram

It would seem from the above excerpts of the interviews that students might have the idea that the 3p electron of aluminium was further away compared to the 3s electron of magnesium from the way they were taught to 'fill' electrons in various orbitals of an atom according to Aufbau principle, using energy level or 'electrons-in-box' (Hill & Holman, 1980) diagrams (see Figure 5.2), or notations such as '$1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^1$'. The diagrams or notations indicated energy level, not distance away from the nucleus, so teachers need to be more explicit in their explanations of what the diagrams meant when they use such diagrams. Item 5 had a similar option which stated that sodium had a higher first ionisation energy compared to magnesium because the 3s electrons of magnesium were further away from the nucleus (A5). However, it attracted only 41 students (4%). This could indicate that students took the 3p sub-shell to be further away from the nucleus than the 3s sub-shell; the formalism for showing the pairing up electrons in the same 3s sub-shell of magnesium did not lead to the same impression of moving away from the nucleus as the representation of entering an arrow into a box in a 'new' sub-shell, the 3p sub-shell of aluminium. Perhaps the same type of inference is drawn by some students when writing the additional '3p' in '…$3s^2$ $3p^1$' for the electronic configuration of aluminium as compared to magnesium, rather than just changing $3s^1$ to $3s^2$ in magnesium compared to sodium. Items 8 (A3, 7.6%), 9 (A2, 3.9%) and 10 (A2, 6.8%) also had similar options which stated that the outermost electrons of the elements with greater number of electrons would be further away, but these did not prove attractive to students. The questions did not involve additional sub-shells as the electrons of silicon, phosphorus and sulphur of interest are all in the 3p sub-shells, so there was no potential visual indicator of ‘distance’.

Figure 5.2: An ‘electrons-in-box’ or energy level representation of the electronic structure of aluminium



Cross-tabulation showed that, in items 6 and 7, 167 students (18%) consistently indicated that the 3p electron of aluminium was further away (item 6: A2, 50%; item 7: A4, 26%), hence the first ionisation energy of aluminium was lower. The percentages of students consistently choosing the ‘outermost electrons of the elements with greater number of electrons would be further away’ options across items 5 to 7 (item 5: A5, 4%; item 6: A2, 50%; item 7: A4, 26%) and 8 to 10 (items 8: A3, 7.6%; item 9: A2, 3.9%; item 10: A2, 6.8%) were much lower, at 2% (15 students) and 1% (10), respectively. A summary of the results from cross-tabulation of items is given in Table 5.12.

Table 5.12: A summary of the results from cross-tabulation of items

Alternative conception	Items cross-tabulated	Percentage of students
Stable octet	Q1(A2), Q3(4)	34
	Q1(A2), Q3(4), Q4(A1)	6
Stable fully-filled sub-shell	Q5(B1), Q6(A1)	3
	Q5(B1), Q6(A1), Q7(A1)	0
Stable half-filled sub-shell	Q8(B2), Q9(A3)	13
	Q8(B2), Q9(A3), Q10(A1)	3
Conservation of force	Q2(A3), Q4(A2)	14
Outermost electrons of the elements with greater number of electrons would be further away	Q6(A2), Q7(A4)	18
	Q5(A5), Q6(A2), Q7(A4)	2
	Q8(A3), Q9(A2), Q10(A2)	1

Another example of students using relation-based reasoning was when they indicated that sodium had a higher first ionisation energy than aluminum because the 3p electron of aluminum experienced greater shielding compared to the 3s electron of sodium (Item 7, A3, 24%). These students might not have considered the effect of an increase in the nuclear charge of aluminum compared to sodium. Five students chose both A3 (the 3p electron of aluminium experiences greater shielding compared to the 3s electron of sodium) and A4 (the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium) in item 7, indicating that they believed both factors were in play – the factors did not conflict with each other, and indeed seemed to complement each other as the common element was the electron in the 'additional' 3p sub-shell. These two options also surfaced in several interviews, and are illustrated by the two excerpts below:

P26: A3 and 4.
I: A3 and 4…why did you choose A3 and 4?
P26: Because p (electron) is higher…and…it will experience greater shielding effect… although aluminium has more protons.
I: What are the two relevant factors?

P26 One is the shielding effect…the other is…is…further…

I: Further away…ok…and how do you know it is further away?

P26: Because it is 3p.

I: Why do you say that 3p is further away?

P26: Because it is like…you fill 2s, 3s…then after that 3p…then 3d.

I: Because of the sequence of filling of electron so you say that it is further.

P26: Yah.

I: Ok, let us look at question 7…what is your answer?

P29: A3

I: Why did you choose that?

P29: Because…I already have the reason…I think 3 is most suitable because…greater shielding effect will cause the…will require more (less?) energy to ionise the atom.

I: How do you know it has greater shielding effect?

P29: Because it has…it has a 3p orbital…that's why it has the….then it's like further away from the nucleus.

I: How do you know it is further away from the nucleus?

P29: Because it has a 3p orbital…compared to…whereas sodium has only up to 3s.

I: So, you say that the 3p orbital of aluminium is further away compared to the 3s of magnesium because of an additional sub-shell.

P29: Yes.

In addition to the consistency of student's alternative conceptions, the consistency of students' correct answers was also determined. Items 1 to 4 form a subset of questions (sodium atom and its ion) in the IEDI, with items 5 to 7 (variation of ionisation energy from sodium to aluminium) forming another subset, and items 8 to 10 (variation of ionisation energy from silicon to sulphur) forming the third subset. The percentages of students who correctly answered all questions in the subsets are given in Table 5.13. Only 17% managed to correctly answer item 3 (A1), and this accounted for the low percentage of students who correctly answered items 1 to 4.

Similarly, the low percentage of students who correctly answered in items 6 (A4, 5%), accounted for the poor performance in items 5 to 7. Items 8 to 10 each had more than 30% correct responses, so this gave rise to the better performance of students in these three items.

Table 5.13: Percentage of Grade 11 and 12 students (n=979) who correctly answered all questions in each subset of questions in the IEDI

Subset (items)	Percentage of students
Sodium atom and its ion (1, 2, 3 & 4)	1.8
Variation of ionisation energy from sodium to aluminium (5, 6 & 7)	1.6
Variation of ionisation energy from silicon to sulphur (8, 9 & 10)	9.6

SUMMARY

The description of the development of the two-tier multiple-choice diagnostic instrument, the IEDI, answered Research Question 2 which is concerned with the development of such an instrument. The discussion of the results from the administration of the IEDI answered Research Question 3 that asked what A-level chemistry students in Singapore understood about ionisation energy. The results presented in this chapter were consistent with those obtained from the earlier developmental stages of this research reported in Chapter Four, and showed that students in Singapore applied the same octet rule framework and conservation of force thinking to explain the factors influencing ionisation energy as the students in the United Kingdom In addition to the above alternative frameworks, many students in Singapore also resorted to relation-based reasoning to explain the trend of ionisation energy across Period 3 elements. The results also showed that students can hold the correct concepts as well as manifold alternative conceptions, and do not apply them consistently.

The information obtained in this chapter as well as the preceding ones provides the basis for the conclusions, recommendations, and discussion on the limitations of the study in the next chapter.

CHAPTER SIX

CONCLUSIONS, RECOMMENDATIONS AND LIMITATIONS

INTRODUCTION

In this chapter, a brief outline on how the research questions in the study were answered is presented. The collection and analysis of data during the study provided the basis for the conclusions, recommendations and discussion on the limitations of the study.

SUMMARY OF THE STUDY AND CONCLUSIONS

The three research questions which guided this study on ionisation energy are:

1. What are the concepts and propositional knowledge necessary for A-level chemistry students to understand the topic of ionisation energy?
2. How can a two-tier multiple-choice diagnostic instrument which is consistent with the identified concepts, propositional knowledge and known student alternative conceptions related to ionisation energy be developed?
3. What do A-level chemistry students in Singapore understand about the concepts and propositional knowledge related to ionisation energy?

Research Question 1 established the content boundaries for the investigations in this study. The content framework for A-level ionisation energy was described in Chapter Three through the preparation of a concept map, a list of propositional knowledge statements, and the matching of the concept map with the propositional knowledge statements.

Chapter Four and Five described the development of the multiple-choice diagnostic instrument, the IEDI, which was the main focus of Research Question 2. The development of the IEDI was based on the procedures outlined by Treagust (1995), and was described in Chapter Two. The items in the IEDI were developed based on the content framework described in Chapter Three, literature on alternative conceptions elaborated in Chapter Two, and the data collected from students in Chapter Four. The IEDI was "both the outcome of a research process and an instrument for data collection [in the same study, providing data which would] triangulate the interpretation of the existing database and broaden the ‘sample size’ ” (Taber, 2000a, p. 471).

Research Question 3 was answered through the administration of the IEDI to Grade 11 and 12 students, and the results, as well as the alternative conceptions identified from the analysis of the results were described in Chapter Five. It was found that the Grade 11 and 12 students had significant alternative conceptions, and these alternative conceptions were classified under the headings ‘Octet rule framework’, ‘Stable fully-filled or half-filled sub-shells’, ‘Conservation of force thinking’ and ‘Relation-based reasoning’. The alternative conceptions provided information on the Grade 11 and 12 students’ lack of understanding of the concepts in ionisation energy as presented in the curriculum, and the incorrect associations made by students between the various concepts in their attempts to understand the topic.

RECOMMENDATIONS

Based on the findings of this study and the literature reviewed in Chapter Two, recommendations for helping students improve their understanding of ionisation energy are given in this section. It also includes recommendations for further research.

Teaching and learning ionisation energy in school

Since the students would hardly have encountered the concepts on ionisation energy in everyday life, it was likely that the alternative conceptions arose from the way ionisation energy was taught and learnt. The authors believed that the octet rule framework was carried over from the learning of bonding in secondary chemistry (Taber, 1997a, 1999a; Tan & Treagust, 1999) – for example, during teaching practice observations, it was common to hear pre-service teachers saying that ‘the sodium atom needs to lose an electron to achieve a stable octet electronic configuration’ when teaching ionic bonding. As the octet rule framework did not conflict with the accepted scientific concept in explaining why, for example, the second ionisation energy of sodium was higher than its first ionisation energy (second electron was removed from an inner shell of electrons which was closer to the nucleus), students could unsuspectingly hold both the correct concept and alternative conception. They would see nothing wrong with the alternative conception and treat it as an additional explanation for the phenomenon. Only when they were challenged, during interviews, to explain why an octet of electrons conferred stability to the particle did some students feel a degree of discomfort with the octet rule framework. Thus, teachers need to challenge the octet rule framework in class by asking students to explain why an octet of electrons gives a particle stability, and even revisit the concepts involved in chemical bonding.

As mentioned earlier in the paper, a textbook also used the ‘stable fully-filled s sub-shell’ and ‘stable half-filled p sub-shell’ heuristics to explain, for example, why magnesium had a higher first ionisation energy than aluminium, or why phosphorus had a higher first ionisation energy than sulphur. Four pre-service teachers were asked, in interviews, to explain the trend of ionisation energy across the elements, sodium to aluminium, and silicon to sulphur, and all of them referred to the ‘stable fully-filled s sub-shell’ and ‘stable half-filled p sub-shell’ heuristics in addition to the correct concepts in their explanations. Thus, the use of heuristics in the teaching of ionisation energy could be the most likely cause of the ‘stable fully-filled and half-filled orbital’ explanations. Again, there was no conflict between the curriculum model and the ‘stable fully-filled or half-filled sub-shell’ reasoning in explaining why the first ionisation energy of magnesium was higher than that of sodium and aluminium, or why the first ionisation of phosphorus was higher than that of silicon and sulphur. Therefore, the ‘stable fully-filled or half-filled sub-shell’ reasoning could be easily accepted as an explanation in addition to the curriculum model. It was also likely to be more easily remembered as it was a natural progression from the octet rule framework with which many students were familiar. Teachers need to be wary of using such heuristics in their teaching. Similar to the octet rule framework, teachers need to challenge their students to explain why fully-filled or half-filled sub-shells were stable to create dissatisfaction in their alternative conception in order for conceptual change to take place (Posner et al., 1982).

The conservation of force thinking could have arisen because the students did not integrate their knowledge of electrostatics learned in physics with the concepts of ionisation energy learnt in chemistry (Taber, 1998a, 2003a) or the students might not have studied A-level physics at all. As Taber (2000a) mentioned, the conservation of force thinking (like the idea that full shells are desirable) has “an intuitive attraction to many students" (p. 156) – one will get a greater portion of a cake if there are less people sharing it. It also enables one to correctly predict successive ionisation energies. Thus, teachers should be careful not to use the phrase 'sharing of nuclear charge' during lessons. If only one or two of the three factors influencing ionisation energy (nuclear charge, distance from the nucleus and shielding/screening effect) were used during lessons to discuss the difference in ionisation energies of two or more elements, then students might not realise that they had to consider all three factors, not just one or two – this could be the cause of relation-based thinking. Teachers also need to check students' understanding of 'electrons-in-box' energy level diagrams and electronic configuration notations so that students would not leave with the idea that the diagrams and notations dealt with distance away from the nucleus.

It is worth noting that the lack of consistency found in the principles used to answer the earlier questions in the IEDI (Q1-4), and the use of relation-based thinking in the later items (Q5-10), may be closely related phenomena. So those students who, for example, used appropriate electrostatic ideas to answer Q1 but were attracted to the idea that full shells imply stability in Q3, may be selecting what seems the most appropriate response from a repertoire of potentially relevant principles in the same way as those who used ideas about, say, increased shielding whilst ignoring increased nuclear charge when comparing elements in Period 3. In one situation the students are selecting from alternatives with different status relative to the curriculum ('alternative' conceptions vs. appropriate concepts), and in the other situation they are selecting only one of the relevant appropriate alternatives – so in both cases they judge one of a number of potentially relevant explanatory principles as 'the' best answer in the context of a particular item.

The results from the study seemed to indicate that teachers need to teach or review basic Coulombic principles ($F \propto q_1q_2/r^2$) when they teach ionisation energy. As mentioned in the previous paragraph, teachers should explicitly consider all three factors (nuclear charge, distance from the nucleus and shielding/screening effect) to explain the trend of ionisation energy across a period. Taber (2002a; 2003a) recommends the teaching of the concept of core charges where the atom is thought of as "a shell of valence electrons enclosing a core – the nucleus and inner shells" (Taber, 2002a, p. 106, cf. Taber, 2003b). The valence electrons are said to be attracted by the nucleus but repelled by the electrons in the core (shielding). For example, the core charge of sodium is +1 [+11 + (-10)] and that of aluminium is +3 [+13 + (-10]). This can help students to understand why the first ionisation energy of aluminium is greater than that of sodium, why atomic radii decrease across a period, and also why the 3p electron of aluminium is, in generally, closer to nucleus than the 3s electron of sodium. However, core charge, by itself, cannot explain why the first ionisation energies of magnesium and phosphorus are greater than that of aluminium and sulphur, respectively. It will not be considered a problem if the students use core charge to predict the above trends of first ionisation energy incorrectly as they are using a concept which is scientifically acceptable and able to predict the general trend of ionisation energy across a period. The students only need to know additional information to explain the anomalies, for example, that the shielding of the 3p electron of aluminium and the repulsion between the paired 3p electrons of sulphur outweigh their increased core charges compared to magnesium and phosphorus, respectively.

Repulsion between electrons or the ‘size’ of the valence shell has to also be considered to explain successive ionisation energies of an atom, for example, why the third ionisation energy of sodium is higher than its second ionisation energy (Taber, 2003a). The second and third electrons in the L shell of sodium are attracted by a core charge of +9 [+11 + (-2)] but when the second electron is removed, there will be less repulsion between the seven remaining electrons, resulting in a smaller L shell. Thus the third electron will be closer to the nucleus and is more strongly attracted by the nucleus, requiring more energy for its removal.

A possible analogy to teach the nuclear attraction for an electron is to say that it is similar to the heat one receives from a bonfire - this is dependent on how big the bonfire is, the distance one is away from the bonfire and whether one is blocked (screened/shielded) from the bonfire, but is independent of how many people are present at the same distance away from the bonfire. This analogy may prevent students from thinking that electrons ‘share’ the attraction from the nucleus. However, this analogy does not take into account the equal and mutual attraction of the nucleus and the electron, as well as the repulsion between electrons, so this has to be highlighted. In addition, to prevent confusion in the use of the bonfire analogy, there may be a need to stress that electrostatic attraction is involved in nuclear attraction for electrons while convection and radiation are evolved in the net flow of heat from the bonfire to a person.

Further research

From the discussion in the previous chapter, it was seen that an introductory tertiary chemistry textbook used the octet rule framework and 'stable fully-filled or half-filled sub-shell' reasoning to explain the trend of ionisation energy. Thus, as an extension of this study, curriculum materials, for example, a wider range of A-level chemistry textbooks as well as teacher-prepared lecture notes and tutorial worksheets could be analysed to determine if they contain examples of statements or drawings that could lead to alternative conceptions (Sanger & Greenbowe, 1999).

Lenton and Turner (1999) found that science graduates did not necessarily understand and have sound knowledge of all parts of their own specialised subject, and that teaching or training in the subject area during a teacher-preparation course did not necessarily improve subject matter knowledge. "Teachers' knowledge about the subject matter and their conceptions about the phenomena they teach can enhance or limit students' learning" (Valanides, 2000, p. 250), so Lenton and Turner (1999) are concerned that the pre-service teachers may be "perpetuating the teaching of basic misconceptions in science" (p. 71). Indeed, studies have shown that pre-service teachers have alternative conceptions similar to that of students, for example, in the areas of chemical equilibrium (Quilez-Pardo & Solaz-Portoles, 1995), redox reactions (De Jong, Acampo, & Verdonk, 1995), and behaviour of gases (Lin, Cheng, & Lawrenz, 2000). Teachers may unwittingly transmit their alternative conceptions to their students, and when they have the same alternative conceptions as their students, they think that there is nothing wrong with their students' conceptions (Wandersee, Mintzes, & Novak, 1994). Given the number of students taught over a teaching career, the generation of alternative conceptions can be quite significant (Valanides, 2000). Thus, in addition to studying students' understanding of difficult science concepts, the study could also be extended to determine teachers' understanding of the concepts. This is to enable teachers to be aware of their own difficulties and alternative conceptions, and how these problems may affect their teaching and their students' learning of the concepts.

An instructional package on ionisation energy based on the findings of this study could also be developed, and design experiments (Collins, 1999) could be implemented to determine if the instructional package has an effect on students' understanding and alternative conceptions of ionisation energy.

LIMITATIONS OF THE STUDY

The results and conclusions generated in this study refer specifically to the sample groups involved in the study. Generalisation of the findings to all A-level chemistry students in Singapore must be considered with caution due to the nature and the limited number of A-level institutions involved in the study. Not all concepts and propositions related to A-level ionisation energy were measured by the IEDI, so the conclusions refer specifically to the concepts and propositions examined by the test items. The effects of the students' learning styles, the attitudes of the students towards the learning of chemistry, the classroom climate, as well as the effects of the different teachers, for example, their content and pedagogical content knowledge, teaching and management styles on the findings are unknown.

There are problems associated with the pencil-and-paper tests. For example, multiple-choice tests "make some demands on the reading/comprehension skills of the respondents" (Taber, 1999a, p. 99), and students do not "always perceive and interpret test statements in the way that test designers intend" (Hodson, 1993, p. 97). Students may not understand or may misinterpret the questions and options in the IEDI, and since they have little recourse for clarification, this may affect the validity and reliability of the test. However, the interviews included in the present study provide triangulation for the IEDI, and suggest this was not a major problem in the present research.

Another potential criticism of this type of work is that the elicited students' conceptions could be triggered by the questions used in the study (cf. Piaget, 1973 {1929}), rather than being established conceptions that are brought to light, that is, the students may never have thought about the concepts or phenomena before, but had to invent something to answer the researcher or the items in the IEDI. This would be unlikely in the present research given the match between the questions used and the A level specification (e.g., Appendix C cf. Appendix A). Students' guessing of answers also will affect validity and reliability of the test, though Tamir (1990) believes that if a test consists of cognitively high level items, students should be advised to attempt all items, making 'educated guesses' where necessary. The limited number of distracters that can be given in a question also meant that only the most common alternative conceptions were likely to be diagnosed (Taber, 1999b).

SUMMARY

This chapter summarises how the research questions raised in Chapter One were answered. The content framework for A-level ionisation energy was defined by a concept map, a list of propositional knowledge statements, and the matching of the concept map with the propositional knowledge statements. A two-tier diagnostic instrument was developed and administered to Grade 11 and 12 chemistry students, and it was found that the students had significant alternative conceptions, and these were classified under the headings ‘Octet rule framework’, ‘Stable fully-filled or half-filled sub-shells’, ‘Conservation of force thinking’ and ‘Relation-based reasoning’. Recommendations for the teaching and learning of ionisation energy were made and these included challenging students’ use of the octet framework, avoiding the use of the ‘stable fully-filled s sub-shell’ and ‘stable half-filled p sub-shell’ heuristics, checking students’ understanding of ‘electrons-in-box’ energy level diagrams and electronic configuration notations, discussing all three factors influencing ionisation energy when explaining the difference in ionisation energies of two or more elements, and teaching the concept of core charges and basic Coulombic principles. Further research involving the analysis of A-level textbooks and teacher-prepared materials, and determining A-level chemistry teachers’ understanding of ionisation energy was suggested, and the limitations of the study was also discussed.

REFERENCES

Abimbola, I.O. (1988). The problem of terminology in the study of student conceptions in science. *Science Education, 72*(2), 175-184.

Ausubel, D. (1968). *Educational Psychology: A Cognitive View*. Boston: Holt, Rinehart and Winston, Inc.

Ausubel, D. P. (2000). *The Acquisition and Retention of Knowledge: A Cognitive View*. Dordrecht: Kluwer Academic Publishers.

Bar, V. & Travis, A.S. (1991). Children's views concerning phase changes. *Journal of Research in Science Teaching, 28*(4), 363-382.

Barker, V. (2000). *Beyond Appearances: Students' Misconceptions About Basic Chemical Ideas.* A report prepared for the Royal Society of Chemistry, London: Education Division, Royal Society of Chemistry. [Available on LearnNet at www.chemsoc.org/LearnNet].

Barker, V. & Millar, R. (2000). Students' reasoning about basic chemical thermodynamics and chemical bonding: What changes occur during a context-based post-16 chemistry course? *International Journal of Science Education, 21*(6), 645-665.

Ben-Zvi, R. & Hofstein, A. (1996). Strategies for remediating learning difficulties in chemistry. In Treagust, D.F., Duit, R., & Fraser, B.J. (Eds.), *Improving Teaching and Learning in Science and Mathematics* (pp. 109–119). New York: Teachers College Press.

Boo, H. K. (1998). Students' understanding of chemical bonds and the energetics of chemical reactions. *Journal of Research in Science Teaching*, *35*(5), 569-581.

Cann, P. (2000). Ionization energies, parallel spins, and the stability of half-filled shells. *Journal of Chemical Education, 77*(8), 1056- 1061.

Caramazza, A., McCloskey, M. & Green, B. (1981). Naïve beliefs in "sophisticated" subjects: Alternative conceptions about trajectories of objects. *Cognition*, *9*, 117-123.

Caravita, S. & Halldén, O. (1994). Re-framing the problem of conceptual change, *Learning and Instruction*, *4*, 89-111.

Carr, M. (1984). Model confusion in chemistry. *Research in Science Education*, *14*, 97-103.

Carr, M. (1996). Interviews about instances and interviews about events. In Treagust, D.F., Duit, R.,& Fraser, B.J. (Eds.), *Improving Teaching and Learning in Science and Mathematics* (pp. 44-53). New York: Teachers College Press.

Chang. J.Y. (1999). Teachers college students' conceptions about evaporation, condensation, and boiling. *Science Education, 83*(5), 511-526.

Cho, H., Kahle, J. B. & Nordland, F. H. (1985). An investigation of high school biology textbooks as sources of alternative conceptions and difficulties in genetics and some suggestions for teaching genetics. *Science Education*, *69*(5), 707-719.

Collins, A. (1999). The changing infrastructure of education research. In Lagemann, E.C. & Shulman, L.S. (Eds.), *Issues in Educational Research: Problems and Possibilities* (pp. 289-298). San Francisco: Jossey-Bass Publishers.

Cox, R. A. (1996). Is it naïve to expect school science books to be accurate? *School Science Review*, *78*(282), 23-31.

de Jong, O., Acampo, J., & Verdonk, A. (1995). Problems in teaching the topic of redox reaction: Actions and conceptions of chemistry teachers. *Journal of Research in Science Teaching, 32*(10), 1097-1110.

de Posada, J. M. (1999). The presentation of metallic bonding in high school science textbooks during three decades: Science education reforms and substantive changes of tendencies. *Science Education*, *83*(4), 423-447.

Doran, R. L. (1972). Misconceptions of selected science concepts held by elementary school students. *Journal of Research in Science Teaching*, *9*(2), 127-137.

Driver, R. (1995). Constructivist approaches to science teaching. In Steffe, L.P. & Gale, J. (Eds.), *Constructivism in Education* (pp. 385-400). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Driver, R. & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education, 5*, 61-84.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996) *Young People's Images of Science*, Buckingham: Open University Press.

Driver, R. & Oldham, V. (1986). A constructivist approach to curriculum development in science. *Studies in Science Education, 13*, 105-122.

Driver, R. & Scott, P.H. (1996). Curriculum development as research: A constructivist approach to science curriculum development and teaching. In

Treagust, D.F., Duit, R.,& Fraser, B.J. (Eds.), *Improving Teaching and Learning in Science and Mathematics* (pp. 94–108). New York: Teachers College Press.

Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994) *Making Sense of Secondary Science: Research into Children's Ideas*. London: Routledge.

Duit, R. (1995). The constructivist view: A fashionable and fruitful paradigm for science education research and practice. In Steffe, L.P. & Gale, J. (Eds.), *Constructivism in Education* (pp. 271-285). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Duit, R., & Treagust, D.F. (1995). Students' conceptions and constructivist teaching approaches. In Fraser, B.J., & Walberg, H.J. (Eds.), *Improving Science Education* (pp. 46-69). Chicago, Illinois: The National Society for the Study of Education.

Duit, R., Treagust, D.F., & Mansfield, H. (1996). Investigating student understanding as a prerequisite to improving teaching and learning in science and mathematics. In Treagust, D.F., Duit, R.,& Fraser, B.J. (Eds.), *Improving Teaching and Learning in Science and Mathematics* (pp. 17–31). New York: Teachers College Press.

Ebenezer, J.V. & Erickson, G.L. (1996). Chemistry students' conceptions of solubility: A phenomenography. *Science Education, 85*(5), 509-535.

Fensham, P. J., Garrard, J. & West, L. W. (1981). The use of cognitive mapping in teaching and learning strategies. *Research in Science Education*, *11*, 121-129.

Fetherstonhaugh, T. & Treagust, D.F. (1992). Students' understanding of light and its properties: Teaching to engender conceptual change. *Science Education, 76*(6), 653-672.

Fisher, K. M. (1985). A misconception in biology: Amino acids and translation. *Journal of Research in Science Teaching*, *22*(1), 53.62.

Gabel, D.L. (1989). Let us go back to nature study. *Journal of Chemical Education, 66*(9), 727-729.

Gabel, D.L. & Bunce, D.M. (1994). Research on problem solving: chemistry. In D.L. Gabel (Ed*.), Handbook of Research on Science Teaching and Learning* (pp. 177-210). New York: Macmillan.

Gardner, P. L. (1986). Physics student's comprehension of motion with constant velocity. *Australian Science Teachers' Journal*, *31*(27), 27-32.

Garnett, P. J., Garnett, P. J. & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education, 25*, 69-95.

Garnett, P.J., Garnett, P.J., & Treagust, D.F. (1990). Implications of research on students' understanding of electrochemistry for improving science curricula and classroom practice. *International Journal of Science Education, 12*(2), 147-156.

Gilbert, J. K., Osborne, R. J. & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education, 66*(4), 623-633.

Gilbert, J.K. & Watts, D.M. (1983). Concepts, misconceptions and alternative conceptions: Changing perspectives in science education. *Studies in Science Education, 10,* 61-98.

Griffiths, A. K. & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611-628.

Halloun, I.A. & Hestenes, D. (1985). The initial knowledge state of college physics students. *American Journal of Physics, 5,* 1043-1055.

Harrison, A.G. & Treagust, D.F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education, 80*(5), 509-534.

Harrison, A. G. & Treagust, D. F. (2000). Learning about atoms, molecules, and chemical bonds: a case study of multiple-model use in grade 11 chemistry. *Science Education*, *84*, 352-381.

Hashweh, M.Z. (1986). Toward an explanation of conceptual change. *European Journal of Science Education. 8*(3), 229-249.

Haslam, F. & Treagust, D. F. (1987). Diagnosing secondary students misconceptions of photosynthesis and respiration in plants using a two-tier multiple choice instrument. *Journal of Biological Education*, *21*, 203-211.

Hewson, P. (1981). A conceptual change approach to learning science. *European Journal of Science Education, 3*(4), 383-396.

Hewson, P.J. (1996). Teaching for conceptual change. In Treagust, D.F., Duit, R.,& Fraser, B.J. (Eds.), *Improving Teaching and Learning in Science and Mathematics* (pp. 131–140). New York: Teachers College Press.

Hill, G.C. & Holman, J.S. (1980). *Chemistry in Context*. Frome and London: The English Language Book Society and Nelson.

Hodson, D. (1993). Re-thinking old ways: Towards a more critical approach to practical work in school science. *Studies in Science Education*, *22*, 85-142.

Johnson, P. & Gott, R. (1996). Constructivism and evidence from children’s ideas. *Science Education*, *80*(5), 561-577.

Johnstone, A.H. (2000). Teaching of chemistry – logical or psychological? *Chemistry Education: Research and Practice*, *1*(1), 9-15. [Available at http://www.uoi.gr/cerp/]

Kinchin, I.M. (2000). Using concept maps to reveal understanding: a two-tier analysis. *School Science Review*, *81*(296), 41-46.

Kind, V. & Taber, K. S. (in press). *Teaching Secondary Subjects 11-19: Science*. London: Routledge Falmer.

Kwon, Y.J. & Lawson, A.E. (2000). Linking brain growth with the development of scientific reasoning ability and conceptual change during adolescence. *Journal of Research in Science Teaching*, *37*(1), 44-62.

Lazarowitz, R. & Tamir, P. (1994). Research on using laboratory instruction in science. In D.L. Gabel (Ed.*)*, *Handbook of Research on Science Teaching and Learning* (pp. 94-128). New York: Macmillan.

Leach, J. & Scott, P. (1995). The demands of learning science concepts - issues of theory and practice. *School Science Review*, *76*(277), 47-51.

Leach, J, & Scott, P. (2002). Designing and evaluating science teaching sequences: an approach drawing upon the concept of learning demand and a social constructivist perspective on learning, *Studies in Science Education*, *38*, 115-142.

Lee, J.D. (1977). *A New Concise Inorganic Chemistry (3rd Ed).* Wokingham, Berkshire: Van Nostrand Reinhold.

Lee, K.W.L. (1999). A comparison of university lecturers’ and pre-service teachers’ understanding of a chemical reaction at particulate level. *Journal of Chemical Education*, *76*(7), 1008-1012.

Lenton, G. & Turner, L. (1999). Student-teachers’ grasp of science concepts. *School Science Review*, *81*(295), 67-72.

Lin, H.S., Cheng, H.J., & Lawrenz, F. (2000). The assessment of students’ and teachers’ understanding of gas laws. *Journal of Chemical Education*, *77*(2), 235-237.

Markham, K.M. & Mintzes, J.J. (1994). The concept map as a research and evaluation tool: Further evidence of validity. *Journal of Research in Science Teaching, 31*(1), 91-101.

Markow, P.G. & Lonning, R.A. (1998). Usefulness of concept maps in college chemistry laboratories: students' perceptions and effects on achievement. *Journal of Research in Science Teaching, 35*(9), 1015-1029.

McCloskey, M. (1983). Intuitive physics. *Scientific American, 248*, 122-130.

McDermott, D.P. (1988). Chemistry and the framework of learning. *Journal of Chemical Education, 65*(6), 539-540.

Nakhleh, M.B. (1992). Why some students don't learn chemistry: chemical misconceptions. *Journal of Chemical Education, 69*(3), 191-196.

Novak, J. D., & Gowin, D. B. (1984). *Learning How to Learn.* New York and Cambridge, UK: Cambridge University Press.

Novak, J.D. & Musonda, D. (1991). A twelve-year longitudinal study of science concept learning. *American Educational Research Journal, 28*(1), 117-153.

Nussbaum, J. & Novak, J. D. (1976). An assessment of children's concepts to the earth utilizing structured interview. *Science Education*, *60*(4), 535-550.

Odom, A. L. & Barrow, L. H. (1995). Development and application of a two-tier diagnostic test measuring college biology students' understanding of diffusion and osmosis after a course of instruction. *Journal of Research in Science Teaching*, *32*(1), 45-61.

Osborne, J.F. (1996). Beyond constructivism. *Science Education, 80*(1), 53-82.

Osborne, R. J., Bell, B. F. & Gilbert, J. K. (1983). Science teaching and children's view of the world. *European Journal of Science Education*, *5*(1), 1-14.

Osborne, R. J. & Gilbert, J. K. (1980). A method for investigating concept understanding in science. *European Journal of Science*, *2*(3), 311-321.

Osborne, R. J. & Wittrock, M. C. (1985). The generative learning model and its implication for science education. *Studies in Science Education*, *12*, 59-87.

Palmer, D.H. (1999). Exploring the link between students' scientific and nonscientific conceptions. *Science Education, 83*(6), 639-653.

Pedrosa, M. A. & Dias, M. H. (2000). Chemistry textbook approaches to chemical equilibrium and student alternative conceptions. *Chemistry Education: Research and Practice*, *1*(2), 227-236. [Available at http://www.uoi.gr/cerp/]

Peterson, R.F. (1986). *The Development, Validation and Application of a Diagnostic Test Measuring Year 11 and 12 Students' Understanding of Covalent Bonding and Structure.* Unpublished Master's thesis, Curtin University of Technology, Western Australia.

Peterson, R. F. & Treagust, D. F. (1989). Grade-12 students’ alternative conceptions of covalent bonding and structure. *Journal of Chemical Education*, *66*(6), 459-460.

Peterson, R. F., Treagust, D. F. & Garnett, P. (1989). Development and application of a diagnostic instrument to evaluate grade-11 and –12 students’ concepts of covalent bonding and structure following a course of instruction. *Journal of Research in Science Teaching*, *26*(4), 301-314.

Piaget, J. (1973). *The Child’s Conception of The World* (tr. Joan & Andrew Tomlinson). St. Albans, U.K.: Granada (first published in Great Britain by Routledge & Kegan Paul, 1929).

Posner, G. J., Strike, K. A., Hewson, P. & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Quilez, J. & Solaz, J.J. (1995). Students’ and teachers’ misapplication of Le Chatelier’s principle: Implications for the teaching of chemical equilibrium. *Journal of Research in Science Teaching*, *32*(9), 939-957.

Ross, B. and Munby, H. (1991). Concept mapping and misconceptions: A study of high-school students’ understandings of acids and bases. *International Journal of Science Education*, *13*(1), 11-23.

Sanger, M. J. & Greenbowe, T. J. (1999). An analysis of college chemistry textbooks as sources of misconceptions and errors in electrochemistry. *Journal of Chemical Education*, *76*(6), 853-860.

Schmidt, H.J, (1991). A label as a hidden persuader: chemists’ neutralization concept. *International Journal of Science Education, 13* (4), 459-471.

Schmidt, H.J. (2000). Should chemistry lessons be more intellectually challenging? *Chemistry Education: Research and Practice*, *1*(1), 17-26. [Available at http://www.uoi.gr/cerp/]

Scott, P., Asoko, H., Driver, R., & Emberton, J. (1994). Working from children’s ideas: Planning and teaching a chemistry topic from a constructivist perspective. In Fensham, P.J., Gunstone, R.F. & White, R.T. (Eds.), *The Content of Science: A*

Constructivist Approach to its Teaching and Learning (pp. 201-220). London: Falmer Press.

Shipstone, D. M. (1984). A study of children's understanding of electricity in simple DC circuits. *European Journal of Science Education*, *6*, 185-198.

Solomon, J. (1992). *Getting to Know about Energy - in School and Society*. London: Falmer Press

Solomon, J. (1994). The rise and fall of constructivism. *Studies in Science Education, 23*, 1-19.

Taber, K. S. (1997a). Student understanding of ionic bonding: molecular versus electrostatic framework? *School Science Review*, *78*(285), 85-95.

Taber, K. S. (1997b). *Understanding Chemical Bonding – the Development of A-level Students' Understanding of the Concepts of Chemical Bonding*. PhD thesis, University of Surrey.

Taber, K.S. (1998a). The sharing-out of nuclear attraction: or "I can't think about physics in chemistry. *International Journal of Science Education, 20*(8), 1001-1014.

Taber, Keith S. (1998b) An alternative conceptual framework from chemistry education. *International Journal of Science Education*, *20*(5), 597-608.

Taber, K. S. (1999a). Ideas about ionisation energy: a diagnostic instrument. *School Science Review*, *81*(295), 97-104.

Taber, K.S. (1999b). Alternative frameworks in chemistry. *Education in Chemistry, 36*(5), 135-137.

Taber, K.S. (2000a). Case studies and generalizability: grounded theory and research in science education. *International Journal of Science Education*, *22*(5), 469-487.

Taber, K. S. (2000b) *Trainee Science Teachers' Conceptions of Chemical Stability.* [Available via Educati*on-line*, at http://www.leeds.ac.uk/educol/].

Taber, K. S. (2000c) Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure, *International Journal of Science Education*, 22 (4), pp.399-417

Taber, K. S. (2001). Building the structural conception of chemistry: Some considerations from educational research. *Chemistry Education: Research and Practice*, *2*(2), 123-158. [Available at http://www.uoi.gr/cerp/]

Taber, K.S. (2002a). A core concept in teaching chemistry. *School Science Review, 84*(306), 105 -110.

Taber, K. S. (2002b). *Chemical Misconceptions - Prevention, Diagnosis and Cure*, 2 volumes. London: Royal Society of Chemistry.

Taber, K. S. (2002c). "Intense, but it's all worth it in the end": the colearner's experience of the research process. *British Educational Research Journal*, *28*(3), 435-457.

Taber, K. S. (2003a). Understanding ionisation energy: physical, chemical and alternative conceptions. *Chemistry Education: Research and Practice, 4*(2), 149-169. [Available at http://www.uoi.gr/cerp/]

Taber, K. S. (2003b) The atom in the chemistry curriculum: fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry*, *5*(1), 43-84.

Taber, K. S. (in press) Learning quanta: barriers to stimulating transitions in student understanding of orbital ideas. *Science Education*.

Taber, K. S. & Watts, M. (2000). Learners' explanations for chemical phenomena. *Chemical Education: Research and Practice*, *1,* 329-353. [Available at http://www.uoi.gr/cerp/]

Tamir, P. (1971). An alternative approach to the construction of multiple choice test items. *Journal of Biological Education, 5,* 305-307.

Tamir, P. (1990). Justifying the selection of answers in multiple choice items. *International Journal of Science Education, 12*(3), 563-573.

Tan, K.-C.D., Goh, N.K., Chia, L.S., & Treagust, D.F. (2002). Development and application of a two-tier multiple choice diagnostic instrument to assess high school students' understanding of inorganic chemistry qualitative analysis. *Journal of Research in Science Teaching, 39*(4), 283-301.

Tan, K.-C, D. (2002). Content framework for teaching and learning inorganic qualitative analysis at the high school level. *Australian Journal of Education in Chemistry, 58*, 7-12.

Tan, K.-C.D. & Treagust, D. F. (1999). Evaluating students' understanding of chemical bonding. *School Science Review, 81*(294), 75-83.

Taylor, N. & Coll, R. (1997). The use of analogy in the teaching of solubility to pre-service primary teachers. *Australian Science Teachers' Journal, 43*(4), 58-64.

Towns, M. H. & Robinson, W. R. (1993). Student use of test-wiseness strategies in solving multiple choice chemistry examinations. *Journal of Research in Science Teaching, 30*(7), 709-722.

Treagust, D. F. (1986). Evaluating students' alternative conceptions by means of diagnostic multiple choice items. *Research in Science Education*, *16*, 199-207.

Treagust, D. F. (1988). The development and use of diagnostic instruments to evaluate students' alternative conceptions in science. *International Journal of Science Education*, *10*(2), 159-169.

Treagust, D. F. (1995). Diagnostic assessment of students' science knowledge. In S. M. Glynn & R. Duit. (Eds.), *Learning Science in the Schools: Research Reforming Practice* (pp. 327-346). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Treagust, D.F., Duit, R., & Fraser, B.J. (1996). Overview: Research on students' preinstructional conceptions – the driving force for improving teaching and learning in science and mathematics. In Treagust, D.F., Duit, R.,& Fraser, B.J. (Eds.), *Improving Teaching and Learning in Science and Mathematics* (pp. 1–14). New York: Teachers College Press.

Tyson, L., Treagust, D. F., & Bucat, R. B. (1999). The complexity of teaching and learning chemical equilibrium. *Journal of Chemical Education*, *76*(4), 554-558.

Valanides, N. (2000). Primary student teachers' understanding of the particulate nature of matter and its transformation during dissolving. *Chemistry Education: Research and Practice*, *1*(2), 249-262 [Available at http://www.uoi.gr/cerp/]

Voska, K. W. & Heikkinen, H. W. (2000). Identification and analysis of student conceptions used to solve chemical equilibrium problems. *Journal of Research in Science Teaching*, *37*(2), 160-176.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction*, *4*, 45-69.

Wandersee, J. H., Mintzes, J. J. & Novak, J. D. (1994). Research on alternative conceptions in Science. In D. L. Gabel (Ed.), *Handbook of Research on Science Teaching and Learning* (p. 177-210). New York: Macmillan.

Watts, D. M. (1983). A study of school children's alternative frameworks of the concept of force. *European Journal of Science*, *5*(2), 217-230.

Watts, D. M. & Gilbert, J. (1983). Enigmas in school science: students' conceptions for scientifically associated words, *Research in Science and Technological Education*, *1*(2), 161-171.

White, R. T. & Gunstone, R. F. (1992). *Probing Understanding*. London: The Falmer Press.

Willson, M. & Williams, D. (1996). Trainee-teachers' misunderstandings in chemistry: diagnosis and evaluation using concept mapping. *School Science Review, 77*(280), 107-113.

Wittrock, M.C. (1994). Generative science teaching. In Fensham, P.J., Gunstone, R.F. & White, R.T. (Eds.), *The Content of Science: A Constructivist Approach to its Teaching and Learning* (pp. 225-262). London: Falmer Press.

Yarroch, W. L. (1985). Student understanding of chemical equation balancing. *Journal of Research in Science Teaching*, *22*(5), 449-459.

Appendix A

Assessment objectives on ionisation energy in the A-level syllabus for 2001

Atomic structure

1. Explain the factors influencing the ionisation energies of elements.
2. Explain trends in ionisation energy across a period and down a group of the Periodic Table.
3. Deduce the electronic configurations of elements from successive ionisation energy data.
4. Interpret successive ionisation energy data of an element in terms of the position of that element within the Periodic Table.

Chemical energetics

Apply Hess' Law to construct simple energy cycles, e.g., Born-Haber cycle, and carry out calculations involving such cycles and relevant energy terms (including ionisation energy and electron affinity).

The periodic table: Chemical periodicity

Periodicity of physical properties of the elements: variation with proton number across the third period (sodium to argon)

1. Explain the variation in first ionisation energy.
2. Deduce the nature, possible position in the Periodic Table, and identity of unknown elements from given information of physical and chemical properties.

APPENDIX B

The third version of the justification multiple-choice instrument

For Questions 1 to 5, please refer to the statement below.

Sodium atoms are ionised to form sodium ions as follows:
$Na(g) \rightarrow Na^+(g) + e$

1. All electrons in the sodium atom (electronic configuration 2.8.1) are attracted equally to the nucleus.
   A True.
   B False.
   C I do not know the answer. ( )

   Reason:

2. Once the outermost electron is removed from the sodium atom forming the sodium ion (Na^+), the sodium ion will not combine with an electron to reform the sodium atom.
   A True.
   B False.
   C I do not know the answer. ( )

   Reason:

3. When an electron is removed from the sodium atom, the attraction of the nucleus for the ‘lost’ electron will be redistributed among the remaining electrons in the sodium ion (Na^+).
   A True.
   B False.
   C I do not know the answer. ( )

   Reason:

4. The $Na^+(g)$ ion is more stable than the $Na(g)$ atom.
   A True.
   B False.
   C I do not know the answer. ( )

   Reason:

5. After the sodium atom is ionised (i.e. forms Na^+ ion), more energy is required to remove a second electron (i.e. the second ionisation energy is greater than the first ionisation energy) from the Na^+ ion.
   A True.
   B False.
   C This should not happen as the Na^+ ion will not lose any more electrons.
   D I do not know the answer. ( )

   Reason:

6. Sodium, magnesium and aluminium are in Period 3. How would you expect the first ionisation energy of sodium ($1s^2\ 2s^2\ 2p^6\ 3s^1$) to compare to that of magnesium ($1s^2\ 2s^2\ 2p^6\ 3s^2$)?
   A. The first ionisation energy of sodium is greater than that of magnesium.
   B. The first ionisation energy of sodium is less than that of magnesium.
   C. The first ionisation energy of sodium is equal to that of magnesium.
   D. I do not know the answer. ( )

   Reason:

7. How do you expect the first ionisation energy of magnesium ($1s^2\ 2s^2\ 2p^6\ 3s^2$) to compare to that of aluminium ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$)?
   A. The first ionisation energy of magnesium is greater than that of aluminium.
   B. The first ionisation energy of magnesium is less than that of aluminium.
   C. The first ionisation energy of magnesium is equal to that of aluminium.
   D. I do not know the answer. ( )

   Reason

8. How do you expect the first ionisation energy of sodium ($1s^2\ 2s^2\ 2p^6\ 3s^1$) to compare to that of aluminium ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$)?
   A. The first ionisation energy of sodium is greater than that of aluminium.
   B. The first ionisation energy of sodium is less than that of aluminium.
   C. The first ionisation energy of sodium is equal to that of aluminium.
   D. I do not know the answer. ( )

   Reason

9. Silicon, phosphorus and sulphur are in Period 3. How would you expect the first ionisation energy of silicon ($1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^2$) to compare to that of phosphorus ($1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^3$)?
A The first ionisation energy of silicon is greater than that of phosphorus.
B The first ionisation energy of silicon is less than that of phosphorus.
C The first ionisation energy of silicon is equal to that of phosphorus.
D I do not know the answer. ( )

Reason:

10. How would you expect the first ionisation energy of phosphorus ($1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^3$) to compare to that of sulphur ($1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^4$)?
A The first ionisation energy of phosphorus is greater than that of sulphur.
B The first ionisation energy of phosphorus is less than that of sulphur.
C The first ionisation energy of phosphorus is equal to that of sulphur.
D I do not know the answer. ( )

Reason:

11. How would you expect the first ionisation energy of silicon ($1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^2$) to compare to that of sulphur ($1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^4$)?
A The first ionisation energy of silicon is greater than that of sulphur.
B The first ionisation energy of silicon is less than that of sulphur.
C The first ionisation energy of silicon is equal to that of sulphur.
D I do not know the answer. ( )

Reason:

APPENDIX C

The Ionisation Energy Diagnostic Instrument (IEDI)

Instructions
Choose the most suitable option and the reason for your choice in each question by filling the appropriate circles in the answer sheet. **If you feel that <u>all options given are inappropriate</u>**, indicate the question number and write down what you think the correct answer should be behind the answer sheet.

For Questions 1 to 4, please refer to the statement below.

Sodium atoms are ionised to form sodium ions as follows:

$Na(g) \rightarrow Na^+(g) + e$

1. Once the outermost electron is removed from the sodium atom forming the sodium ion (Na^+), the sodium ion will not combine with an electron to reform the sodium atom.
   A True.
   B False.
   C I do not know the answer.

   Reason:
   (1) Sodium is strongly electropositive, so it only loses electrons.
   (2) The Na^+ ion has a stable/noble gas configuration, so it will not gain an electron to lose its stability.
   (3) The positively-charged Na^+ ion can attract a negatively-charged electron.

2. When an electron is removed from the sodium atom, the attraction of the nucleus for the 'lost' electron will be redistributed among the remaining electrons in the sodium ion (Na^+).
   A True.
   B False.
   C I do not know the answer.

   Reason:
   (1) The amount of attraction between an electron and the nucleus depends on the number of protons present in the nucleus and the distance of the electron from the nucleus. It does not depend on how many other electrons are present, although electrons do repel each other (and can shield one another from the nucleus)
   (2) The electron which is removed will take away the attraction of the nucleus with it when it leaves the atom.
   (3) The number of protons in the nucleus is the same but there is one less electron to attract, so the remaining 10 electrons will experience greater attraction by the nucleus.

3. The Na(g) atom is a more stable system than the Na^+(g) ion and a free electron.
   A True.
   B False.
   C I do not know the answer.

   Reason:
   (1) The Na(g) atom is neutral and energy is required to ionise the Na(g) atom to form the Na^+ (g) ion.
   (2) Average force of attraction by the nucleus on each electron of Na^+ (g) ion is greater than that of Na(g) atom.
   (3) The Na^+(g) ion has a vacant shell which can be filled by electrons from other atoms to form a compound.
   (4) The outermost shell of Na^+(g) ion has achieved a stable octet/noble gas configuration.

4. After the sodium atom is ionised (i.e. forms Na^+ ion), more energy is required to remove a second electron (i.e. the second ionisation energy is greater than the first ionisation energy) from the Na^+ ion.
   A True.
   B False.
   C This should not happen as the Na^+ ion will not lose any more electrons.
   D I do not know the answer.

   R*eason:*
   (1) Removal of the second electron disrupts the stable octet structure of Na^+ ion.
   (2) The same number of protons in Na^+ attracts one less electron, so the attraction for the remaining electrons is stronger.
   (3) The second electron is located in a shell which is closer to the nucleus.
   (4) The second electron is removed from a paired 2p orbital and it experiences repulsion from the other electron in the same orbital.

5. Sodium, magnesium and aluminium are in Period 3. How would you expect the first ionisation energy of sodium ($1s^2\ 2s^2\ 2p^6\ 3s^1$) to compare to that of magnesium ($1s^2\ 2s^2\ 2p^6\ 3s^2$)?
   A. The first ionisation energy of sodium is greater than that of magnesium.
   B. The first ionisation energy of sodium is less than that of magnesium.
   C. I do not know the answer.

   Reason:
   (1) Magnesium has a fully-filled 3s sub-shell which gives it stability.
   (2) Sodium will achieve a stable octet configuration if an electron is removed.
   (3) In this situation, the effect of an increase in nuclear charge in magnesium is greater than the repulsion between its paired electrons in the 3s orbital.
   (4) The paired electrons in the 3s orbital of magnesium experience repulsion from each other, and this effect is greater than the increase in the nuclear charge in magnesium.
   (5) The 3s electrons of magnesium are further from the nucleus compared to those of sodium.

6. How do you expect the first ionisation energy of magnesium ($1s^2\ 2s^2\ 2p^6\ 3s^2$) to compare to that of aluminium ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$)?
   A. The first ionisation energy of magnesium is greater than that of aluminium.
   B. The first ionisation energy of magnesium is less than that of aluminium.
   C. I do not know the answer.

   Reason
   (1) Removal of an electron will disrupt the stable completely-filled 3s sub-shell of magnesium.
   (2) The 3p electron of aluminium is further from the nucleus compared to the 3s electrons of magnesium.
   (3) In this situation, the effect of an increase in nuclear charge in aluminium is greater than the repulsion between the electrons in its outermost shell.
   (4) In this situation, the effect of an increase in nuclear charge in aluminium is less than the repulsion between the electrons in its outermost shell.
   (5) The paired electrons in the 3s orbital of magnesium experience repulsion from each other, whereas the 3p electron of aluminium is unpaired.

7. How do you expect the first ionisation energy of sodium ($1s^2\ 2s^2\ 2p^6\ 3s^1$) to compare to that of aluminium ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$)?
   A. The first ionisation energy of sodium is greater than that of aluminium.
   B. The first ionisation energy of sodium is less than that of aluminium.
   C. I do not know the answer.

   Reason
   (1) Aluminium will attain a fully-filled 3s sub-shell if an electron is removed.
   (2) Sodium will achieve a stable octet configuration if an electron is removed.
   (3) The 3p electron of aluminium experiences greater shielding from the nucleus compared to the 3s electron of sodium.
   (4) The 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium.
   (5) In this situation, the effect of an increase in nuclear charge in aluminium is greater than the shielding of the 3p electron by the 3s electrons.

8. Silicon, phosphorus and sulphur are in Period 3. How would you expect the first ionisation energy of silicon ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$) to compare to that of phosphorus ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^3$)?
   A The first ionisation energy of silicon is greater than that of phosphorus.
   B The first ionisation energy of silicon is less than that of phosphorus.
   C I do not know the answer.

   Reason:
   (1) Silicon has less electrons than phosphorus, thus its 3p electrons face less shielding.
   (2) The 3p sub-shell of phosphorus is half-filled, hence it is stable.
   (3) The 3p electrons of phosphorus are further away from the nucleus compared to that of silicon.
   (4) In this situation, the effect of an increase in nuclear charge in phosphorus is greater than the repulsion between its 3p electrons.

9. How would you expect the first ionisation energy of phosphorus ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^3$) to compare to that of sulphur ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^4$)?

   A The first ionisation energy of phosphorus is greater than that of sulphur.
   B The first ionisation energy of phosphorus is less than that of sulphur.
   C I do not know the answer.

   Reason
   (1) More energy is required to overcome the attraction between the paired 3p electrons in sulphur.
   (2) 3p electrons of sulphur are further away from the nucleus compared to that of phosphorus.
   (3) The 3p sub-shell of phosphorus is half-filled, hence it is stable.
   (4) In this situation, the effect of an increase in nuclear charge in sulphur is greater than the repulsion between its 3p electrons.
   (5) In this situation, the effect of an increase in nuclear charge in sulphur is less than the repulsion between its 3p electrons.

10. How would you expect the first ionisation energy of silicon ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$) to compare to that of sulphur ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^4$)?
   A The first ionisation energy of silicon is greater than that of sulphur.
   B The first ionisation energy of silicon is less than that of sulphur.
   C I do not know the answer.

   Reason
   (1) Sulphur will have its 3p sub-shell half-filled if an electron is removed.
   (2) The 3p electrons of sulphur are further away from the nucleus compared to that of silicon.
   (3) In this situation, the effect of an increase in nuclear charge in sulphur is greater than the repulsion between its 3p electrons.
   (4) In this situation, the effect of an increase in nuclear charge in sulphur is less than the repulsion between its 3p electrons.