Open Access Repository
www.ssoar.info

The insidious nature of 'hard core' alternative conceptions: Implications for the constructivist research programme of patterns in high school students' and pre-service teachers' thinking about ionisation energy

Taber, Keith Stephen; Tan, Daniel Kim Chwee

Postprint / Postprint
Zeitschriftenartikel / journal article

Zur Verfügung gestellt in Kooperation mit / provided in cooperation with:
www.peerproject.eu

Empfohlene Zitierung / Suggested Citation:
Taber, K. S., & Tan, D. K. C. (2011). The insidious nature of 'hard core' alternative conceptions: Implications for the constructivist research programme of patterns in high school students' and pre-service teachers' thinking about ionisation energy. *International Journal of Science Education*, *33*(2), 259-297. https://doi.org/10.1080/09500691003709880

Nutzungsbedingungen:
Dieser Text wird unter dem "PEER Licence Agreement zur Verfügung" gestellt. Nähere Auskünfte zum PEER-Projekt finden Sie hier: http://www.peerproject.eu Gewährt wird ein nicht exklusives, nicht übertragbares, persönliches und beschränktes Recht auf Nutzung dieses Dokuments. Dieses Dokument ist ausschließlich für den persönlichen, nicht-kommerziellen Gebrauch bestimmt. Auf sämtlichen Kopien dieses Dokuments müssen alle Urheberrechtshinweise und sonstigen Hinweise auf gesetzlichen Schutz beibehalten werden. Sie dürfen dieses Dokument nicht in irgendeiner Weise abändern, noch dürfen Sie dieses Dokument für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, aufführen, vertreiben oder anderweitig nutzen.
Mit der Verwendung dieses Dokuments erkennen Sie die Nutzungsbedingungen an.

Terms of use:
This document is made available under the "PEER Licence Agreement ". For more Information regarding the PEER-project see: http://www.peerproject.eu This document is solely intended for your personal, non-commercial use.All of the copies of this documents must retain all copyright information and other information regarding legal protection. You are not allowed to alter this document in any way, to copy it for public or commercial purposes, to exhibit the document in public, to perform, distribute or otherwise use the document in public.
By using this particular document, you accept the above-stated conditions of use.

gesis
Leibniz-Institut
für Sozialwissenschaften

Mitglied der
Leibniz-Gemeinschaft

Diese Version ist zitierbar unter / This version is citable under:
https://nbn-resolving.org/urn:nbn:de:0168-ssoar-254297

The insidious nature of ‘hard core’ alternative conceptions: Implications for the constructivist research programme of patterns in high school students’ and pre-service teachers’ thinking about ionisation energy.

Journal:	*International Journal of Science Education*
Manuscript ID:	TSED-2009-0205.R2
Manuscript Type:	Research Paper
Keywords:	alternative conception, chemistry education, conceptual change, teacher knowledge, misconception
Keywords (user):	research programme

The insidious nature of 'hard core' alternative conceptions: Implications for the constructivist research programme of patterns in high school students' and pre-service teachers' thinking about ionisation energy.

Abstract

The present study contributes to the constructivist research programme (RP) into learning science by comparing patterns in responses from two groups of learners - senior high schools students and pre-service teachers - in the same educational context (Singapore), to a diagnostic instrument relating to the topic of ionisation energies. This topic is currently included in the curriculum for 16-19 year-old students studying chemistry in Singapore (and elsewhere). The comparison shows that although (a) graduate pre-service teachers offered some types of incorrect responses less frequently than high school students; (b) they retained high levels of alternative conceptions commonly found among high school students; and - of particular note - (c) certain alternative conceptions were found to be *more* common among the graduates. This suggest the intuitive appeal of certain alternative conceptions is such that they can readily be reproduced down 'generations' of learners. The findings are explored in terms of a range of conceptual resources that have been developed within the constructivist RP. The analysis suggests that the curriculum sets out inappropriate target knowledge for senior high school students, given the nature of the subject matter and the prior learning of the students. It is also suggested that it may be fruitful to consider conceptual learning in terms analogous to the RP found in science, and that from this perspective certain insidious alternative conceptions can be understood as derived from commitments that are taken-for-granted and protected from explicit challenge by a protective belt of refutable auxiliary conceptions.

(247) (~~250~~)

The insidious nature of 'hard core' alternative conceptions: Implications for the constructivist research programme of patterns in high school students' and pre-service teachers' thinking about ionisation energy.

Introduction

This paper discusses findings from two studies in which a diagnostic instrument was administered to samples from populations of students and new teachers in the same wider educational context: Singapore. The populations were senior high school students studying for university entrance level (A level) chemistry examinations and graduate pre-service chemistry teachers.

The pre-service teachers would be expected to show progression in learning over the A level students, having successfully completed their own A level (or equivalent) studies and subsequently successfully undertaken a degree course in chemistry or a cognate subject. The purpose of the present paper is to compare the findings from the two studies, and to consider the significance of the outcome in terms of the nature of students' alternative conceptions, and how they interact with teaching.

Although it might expected that alternative conceptions will be less common among students as their educational level increases, it is known that some such conceptions are very stable despite teaching. Indeed, in some topics notable incidences of alternative conceptions have been found among those preparing for teaching (Trumper, 2001). When this happens, it seems likely that teachers' alternative conceptions may contribute to students developing similar ideas, so it would be useful to identify characteristics of such 'insidious' conceptions that may actually be reproduced down 'generations' of learners through formal schooling.

The present paper compares data from two studies in the same educational context, which applied the same methodology to investigate the understanding of substantial samples from populations at different educational level. This allows us to compare the responses from the two groups to consider the extent to which degree level study has eroded commitment to alternative conceptions. We will argue that our findings suggest that the alternative conceptions commonly found among students in the topic of ionisation energies are shared to a similar extent by their teachers, with the clear implication that teaching may well be a major source of these ideas, and suggesting that learners have a high level of commitment to the ideas once they are acquired, so that they tend to form the 'hard core' for developing understanding about the topic.

Background to the research

The present research may be considered to be part of a well-established tradition of exploring student thinking in science, that has uncovered a wide range of common ideas at odds with the target knowledge taught in school and college science (Driver, Squires, Rushworth, & Wood-Robinson, 1994; Duit, 1991, 2007). The findings of this research have been reported under a range of different labels, such as misconceptions, alternative conceptions, intuitive theories and alternative frameworks (Driver & Erickson, 1983; Driver et al., 1994; Gilbert & Watts, 1983; Pope & Denicolo, 1986).

Researching alternative conceptions

Despite this variation in terminology, most of the research into learners' ideas can be seen as part of a coherent programme of research within science education (Gilbert & Swift, 1985; Taber, 2006, 2009b). Although learners' ideas are often considered to be of intrinsic interest, the prime rationale for initiating this research programme (RP) was to inform the teaching of the scientific theories and models that are represented as 'target knowledge' in the school science curriculum (Driver & Easley, 1978; Driver & Erickson, 1983; Gilbert, Osborne, & Fensham, 1982; Gilbert & Watts, 1983; Osborne & Wittrock, 1983).

As the RP aims to inform teaching, it is not limited to identifying students' alternative ideas, and the frequencies with which they occur, but rather is also concerned with the origins and nature of students' conceptions, and how they interact with teaching. The various conceptions that have been identified vary along a range of dimensions (Claxton, 1993; diSessa, 2002; Driver, 1983, 1989; Driver & Easley, 1978; Driver, Guesne, & Tiberghien, 1985; Gilbert et al., 1982; Gilbert & Watts, 1983; Millar, 1989; Pope & Denicolo, 1986; Pope & Gilbert, 1983; Solomon, 1992; Taber, 2000, 2008b). So, some ideas may be strongly committed to and tenaciously retained despite being contrary to teaching (Taber, 2001a), where others seem to be readily set aside (Claxton, 1993). Sometimes students can be very explicit about their ideas (McCloskey, 1983), whereas other notions seem to be largely applied at an intuitive level, and are identified only indirectly (diSessa, 1993). Some studies suggest that at times an alternative idea will effectively block new learning (e.g. Chi, 1992), whereas other research finds that alternative conceptions may act as intermediate conceptions on conceptual trajectories leading to target knowledge (Driver, 1989). Yet other studies suggest that in some circumstances learners can adopt manifold conceptions of a topic with new ideas supplementing existing ways of thinking (e.g. Taber, 2000). Sometimes identified alternative conceptions seem to be somewhat isolated ideas (Claxton, 1993), whereas others seem to be integrated into theory-like conceptual frameworks (Taber, 1998a).

If this apparent variety is a genuine reflection of the nature of student thinking, then continued work in the RP should be exploring: the range of characteristics of learners' conceptions; from where they derive; how they interact with different teaching approaches; and how they are coordinated (or not) with other related aspects of a student's knowledge (Taber, 2009b). This, in principle, should lead to advice to teachers on *when* it is appropriate to challenge or to ignore alternative conceptions, or when and how to consider them as conceptual resources (Hammer, 2004) that can be developed towards target knowledge. To the extent that the development of some unhelpful conceptions may be encouraged by factors such as certain linguistic cues (Schmidt, 1991) and teaching models or approaches (Justi & Gilbert, 2000; Taber, 2001b), research may also be able to suggest teaching approaches to be avoided or adopted to help channel student thinking in the desired directions (Hammer, 2004). Research that has these characteristics may be characterised as part of a 'progressive' RP to inform science pedagogy (Taber, 2006, 2009b).

The nature of a scientific RP

We would then locate the present study within what is commonly referred to as the 'constructivist' RP into teaching and learning science (Taber, 2006, 2009b), which we consider a *scientific* RP that seeks to explore the nature and conditions of learning in science, and to inform the development of science pedagogy. The notion of scientific RPs was proposed by the philosopher Imre Lakatos (1970), to show how individual studies can contribute to developing knowledge within established research traditions. In the Lakatosian model, a RP has 'hard core' assumptions and what Lakatos called 'heuristic' apparatus guiding development of the programme. The hard core of a research programme is in effect its *metaphysical* foundation – it is the set of commitments that are *taken for granted*, and which are considered non-falsifiable within the programme. New information about a topic is used to build up more detailed understanding, but always consistent with the hard core. This more peripheral body of ideas is known as the 'protective belt', because when new data are inconsistent with the theoretical content of the RP, it is assumed that changes need to be made within the protective belt (which thus 'protects' the hard core from falsification).

The Lakatosian notion of RP can be seen as an attempt to bridge Kuhn's account of science where scientists commit to ideas so strongly it becomes difficult to recognise anomalies, and Popper's prescription with its implication that scientists should readily discard theories whenever apparently contradicted by experiments (Taber, 2009b). In a Lakatosian RP anomalies are recognised, but largely tolerated ('quarantined') as long as the overall RP is considered to be progressive, that is continuing to suggest new directions for empirical investigation, and making predictions which are found to be broadly consistent with empirical findings. Ultimately a RP may be discarded when a more promising alternative is available, but this tends to be a more global judgment about the potential of the programme for further progress, rather than responding to individual falsifications. So, for example, the Newtonian programme, with its hard-core commitment to absolute space and time, tolerated known anomalies about orbital behaviour until Einstein offered the basis of an alternative RP considered more fruitful.

Hard core commitments of the constructivist RP would include the beliefs that a student's current knowledge and understanding is a major factor in subsequent learning (Driver, 1989), and that more effective teaching can in principle be informed by a better understanding of the origins, nature and development of learners' ideas in science topics (Driver & Oldham, 1986; Leach & Scott, 2002; Russell & Osborne, 1993).

These hard core commitments suggest general directions for research (e.g. exploring student' ideas) that lead to particular theoretical constructs - such as the notion of alternative conceptual frameworks (Driver & Erickson, 1983; Gilbert & Watts, 1983) - and specific knowledge claims – for example, the octet framework represents common features of how learners understand fundamental aspects of chemistry (Taber, 1998a) – which are themselves open to further testing. Lakatos (1970) refers to a RP developing a protective belt of auxiliary theory that offers 'refutable variants' that are evaluated by the extent to which they help explain existing data, and suggest useful directions for further research.

Considering learners as Lakatosian scientists

Indeed, one perspective that has been suggested to illuminate why some identified alternative conceptions seem to be readily overcome whilst others are so tenacious, is to consider that *a student learning science* can be understood to respond to new information in much the same way as a scientist working within a Lakatosian RP (Watts & Pope, 1982). Considering student thinking in terms of Lakatos' model of RP has also informed one analytical scheme for exploring students' arguments about socio-scientific issues (Chang & Chiu, 2008).

Whilst comparisons between the progress of science and individual learning need to be made with caution, Watts and Pope's (1982) suggestion that some ideas that a learner develops may take on a hard-core status (attracting high levels of commitment), whilst others can be considered to be more peripheral and so readily shed, can have value for thinking about conceptual change among science learners. We suggest that in the topic explored in this paper, ionisation energy, certain common alternative conceptions reflect hard core commitments that are part of many learners taken-for-granted ways of thinking about the topic.

Origins of alternative conceptions

There is no single source that can account for all of the reported learners' alternative conceptions in science. Indeed, from a constructivist perspective (Fensham, Gunstone, & White, 1994), new science learning is always interpreted in terms of existing aspects of the students' 'cognitive structure' (White, 1985), and so the development of complex ideas is in effect an iterative process that is likely to indirectly involve the interaction of knowledge originating in various sources (Taber, 2008a).

However, to a first approximation (bearing in mind that these categories should not be seen as independent and exclusive), we might identify several main sources of learners' ideas: intuition (diSessa, 1993); the life-world (Solomon, 1992); language (Schmidt, 1991); creative acts of analogy (Taber, 2001b); and teaching. Teaching may act as a source of alternative conceptions if students are directly taught ideas that are not adequate reflections of the target knowledge, either due to misjudgments in the teaching models used (Justi & Gilbert, 2000), or due to flawed teacher knowledge.

The latter option actually comprises several quite different possibilities. Much of the teaching of science concerns models (Gilbert & Boulter, 2000). Indeed, scientific knowledge is often in the form of models, and this may be represented in simplified form as curriculum models that make up the prescribed 'target knowledge'; then teachers use a range of teaching models to introduce the ideas to the students (Gilbert et al., 1982). As students often do not appreciate the nature of models (e.g. as tools for thought that may have limited ranges of application), they may often understand them to be more literal and realistic than intended (Driver, Leach, Millar, & Scott, 1996; Grosslight, Unger, Jay, & Smith, 1991), causing learning difficulties when they are expected to shift between apparently inconsistent models during science learning.

Appreciating the nature of the models that are used in teaching, and how these are likely to be perceived by students, may be considered as part of a teachers' pedagogic content knowledge (Gess-Newsome & Lederman, 1999). However, it is also widely recognised that teachers' *actual* subject knowledge is inevitably imperfect, and even experienced teachers potentially have much to learn about the topics they teach (Goodwin, 2002). So, Bannerjee (1991), for example, reported Indian teachers having widespread misconceptions in the topic of chemical equilibrium. Bannerjee noted that in this study, which included undergraduates and schoolteachers,

> A comparative study of the responses given by students and teachers reveals that the extent of misconceptions is equally high among both groups. One possibility is that teachers might have developed these misconceptions during their student days. The misconceptions are retained, despite professional experience over the years.
>
> (Banerjee, 1991: 491)

Similarly, Dal (2006: 38) reports a Turkish study where "both the students and the student teachers had surprisingly similar alternative conceptions [of volcanoes and volcanic activity] despite the fact that the latter received more instruction on this topic".

A range of studies report subject knowledge deficiencies among trainee teachers ('pre-service' teachers), for example in astronomy (Trumper, 2001); matter conservation (Haidar, 1997); chemical equilibrium (Quilez-Pardo & Solaz-Portoles, 1995), redox reactions (De Jong, Acampo, & Verdonk, 1995), and behaviour of gases (Lin, Cheng, & Lawrenz, 2000). It seems likely that *teachers' own alternative conceptions themselves make up one significant factor in the development of some alternative conceptions among students*, and so an important focus of the constructivist RP should be the characteristics of alternative conceptions which remain unchallenged by degree level study and initial teacher education courses, and may be actually presented as target knowledge in science teaching.

Learning about the ionisation energy topic

Target knowledge about ionisation energies

In the Singapore context, students studying chemistry at senior high school (university entrance) level take the Singapore-Cambridge GCE A Level (General Certificate of Education, Advanced Level) examination (for which the Ministry of Education, Singapore and the University of Cambridge Local Examinations Syndicate are the joint examining authorities). The syllabus, sets out that

> "Candidates should be able to: explain the factors influencing the ionisation energies of elements; explain the trends in ionisation energies across a period and down a Group of the Periodic Table; deduce the electronic configurations of elements from successive ionisation energy data; interpret successive ionisation energy data of an element in terms of the position of that element within the Periodic Table…[for the third period (sodium to argon)] explain the variation in first ionisation energy"
>
> (Singapore Examinations and Assessment Board, 2009: 8, 16)

Alternative conceptions of ionisation energies

Two particular alternative conceptions were identified in an interview study with UK students studying A level chemistry in a Further Education college. The first of these was that students tended to judge the neutral sodium atom as less stable than a separated electron and Na^+ ion. This conception was one aspect of a common conceptual framework, where students conceptualised chemistry at the submicroscopic (molecular level) around an explanatory principle based on the perceived stability, and desirability, of species with full outer shells or octets (Taber, 1998a). Attaining such a configuration was considered by students to be a sufficient driver to explain chemical reactions. From this perspective, some students expected the ionisation of sodium would be spontaneous, because the resulting cation would have an octet of electrons in its outer shell.

The second conception identified in the interview study concerned the way nuclear charge interacts with the valence shell electrons. It was found that students considered force to be *emanating from* the nucleus (rather than being an interaction between charges), and being *shared between* the electrons present (Taber, 1998b). They would explain the increase in successive ionisation energies as due to the nuclear charge being shared among fewer electrons with each ionisation.

Subsequently, a diagnostic instrument used to collect data from a sample of over three hundred students in 17 institutions suggested that many UK A level chemistry students would commonly agree with statements that were scientifically incorrect but which were based on either the octet framework or the conservation of force conception (Taber, 2003).

A two-tier diagnostic instrument

The UK-based studies were the starting point for the development of a two-tier diagnostic instrument to be used in Singapore. Two-tier multiple-choice tests comprise items with two parts. The first part asks a question requiring a 'factual' response, and the second tier offers a range of possible rationales for the first tier response. An item is considered correctly answered when responses to both parts of an item are correct (Treagust, 1988). A ten-item instrument, the *Ionisation Energy Diagnostic Instrument* (IEDI) was developed through several stages of testing, including interviewing students about their responses, before the version used in the studies discussed here, was finalised (Tan, Goh, Chia, & Taber, 2005).

It was found that some students suggested that electrons in p orbitals are further from the atomic nucleus than electrons in s orbitals in the same shell (i.e. same principal quantum number), and used this to explain the drop in first ionisation energy between group 2 and 3 elements in the same period. This apparently derived from confusing Aufbau rules for filling orbitals with nucleus-electron distances (Tan, Taber, Goh, & Chia, 2005) (see Figure 1). It was also discovered that some students would use notions of the stability of full sub-shells or half-filled sub-shells (as well as of full shells of electrons) as explanatory principles (Tan & Taber, 2005). Response options reflecting these ideas were included in the IEDI, which is presented in the Appendix.

Figure 1. Typical schematic representation of relative energy levels associated with orbital types in isolated multi-electron atom.

The present paper compares the findings from the two studies administering the IEDI in Singapore.

Study 1: Singapore A level students' thinking about Ionisation Energy

The IEDI was administered to a total of 777 Grade 11 and 202 Grade 12 students (i.e. a total of 979 students) from eight out of a total of seventeen A-level institutions in Singapore in June and July 2003. The study showed that students commonly selected response combinations based upon alternative conceptions that had been identified previously in interviews. This study has been reported in the literature (Tan, Taber et al., 2005), and readers interested in the full findings are referred to the published account.

Study 2: Singapore Pre-service teachers' thinking about Ionisation Energy

The IEDI was administered to 237 graduate pre-service chemistry teachers enrolled in a chemistry pedagogy course during the period 2003 to 2006 in a teacher education institution in Singapore. All the pre-service teachers who took part in the study had chemistry as their first (main) teaching subject, and were being prepared to teach chemistry up to A level. The majority of them had majored in chemistry as undergraduates, while the rest had biochemistry, material science, material engineering or chemical engineering degrees. The pre-service teachers were forewarned of the testing session, and advised to prepare by reading the relevant A level material on ionisation energy.

As with the senior school students, this study showed that the pre-service teachers commonly selected response combinations based upon alternative conceptions that had been identified previously. Again readers are referred to the published account (Tan & Taber, 2009) for the full findings.

Research Question

The question we address here is ***to what extent do graduate trainee chemistry teachers in Singapore demonstrate alternative conceptions that have been found to be common among A level chemistry students in Singapore?***

This is based upon, what we consider, reasonable, assumptions about the validity of comparing these two studies:

1: that the two samples are reasonably representative of the wider populations of A level chemistry students in Singapore (Study 1), and pre-service chemistry teachers training in Singapore (Study 2).

2: that a cross-sectional comparison between the two populations offers a meaningful insight into the influence of degree level study on thinking about this topic area.

Our first assumption seems reasonable in view of the size of the samples: almost a thousand A level chemistry students in Singapore drawn from almost half of the institutions teaching A level; and all the specialist chemistry teachers-in-training in Singapore (during the data-collection period) in the sample of pre-service teachers.

Our second assumption is based on considering the pre-service teachers in study 2 (who would all previously have studied chemistry to A level or equivalent), as representing a subset of A level students (i.e. similar to those in study 1) who have subsequently undertaken degree level studies in chemistry or a related field. Whilst some A level students may move abroad for undergraduate education, and some pre-service teachers will have studied abroad, most of the pre-service teachers are graduates from one of the two local universities with science/engineering programmes, and the two samples may be considered to derive from substantially the same educational context.

Given that the IEDI diagnosed significant levels of alternative conceptions among the graduate pre-service teachers, our purpose in the present study is compare the two populations to ascertain the extent to which degree level education has challenged common alternative conceptions. This comparison is complicated by the more selective nature of the pre-service teachers. The subset of A level students who go on to train to be teachers will be those (a) who were successful at A level, (b) chose to study chemistry or cognate subjects at university, *and* (c) then made the career choice of training to be chemistry teachers.

A reasonable *prima facie* expectation, then, is that the pre-service teachers reflect a subset of past A level students who were academically successful in, and especially interested in, chemistry, so might be expected as a group to have demonstrated above-average subject knowledge during their A level studies.

Findings: comparing pre-service teachers' thinking with that of A level students

In exploring the research question posed in this study, we will first offer a comparison of overall performance on the IEDI in terms of correct responses, before turning to consider popular incorrect response combinations.

Overall performance on the diagnostic instrument

Taken over the whole test, the more selective, and more highly educated pre-service teachers do outperform the A level students. This is shown in Table 1, which gives the test statistics for the two groups. Despite being asked to review the topic in advance of being tested, the mean performance for the pre-service teachers however was equivalent to a score of 36%, which was not vastly more that the 29% mean for the A level students. This represents *a score of well below half marks in a topic that the pre-service teachers will be expected to teach at A level.*

Table 1. Test statistics for the administration of the QADI to pre-service teachers and A level students

Table 2 shows the percentage of correct responses to the items of the IEDI from the two samples. Inspection of the figures suggests that there are 4 of the 10 items where the pre-service teachers appear to perform considerably better as a group than the A level students, i.e. items 3, 5, 7 and 10.

Table 2: Overall performance (% correct) on IEDI items

However, although almost half of the sample obtained correct answers on three of these items (5, 7 and 10), there is not a single item where *most* of the pre-service teachers selected the correct response combination. Moreover,

- on half of the items in the instrument (items 1, 2, 6, 8, and 9), the proportion of pre-service teachers making the correct response combination is within a few percentage points of the proportion of A level students giving the correct response;
- on one item (item 4) the pre-service teachers as a group perform noticeably worse than the A level students.

It should be noted that the IEDI asks a set of decontextualised questions about an abstract science topic which in some case the participants in our studies may not have formally studied for some months before completing the instrument. The instrument does not include any visual representations or heuristic devices of the type that students might commonly refer to when studying the topic. In an interview context, many of the same participants may well have found that talking through the question would have helped them better access their learning about the topic. We certainly would not wish to suggest that the participants' performance on this instrument should be seen as indicating their general level of chemical learning.

It is also worth noting that a two-tier test is intrinsically difficult (as no credit is given for partially correct responses), and that some students may have agreed with statements based on particular alternative conceptions presented in the IEDI, when they may not have spontaneously suggested the same answers had they been given open-questions. We acknowledge that an alternative format of test might well have given students in both samples a greater opportunity to demonstrate their understanding of the topic.

However, the instrument does test the participants against learning objectives from the courses that they were either taking or intending to teach, and by including distractors based on findings from previous interview studies (Taber, 1998b; Tan, Goh et al., 2005) offers insight into their thinking in this topic area. This is significant for two reasons. Firstly, it allows us to compare the nature of the incorrect response choices in the two samples, which we do next. Secondly, it raises the issue of how well the curriculum material is matched to the needs and readiness of students on A level courses – an issue we consider in the Discussion (below).

Nature of incorrect responses

In reporting the studies with A level students and pre-service teachers, we have suggested that incorrect response options should be considered important for teaching when selected by 10% or respondents. This is a somewhat arbitrary cut-off, but distractors chosen at this frequency - which we will call 'popular' distractors - are likely to reflect the thinking of some students in most comparable classes. Table 3 shows the distractors (incorrect response options) that reached this threshold.

Table 3: Popular distractors on the IEDI (%age selecting response option, cf. %age of correct responses in parentheses). [Figures in square parentheses provided for comparison across studies.]

Table 3 shows 14 popular incorrect response combinations for the A level students, and 14 popular incorrect responses for the pre-service teachers – with 11 of the popular distractors being common across the two groups. Popular distractors were selected *more often* than the correct response for five of the items for the A level students, and for six of the items for the pre-service teachers (with two different distractors proving more popular than the correct response in item 6). Of particular note, four of the popular distractors were selected more than the correct response in both studies (A2 in item 1; A3 in item 2; B4 in item 3; and A2 in item 6).

The commonly selected response options reflected the alternative conceptions identified in the original UK studies (the octet framework; the conservation of force conception) as well as the additional factors that were discovered during the development of the IEDI in Singapore (difficulty coordinating factors; confounding Aufbau rules with nucleus-electron separation; stability of sub-shell configurations).

Coordinating conflicting factors

Items 5-10 concerned the learning objective that for the third period (elements sodium to argon) "candidates should be able to explain the variation in first ionisation energy". This variation is shown in figure 2. Explaining this pattern requires awareness of (a) the different factors at work; (b) whether they tend to increase or decrease ionization energy, and (c) which factors dominate in particular comparisons. In the Discussion section (below), we consider the high level of intellectual challenge faced in making such comparisons.

Figure 2: The pattern in the values of standard molar first ionization enthalpies (SMFIE) across the elements of period 3

One of the findings from the study with A level students was that on a number of items students commonly selected the wrong options where several factors were pertinent. There were six such examples that met our 10% threshold in Study 1.

Two of these examples concerned the relative nucleus-electron separation in different orbitals in the 'same' shell, where respondents selected options based on a 3p electron in one atom being further from the nucleus than an electron in a 3s orbital in another atom. Models predicting appropriate values for average electron-nucleus separation in an atomic system are sophisticated (Dill, 2006), and not studied before university level. However, students are expected to know that atomic radius decreases across period 2 or 3 as nuclear charge increases (Singapore Examinations and Assessment Board, 2009). In item 7, almost one quarter of the A level students selected a rationale (response A4) based on the Al (aluminium) 3p electron being further from the nucleus than the Na (sodium) 3s electron to justify sodium having a higher first ionisation energy (which it does not); marginally more than selected the correct response. The pre-service teachers as a whole performed considerably better; with about half the frequency selecting this distractor, and twice the frequency selecting the correct response (see Table 3).

In Item 6 only a small proportion of the A level students selected what we consider the canonical response, and this was also true among the pre-service teachers. Here the most common response (A2) was that the first ionisation energy drops in going from magnesium to aluminium because of the aluminium 3p electron being further from the nucleus than the magnesium 3s electron. Nearly half of the A level students selected this response, and a slightly *higher* proportion, just over half, of the pre-service teachers made this choice.

The other four examples in this category were:

- in item 5, the popular distractor (A4) was based upon increased repulsion between spin-paired electrons, where the more significant factor was the increase in nuclear charge;
- in item 7, the popular distractor (A3) was based upon a consideration of additional shielding, where the more significant factor was the increase in nuclear charge;

- in item 9, the popular distractor (B4) was based upon the effects of an increase in nuclear charge, where the more significant consideration was the increased repulsion between spin-paired electrons;
- in item 10, the popular distractor (A4) was based upon a consideration of the effect of increased repulsion between spin-paired electrons, where the more significant factor was the increase in nuclear charge

We did not consider these common incorrect responses as representing alternative conceptions, as the responses were logical (the reasons matched the chosen 'factual' option), *and* based on valid considerations. Whilst notable proportions of numbers of the A level students made errors in selecting responses in these items (about a fifth of respondents in three of these items), we do not consider them to demonstrate major problems with understanding concepts. The students either did not know which factor would be dominant, or simply selected a response combination that seemed logical without checking if there were other viable options. Had these students been told which of the ionisation energies being compared were greater, it is quite possible they would have been able to select the associated rationale.

When we compare between the two studies, we find that these errors were much less common in Study 2. In each case, the proportion of pre-service teachers selecting these distractors was only about half the proportion found among A level students. Three of these four items (5, 7 and 10) were among those that noticeably higher proportions of pre-service teachers answered correctly. This shows that this is one area where *the pre-service teachers may be considered to perform considerably better than the A level students*.

Conservation of force

The *conservation of force* conception uses the alternative notion of 'sharing out' of nuclear force as an explanatory principle. Whereas scientists clearly distinguish charge, and the interactions (forces) between charges, students often conflate such basic distinctions. The conservation of force conception takes nuclear force to be a property of a nucleus, and fixed, depending upon the magnitude of nuclear charge.

From this perspective, the nuclear force is shared among the electrons in an atomic system, and the removal of electrons allows those remaining to acquire a greater share.

Responses to two items in the IEDI suggest that this conception is common among learners in Singapore. In item 4, almost one fifth of the A level students in Study 1 selected the response (A2) that the second ionisation energy of sodium is greater than the first (which is true) because the same number of protons are attracting less electrons (the alternative conception). The response patterns of the pre-service teachers in Study 2 were very similar, with almost the same proportion selecting this distractor.

In item 2, very nearly half of all the A level students in Study 1 agreed with an explicit statement of the conservation of force conception (response A3), referring to the redistribution of the attraction for the nucleus when an electron is removed, allowing remaining electrons to experience greater attraction. Less than a third of the students selected the correct response based on Coulombic principles. In Study 2, we again found that pre-service teachers responded in very similar ways, with just over half of the respondents selecting the conservation of force based distractor, and a little under a third the scientific response. Based on our samples, *therefore, there is no evidence that the degree level study of the pre-service teachers had eroded the hold of this alternative conception.*

Applying the octet framework

The octet framework is based on octets of electrons or full outer shells (sometimes, but not always the same thing) being inherently stable, and offering a sufficient explanation for chemical phenomena. Common responses to four of the items in the IEDI reflected this way of thinking about ionisation processes (see Table 3).

In item 1, over two fifths of the A level students in Study 1 responded that an electron removed from Na would not return because the Na^+ produced had a stable configuration (response A2). This was slightly more than the proportion who selected the scientifically acceptable option that the atom would reform because the cation and electron would attract. In study 2 we found a very similar pattern among the pre-service teachers.

In item 3, almost two thirds of the A level students in Study 1 considered that the statement that the Na atom was a more stable system than the separated cation and electron false because the cation had achieved a stable configuration (response B4). The proportion selecting this response combination among the pre-service teachers in study 2 was slightly less, but still a majority of the sample, and nearly twice the proportion responding with the scientifically correct response.

The responses linked to the octet framework were less popular in items 4 and 5, but still attracted significant numbers of respondents. In item 4, about a sixth of the A level students explained the second ionisation energy of sodium being greater than the first in terms of disrupting the stable octet structure (response A1). Slightly more, a little over a quarter, of the pre-service teachers chose this option. In item 5, one available explanation (response B2) for the increase in standard molar first ionisation enthalpies in Mg (magnesium) over Na was that Na could achieve a stable octet configuration. In Study 1 the proportion of A level students selecting this option was slightly below our (10%) threshold for being considered a common incorrect response. However in Study 2, the proportion of pre-service teachers selecting this option was slightly higher, just reaching our threshold. We do not read any significance to this minor difference, but considering these four items together we conclude that *degree level study has made very little difference to the use of the octet framework as an explanatory principle*.

Extending notions of stable configurations

The octet framework is based on the perceived inherent stability of the noble gas structures, which are commonly used by students to explain chemical phenomena, and linked to the notion of ‘full shells’ (although only two of the noble gas elements actually have full shells, and one of these, He, does not have an octet of electrons). A number of common distractors in the IEDI are based on the commonly perceived *inherent* stability of other configurations.

In Study 1, three of these reached our threshold of being chosen by a tenth of the sample. In item 5, a little over a tenth of the A level students selected a response based on the stability of a full 3s sub-shell (response B1). In item 8, about a quarter of the A level students selected the option based on the stability of a half-filled 3p sub-shell (response B2), and in item 9, almost one fifth of the A level students used this rationale (response A3).

These same response options were *more popular* among the pre-service teachers in Study 2. So almost a fifth of the pre-service teachers selected the option based on stable configurations in item 5; over a third in item 8; and over two-fifths in item 9. In the latter two cases, these options were more popular than the correct responses.

In addition, similar options were popular in two other items that had not met the 10% response threshold in Study 1. So in item 6, an argument based on disrupting a full 3s sub-shell (response A1) was selected by almost a fifth of the pre-service teachers, and was more popular than the correct response. In item 10, an argument about a half-filled sub-shell (response A1) was selected by almost a sixth of the pre-service teachers. We found, then, that using perceived stability of filled and half-filled sub-shells as explanatory principles *was considerably more popular among the graduate pre-service teachers than among A level students*.

Discussion

In this paper we have compared the findings from two studies undertaken in Singapore among large samples of A level chemistry students (Study 1), and pre-service teachers preparing to teach chemistry at secondary/high school level (Study 2). Both studies used the two-tier IEDI that had been developed to follow up findings from previous studies in the UK. Our key results here are that:

1. understanding of ionisation energy is poor among both A level chemistry students and graduate pre-service chemistry teachers;
2. whilst the more highly selected and more highly educated pre-service teachers outperform the A level students over the ten-item test, they perform equally poorly on half the items, and less well on one item;
3. pre-service teachers tended to make fewer mistakes when choosing the more significant of competing factors that influence comparisons of ionisation

energy;

4. distractors based on alternative conceptions were popularly chosen by both A level students and pre-service teachers:
   i. whilst the precise pattern of responses differs between the two groups, the popularity of responses based on two common alternative conceptions reported in the literature (‘conservation of force’; ‘the octet rule explanatory principle’) was similar among the pre-service teachers and the A level students;
   ii. in one area (‘stability’ of fully-filled and half-filled sub-shells), the reliance on alternative conceptions was *more* prevalent among the pre-service teachers than among the A level students.

Figure 3 offers a schematic representation of the general trends found in these categories of incorrect student response.

Figure 3: Schematic showing general trends in major categories of respondent errors

As suggested in the results section (above), we consider the nature of common student errors to fall into two categories: those that are primarily related to failures to effectively coordinate a range of variables and concepts (where pre-service teachers make less mistakes than the senior school students); and those that relate to the adoption of alternative conceptions (where the pre-service teachers appear to be at least as likely to hold the alternative conceptions).

Is the Singapore context unusual?

The research reported here is based on studies in one educational context, the city-state of Singapore in South-East Asia. Undoubtedly there are unique characteristics of any particular context. However, the Singapore studies built on earlier UK studies that demonstrated how students commonly used the octet framework and conservation of force conceptions in judging statements about ionisation energy.

The topic of ionisation energies forms part of high school or college chemistry courses in a number of countries. The administration of the IEDI (in translation where appropriate) to high school students or first year undergraduates in New Zealand, England, Spain, the US, and China has shown that similar results can be obtained across this range of educational contexts (Tan et al., 2008). We believe, therefore, that it is very likely that our findings are significant well beyond the specific context of Singapore.

It is clearly a concern for science education when common alternative conceptions found among school students remain unchallenged by further study of the subject area at degree level. The present study does not allow us to know to what extent our findings reflect a general trend rather than something specific about the topic of ionisation energies. Further studies in other topics with known common alternative conceptions would seem to be indicated.

Contributing to the RP to inform teaching

It was suggested above that studies into aspects of student thinking and learning can be understood as part of the constructivist RP into learning in science (Taber, 2009b). A RP has a hard core of central commitments (such as seeing learning as a process of step-wise personal construction of knowledge), and a 'protective belt' of auxiliary theory comprising 'refutable variants' of the RP – ideas consistent with and extending beyond the hard core, but not themselves considered as irrefutable within the programme. A range of concepts and models from research carried out in recent decades have been identified as components of the constructivist RP's protective belt (Taber, 2009b).

It has been argued that as learning science is a complex, multi-facetted, phenomenon, it is appropriate to seek complementary insights by applying a range of distinct constructs as 'analytical lenses', provided that these different interpretive tools are considered to derive from a coherent set of underlying principles (Taber, 2008c). Here the authors draw upon constructs from the conceptual repertoire provided by the protective belt of the constructivist RP to interpret our results, and to indicate how our findings can inform science education.

We first offer an account of the conceptual requirements of the topic, at the level specified in the Singapore-Cambridge A level syllabus (Singapore Examinations and

Assessment Board, 2009). We then consider student learning of this topic in terms of a range of constructs from the theoretical repertoire of the RP: curriculum models; learning demand; learning quanta; conceptual fossils; and finally Watts and Pope's (1982) suggestion of considering student thinking itself to reflect Lakatosian RPs.

Drawing upon the progressive RP: The abstract nature of the subject matter

The constructivist perspective on learning science suggests that effective learning depends upon subject matter being presented to learners in a form which is relatable to, and comprehendible within, their existing 'cognitive structure' (cf. Ausubel, 2000). So teachers need to undertake conceptual analyses of topics that can facilitate the identification of potential learning difficulties prior to planning teaching. We therefore first set out the type of thinking about ionisation energies that would be involved in demonstrating mastery of the target knowledge. Table 4 presents the learning objectives from the A level chemistry course in Singapore (Singapore Examinations and Assessment Board, 2009), alongside the patterns to be explained and the conceptual basis used for offering explanations for those patterns.

Table 4: Conceptual requirements of meeting the learning objectives for the ionisation energies topic in the Singapore A level chemistry course

When the subject matter is analysed in this way, it becomes clear that meeting the learning objectives involves selecting and applying a range of concepts to model ionization processes. The learning objectives are underpinned by an underlying assumption that something measured on a sample of gaseous substance on a macroscopic scale can be understood by discussing processes occurring at the level of individual atoms and electrons. This is known to be a major challenge for many students learning chemistry (Gilbert & Treagust, 2009). Ionisation may be represented by such formulaic representations as:

$$Na_{(g)} \rightarrow Na^{+}_{(g)} + e^{-}$$

Here $Na_{(g)}$ can refer to either a mole of atomized sodium (i.e. substance), or an individual atom (i.e. theoretical model). Such representations are used in teaching as mediators between the molar scale phenomenon, and the theoretical, sub-microscopic models used to explain so much of chemistry (Taber, 2009a).

To achieve some of the learning objectives (i.e. Table 4: ii-iv), a model of the atom considering electrons to be arranged in concentric spherical shells will suffice. Such a model allows students to appreciate that moving across a period (Table 4: learning objective ii) the electron to be ionized is subject to increasing core charge; and that in moving down a group (Table 4: learning objective iii) the electron is initially further from the same core charge (as the increase in nuclear change and the additional shell of shielding electrons can be considered to cancel in this model).

However, this simple model would predict that *successive* ionisations from within the same shell remove electrons subject to the same core charge, and so should be of similar magnitude – which is not what is found. Although a shell model of the atom *can* be used here, it is not sufficient to think purely in terms of the initial state of the species to be ionized. On this model, it makes sense that the second ionisation energy of sodium is very much greater than the first (Table 4: learning objective iv-b), as the second electron to be removed begins closer to a much larger core charge. However, it is not clear from this model why the third ionisation energy should be significantly greater than the second (Table 4: learning objective iv-a), when both processes involve removing an electron from the same shell and subject to the same core charge.

The limitations of only considering the initial state of the species to be ionized (when the electron is in an equilibrium conformation, and so actually initially subject to zero net force) become important in making such comparisons. Rather, to attain learning objective iv-a (Table 4), students need to adopt a dynamic model that allows them to think about how the force on the electron varies as ionization occurs (see Figure 4).

Figure 4: Modelling a comparison of the second and third ionisations of sodium based on a 'shells' representation of the atom.

The final learning objective in Table 4, (v), cannot be achieved by using a shell model of the atom, as the nature of the atomic orbital that an electron is removed from becomes significant. Although increasing core charge, and diminishing atomic radius, lead to a generally increasing first ionisation energy across a period, electrons in p-orbitals are inherently easier to remove than those in s-orbitals and this factor has a greater effect (so there is a drop between Mg and Al on Figure 2). Moreover, where the electron to be removed is spin-paired with another electron in a p-orbital, this also reduces the ionization energy and is a greater effect (so there is a drop between P, phoshorus, and S, sulfur, on Figure 2). Figure 5 shows how these three sets of factors play out to give the pattern across the period.

Figure 5: Factors influencing the pattern of first ionisation energies (SMFIE) across period 3. The figure shows the respective 3rd shell electronic configuration beneath each element symbol, and also indicates the orbital configuration associated with the electron to be removed during ionisation – s or p; singly occupied (s^1, p^1) or spin paired (s^2, p^2) – beneath the data points.

Drawing upon the progressive RP: student learning about multiple models

So to meet the learning objectives a range of abstract concepts needs to be applied and coordinated to demonstrate understanding. Some comparisons students are asked to make can be based on a ‘shell’ model of atomic structure, where others require the application of notions about different types of orbitals. Furthermore, in the latter cases, there are often several co-varying factors that may tend to produce opposing effects, and students are expected to provide explanations that match the actual comparisons of ionisation energy in different case (such as in items 5-10 on the IEDI).

The models drawn upon are somewhat inconsistent: for example the notion of core charge, whilst useful (learning objectives ii-iv in Table 4), assumes no interpenetration of electrons into lower shells, and so is inconsistent with orbital models needed for explaining other examples (learning objective v in Table 4). Justi and Gilbert (2000) have criticised such models of atomic structure that draw upon features that belong to distinct historical models that have been conflated without consideration of temporal sequence or a concern for internal coherence within the hybrid model itself.

The constructivist RP developed in part in response to perceived limitations of the Piagetian RP (Gilbert & Swift, 1985). The Piagetian perspective, based on consideration of the general stage of intellectual development attained by students, would suggest that the abstract and theoretical nature of the topic makes it generally unsuitable for students who had not achieved the stage of ‘formal operations’ (Piaget, 1972). Such an approach has been used to offer a critique of secondary science curriculum topics that would not be suitable for many 14-16 year olds (Shayer & Adey, 1981).

However, the present study concerns learning difficulties experienced by older students who had been selected for studying science based on earlier success: where it would be expected that these students have attained the highest Piagetian stage. A neo-Piagetian approach might point to the need to shift between models in meeting different learning objectives, and consider this to require a further stage of post-formal operations (Kramer, 1983, cf. Finster, 1991). Being able to accept that several inconsistent models may provide useful tools for thinking about the same topic requires epistemological sophistication that is rare at secondary school level (Driver et al., 1996), but which becomes more common during university study (Driver et al., 1996; Perry, 1970).

Drawing upon the progressive RP: cognitive processing of new information

The constructivist RP moved beyond considering the general intellectual structures available for learning, to consider a broader range of factors contingent in student learning. Within the RP both cognitive and conceptual features of learner readiness to learn material are considered. So, for example, how students need to process information during learning and problem solving has been a key theme (Osborne & Wittrock, 1983). The analysis above suggests that the subject matter places a high cognitive load on students, as a range of concepts and considerations need to be drawn upon and coordinated in demonstrating target learning (Tsaparlis, 1994).

In items 6 and 7, distractors based on an argument that an Al 3p electron should be considered to have a greater mean distance from the nucleus than a Na or Mg 3s electron were commonly chosen. To make a comparison between the nucleus–3p–electron mean separation in Al, and the nucleus-3s-electron mean separation in Na or Mg could be considered to imbue the models used with a degree of realism that may not be justified.

In part this could be the failure to realise that the characteristics of an orbital (3p) depends upon the atomic environment in which it is found (so that comparing different orbital types *in different atoms* is more complex that comparing different orbital types in *the same atomic system*). High proportions of both groups selected this response, which may in part be due to the way 3p (in a particular atomic system) is commonly shown diagrammatically as being at a ‘higher’ energy level than 3s (see Figure 1).

The pre-service teachers made fewer mistakes than the senior school students when choosing the more significant of competing factors that influence comparisons of ionisation energy (items 5-10 of the IEDI). Both increased maturity, and several years developing further familiarity with the knowledge domain, would have been advantageous. The latter is likely to have helped in two ways. Increased experience working with material allows it to be more effectively ‘chunked’ so that it can be treated as fewer ‘items’ in working memory (effectively increasing cognitive processing capacity). In addition, greater familiarity with the phenomena to be explained would make it easier to select from only those options that were logically consistent with the actual patterns found in ionization energy. That is, a student who remembered the pattern shown in figure 2 could exclude as viable answers those distractors that were not consistent with the direction of the difference in the ionisation energies of elements being compared.

It is also possible that the higher performance here might be linked to better visualisation processes that simply derive from greater familiarity with the atomic models. Gilbert (2005) has emphasised the role of visualisation in learning science, and this would seem to be one topic where developing mental models that can be ‘run’ to simulate chemical processes mentally (Georgiou, 2005) could be very significant for effective learning (cf. Figure 4).

Such considerations offer feasible explanations of the common errors in selecting the more significant of competing factors that influence ionisation energy, where the pre-service teachers generally made fewer errors. However, such arguments are insufficient to explain why in both studies our respondents commonly selected responses based upon on alternative conceptions inconsistent with the chemistry they studied.

Drawing upon the progressive RP: The development of alternative conceptions

We found that respondents, both among the high school students and the pre-service teachers, commonly considered that nuclear forces were shared out among the electrons in a shell (see Table 3). The chemistry topic of ionisation energies draws upon prerequisite physics knowledge of the interactions between electrical charges (i.e. Coulomb's law). However, work within the constructivist RP has shown that in learning science students do not always apply the expected pre-requisite learning. Even assuming the pre-requisite concepts have previously been taught, this will not ensure that learners have them available, and appreciate their relevance in new learning contexts (Taber, 2005). Also, many students are likely to bring to class existing alternative notions about forces (Watts, 1983). Even when students demonstrate scientifically acceptable ideas in studying one area of science (e.g. using Coulombic principles when studying electricity in physics), they may not apply these ideas where expected outside of that topic (Taber, 2008b).

As we suggested above, understanding patterns in successive ionization energies (learning objective iv-a in Table 4) actually requires appreciating a complex dynamic model (Figure 4), that may be too challenging for many students at senior high school level. The notion that the 'nuclear force' is shared out, so that each time an electron is removed, the remaining electrons get a greater share of that force and so become harder to remove offers an alternative (and much simpler) rationale for patterns in successive ionization energies. It might seem surprising that degree level study does not lead to this alternative conception being replaced by more scientifically acceptable notions: however it is well known from studies within the constructivist RP that some alternative conceptions are tenacious once acquired (McCloskey, 1983). The sharing-out idea appears to be one of those conceptions that has intuitive appeal (diSessa, 1983), and so is firmly held. Moreover, not only is it intelligible and plausible, but it also appears fruitful (Posner, Strike, Hewson & Gertzog, 1982) in that it can be used to offer an explanation for the pattern of successive ionisation energies.

We find a similar pattern with student responses based on the octet alternative conceptual framework (see Table 3). Students readily adopt notions that octets or full shells have some special intrinsic stability. Figure 5 shows this is not the case: if there was some special inherent stability associated with the octet structure then the ionization energy of Ar (argon) should be significantly higher than is shown. Figure 5 shows that Ar fits well with the pattern established by S and Cl (chlorine). The octet rule is adopted by many school pupils as the basis for explaining bonding and chemical reactivity, despite it not offering valid or logical explanations (Taber, 1998a). As the constructivist model would predict, this explanatory principle is then used to interpret other chemical phenomena studied – such as ionisation energies.

Moreover, in our sample we found evidence of the notion of full shells having intrinsic stability being extended to full or even half-full sub-shells (see Table 4). In these cases we found this alternative conception was *more* prevalent among the graduate pre-service teachers than among the high school students. It would seem that a form of explanatory principle that is intuitively attractive for students gets extended to more nuanced cases. As chemistry students become more familiar with, and experienced in applying orbital models of the atom, they come to apply a familiar way of thinking to make sense of these new concepts. Again this would seem consistent with constructivist perspectives on learning.

Drawing upon the progressive RP: identifying learning demand

Leach and Scott (2002) have talked about the notion of ‘learning demand’, i.e. the discrepancy between a students’ current understanding and the target knowledge being taught. Where this demand is significant, careful teacher scaffolding of learning is needed to bridge the ‘gap’, otherwise students will have difficulty understanding the target knowledge and may form alternative conceptions.

Taber (2005) has used the notion of ‘learning quanta’ to draw attention to the way complex scientific knowledge needs to be deconstructed into more manageable components for effective construction of new learning. He has argued that there is a time lag between initially learning new concepts, and being able to rely on them as sound foundations for further learning. The process of consolidating new learning into mental structures occurs over extended periods, and during this time teachers need to support students by reinforcing the ‘fragile’ learning, until it can be considered ‘robust’ enough for students to apply it effectively and without support. Typically learners are first introduced to an undifferentiated basic particle model early in secondary education that is later differentiated into notions of atoms, molecules, ions and so forth (Key Stage 3 National Strategy, 2002). Atomic structure is usually introduced using a ‘shells’ model; that after a few years becomes supplemented, but not necessarily substituted for all purposes, by more complex orbital models. Taber has suggested that student difficulties in learning the models of the atom met in school (Griffiths & Preston, 1992; Harrison & Treagust, 1996, 2000; Petri & Niedderer, 1998) may in part be because students meet sequences of models of the atom without there being sufficient consolidation of each model before the next is introduced.

The insidious nature of some alternative conceptions

Whatever the origins of the alternative conceptions, several years of degree-level study have done little to persuade university graduates in our sample of pre-service teachers that it is inappropriate to explain chemical phenomena in terms of a drive for atoms to complete their shells, or to suggest that nuclear attraction is somehow a conserved entity that can be shared around the atom. This is despite being exposed to, expected to apply, and being tested upon, increasingly more sophisticated scientific models and principles for explaining the natural world.

It certainly seems that in these particular cases, the alternative conceptions acquired by many students during school years become so well established within a learner’s conceptual structures that they are readily elicited years later. Assuming that the alternative conceptions were not actually presented to informants in Study 2 as teaching models in university lectures or texts, they may well still have interpreted some of what they heard and read as undergraduates in these terms. If these non-canonical ideas were challenged, they were not discarded.

Whatever models, laws and principles have been learnt during their degree courses in chemistry and cognate subjects, when the pre-service teachers in our sample were asked to consider a topic at the level they were preparing to teach (and had been asked to review before being tested), many of them were cued to select responses based on the very alternative conceptions we would hope they could be challenging in their own students.

Indeed, our present study suggests this is not merely a matter of the A level context reactivating notions that have been inert during university study – for the pre-service teachers, having had more experience of working with orbital models of the atom, actually showed *a greater tendency* to extend the desirability of a stable configuration as an explanatory principle from octets/full shells to filled and half-filled sub-shells. The graduate pre-service teachers were *more likely* to base explanations on these alternative conceptions than the A level students they are preparing to teach.

Extending the progressive RP: applying the Lakatosian model to student learning

Watts and Pope's (1982) suggestion of considering learners themselves as Lakatosian scientists has received very limited attention within the RP. Here we will suggest that our present study provides grounds for considering that this proposal is worthy of further attention, as it may offer a useful way of thinking about the considerable disparities found in student commitments to different alternative conceptions (Driver & Erickson, 1983; Gilbert & Watts, 1983; Claxton, 1993). In other words, we can consider that students' conceptual trajectories can be understood in terms of 'study programmes' that are analogous to RP: that it a study programme is built around 'hard core commitments' that are 'taken-for-granted' as the student looks to develop their understanding (i.e. build up a protective belt of knowledge) of a topic around hard core foundations. The reception of new information can be considered to be guided by a negative heuristic (which ensures new information is interpreted to be consistent with the hard core) and a positive heuristic (which seeks to extend understanding of the topic in ways consistent with the hard core). These heuristics would not need to applied consciously: rather it is the implicit commitment to the irrefutable nature of the hard core assumptions which can often lead to teaching being reinterpreted in unintended ways.

In terms of our present study, the target knowledge is constructed around a Coulombic model of atomic structure and ionisation processes, and so to be successful in the topic a student would have to build their hard core for learning about the topic around such principles. Yet we have seen that the central assumptions that students often make are quite inconsistent with such principles. Notions that nuclear force is shared between electrons, and that full shells are desirable and inherently stable, appear to derive from the application of deep-rooted intuitions about the world, and so are strongly committed to: providing an alternative basis for the hard core of many learners' study programmes.

The differences between the response patterns of A level students and pre-service teachers are consistent with such a model. The areas where pre-service teachers make fewer errors concern less central principles, where alternative explanations can be constructed within the 'protective' belt without bringing into question the core commitments. The analysis above suggest differences may be understood in terms of how greater intellectual maturity and familiarly with background knowledge allows the pre-service teachers to work more effectively within the protective belts of their understanding of the topic. Interestingly, the area where pre-service teachers make more errors in the topic – by assigning inherent stability to a wider range of electronic configurations – can be interpreted as the development of auxiliary theory through the action of a programme's positive heuristic to extend understanding in ways consistent with hard core assumptions: that is, the commitment to seeing certain types of symmetry in electronic configurations as inherently stable being extended from full shells to sub-shells.

This Lakatosian interpretation offers an explanation of why some, but not all, alternative conceptions have been found to be so tenacious. From this perspective, certain conceptions are based on assumptions that are intuitively very convincing, and to which a strong commitment is therefore implicitly made. Where these conceptions are central to a topic studied in science, they naturally form the 'hard core' about which the student looks to develop an understanding of the topic. The student develops a conceptual framework of auxiliary conceptions around those core commitments, and when faced with discrepant information the student is usually able to protect the hard core by making adjustment within that protective belt of auxiliary ideas.

By analogy with RPs, such 'study programmes' are unlikely to be abandoned until they are recognised as no longer fruitful for developing new knowledge, and an alternative with more promise is available to the student. So in our study, students would be unlikely to switch to a programme based on Coulombic principles as long as they are able to continue to interpret phenomena in terms of the sharing out of nuclear force and the desirability of full shells.

Quite why these particular conceptions appear to be so intuitively attractive, and resistant to challenge during degree courses is not clear. Yet they clearly have potential to be effective 'memes' (Blackmore, 2000): ideas that spread through a population effectively because they are readily accepted, recalled and passed-on. What does seem clear, is that as long as high school teachers commonly hold these alternative conceptions, they can use them in their own teaching explanations, and so they are likely to be acquired by, or reinforced in, their own students.

Conclusion: responding to the insidious nature of alternative conceptions

This study clearly highlights the issue of the extent to which insidious alternative conceptions are linked to hard-core commitments that are retained by graduates as they progress into professional roles (such as teaching) in science and technology. A number of more specific directions for research are suggested by this study, such as the extent to which respondents' selection of distractors based on alternative conceptions may be made almost instinctively without pause for analysis, and so whether a different task (e.g. one that required the respondent to construct a more explicit chain of argument themselves) would lead to a lower incidence of these ideas being elicited among the graduate population.

The study also suggests that the largely neglected suggestion that student learning might itself be fruitfully explored by considering learners as though they behave like Lakatosian scientists (Watts & Pope, 1982) is worthy of further consideration. If it is possible to develop this model to characterise which alternative conceptions tend to become incorporated within the hard core of learners' study programmes, and which tend to only have protective belt status, then this will indicate those conceptions where careful strategies and extended efforts are needed to encourage students to shift to a new study programme.

We also speculate that in this particular topic area, alternative conceptions are being retained as elements of hard core understanding of chemistry *and formally taught* by some teachers, rather than just formed when students *interpret* teaching, and it would be useful to know the extent to which this is actually the case. If this is common, suitable professional development inputs are indicated.

Regardless of what further research may show, the present study would seem to have clear implications for science education at three levels:

- at secondary/ high level: given the tenacious and insidious 'hard core' nature of the desirability of a full shell as an explanatory principle; and the notion that nuclear attraction can be shared out; it seems important that teachers (and textbook authors) are aware of these common conceptions, and take care to make sure they do not inadvertently (or deliberately) use phrasing and explanations which can support the acquisition of these ideas;
- at initial teacher education level: work on auditing, diagnosing and remediating subject knowledge in this topic area is important before graduates are expected to teach the topic;
- at degree level: lecturers should be made aware of these common ways of thinking and so they can hone their own teaching to avoid reinforcing, and to challenge, such insidious alternative conceptions - for example, by making explicit reference to the underlying physical principles (such as Coulomb's law) that support the chemistry.

Considering the present results from the perspective of the constructivist RP has allowed us to offer a feasible account of why learning in this topic is so problematic. Successfully learning about ionization energy at senior high school level would seem to involve being able to apply a range of concepts, and to coordinate different factors that may be simultaneously active, whilst visualizing a dynamic hybrid model at the sub-microscopic level. Given this analysis, learning difficulties in this topic should not be surprising.

This leads us to question whether this material is appropriate in the curriculum at senior high school level. If it *is* considered important that students should master this topic before university level study, then the constructivist analysis (e.g. considering pedagogic notions of ‘learning demand’ and ‘learning quanta’) suggests that this is only likely to happen if much greater thought is given to sequencing and reinforcing student learning of the prerequisite ideas through the secondary school years. Unless that level of commitment is considered justified, it may be more sensible to acknowledge that this is a topic that it is unrealistic to expect school students to tackle. Delaying study until the undergraduate years could allow students to meet the topic only after the necessary conceptual foundations have been consolidated, and may break the cycle of generations of students developing the same alternative conceptions.

(~~9722~~) (11429)

	Pre-service teachers	A level students
No. of cases	*237*	*979*
No. of items	*10*	*10*
Mean (Standard deviation)	*3.59 (2.37)*	*2.91 (1.91)*
Median / Mode	*3.00 / 3*	*3.00 / 2*
Minimum / Maximum	*0 / 9*	0 / 9

Table 1. Test statistics for the administration of the QADI to pre-service teachers and A level students

item	A level students (n=979)	pre-service teachers (n= 237)
1	38.3	40.1
2	30.0	29.1
3	16.8	27.4
4	48.1	41.4
5	29.2	48.5
6	5.4	7.2
7	23.9	46.8
8	34.0	36.3
9	32.1	33.8
10	33.1	48.9

Table 2: Overall performance (% correct) on IEDI items

test item	incorrect response	A level students (n=979)	pre-service teachers (n= 237)	rationale for distractor (nature of respondent 'error')
1	A2	**43.6 (>38.2)**	**43.9 (>40.1)**	octet alternative framework
2	A3	**49.7 (>30.0)**	**54.0 (>29.1)**	conservation of force alternative conception
3	B4	**63.6 (>16.8)**	**55.7 (>27.4)**	octet alternative framework
4	A1	15.6 (<48.1)	27.0 (<41.4)	octet alternative framework
4	A2	18.0 (<48.1)	18.6 (<41.4)	conservation of force alternative conception
5	A4	22.0 (<29.2)	[7.6 (<48.5)]	incorrect coordination of conflicting factors
5	B1	13.1 (<29.2)	19.0 (<48.5)	full sub-shell gives stability conception
5	B2	[9.1 (<29.2)]	11.8 (<48.5)	octet alternative framework
6	A1	**[6.2 (>5.4)]**	**18.1 (>7.2)**	full sub-shell gives stability conception
6	A2	**48.1 (>>5.4)**	**50.6 (>>7.2)**	incorrect coordination of conflicting factors
7	A3	20.7 (<23.9)	12.2 (<46.8)	incorrect coordination of conflicting factors
7	A4	**24.4 (>23.9)**	11.4 (<46.8)	incorrect coordination of conflicting factors
8	B2	24.9 (<34.0)	**37.1 (>36.3)**	half-filled sub-shell gives stability conception
9	A3	19.6 (<32.1)	**41.4 (>33.8)**	half-filled sub-shell gives stability conception
9	B4	10.4 (<32.1)	[5.5 (<33.8)]	incorrect coordination of conflicting factors
10	A1	[6.8 (<33.1)]	15.2 (<48.9)	half-filled sub-shell gives stability conception
10	A4	19.0 (<33.1)	[9.7 (<48.9)]	incorrect coordination of conflicting factors

Table 3: Popular* distractors on the IEDI (percentage selecting response option, cf. percentage of correct responses in parentheses). *[Figures in square parentheses provided for comparison across studies.]

Candidates should be able to	The phenomenon	Conceptual features of an explanation
i) explain the factors influencing the ionisation energies of elements:	Ionisation energy is a measure of the work that needs to be done to remove an electron from an atom or ion. Ionisation energy is quoted as a molar value (in $kJmol^{-1}$), but explanations are usually framed in terms of individual ionisation events.	The work done is the integral of the force that needs to be applied as the electron is separated from the positive residue of the atom or ion The force depends upon the charges (on the electron and the positive residue it is being separated from) and their separation. Initial separation is the distance from the electron to the nucleus. The electron interacts with all the other charges in the atom/ion, but simplifications can be applied (e.g. 'core charge').
ii) explain the trends in ionisation energies across a period;	The general trend is that ionisation energies increase across a period (but see v, below).	The core charge (resultant charge of positive nucleus and negative 'shielding' electrons) increases, and initial electron-nucleus separation, decreases across the period.
iii) explain the trends in ionisation energies down a Group of the Periodic Table;	Ionisation energies decrease down a group.	The initial electron-nucleus separation increases down a group whilst the core charge remains the same (i.e. increase in nuclear charge is cancelled by the increases in the number of shielding electrons)
iv) deduce the electronic configurations of elements from successive ionisation energy data; interpret successive ionisation energy data of an element in terms of the position of that element within the Periodic Table;	(a) Successive ionisations of the same atom require increasing energy; (b) there are especially large jumps where an electron is removed from a shell closer to the nucleus.	(a) Removal of an electron from an atom reduces repulsion between electrons in that shells, so that an equilibrium is reached with the electrons attracted closer to the nucleus, so the next electron to be removed is initially closer to the nucleus. Additionally, once it is effectively outside that electron shell, it is being attracted by a larger positive residue (see figure 4). (b) An electron from an inner shell is initially significantly closer to the nucleus and subject to a much larger core charge (as the nuclear charge is shielded by one less shell of electrons)
v) explain the variation in first ionisation energy for the third period (sodium to argon).	Ionisation energy increases from Na to Mg, decreases to Al, then increases through Si to P, then decreases to S, then increases through Cl to Ne (see figure 2).	The general tend across a period of increasing ionisation energy (see ii above) is complicated by factors that can reduce ionisation energy: an electron being removed from a higher energy sub-shell (p rather than s), or being spin-paired with another negative electron in the same orbital. The most significant factors vary for different comparisons.

Table 4: Conceptual requirements of meeting the learning objectives for the ionisation energies topic in the Singapore A level chemistry course

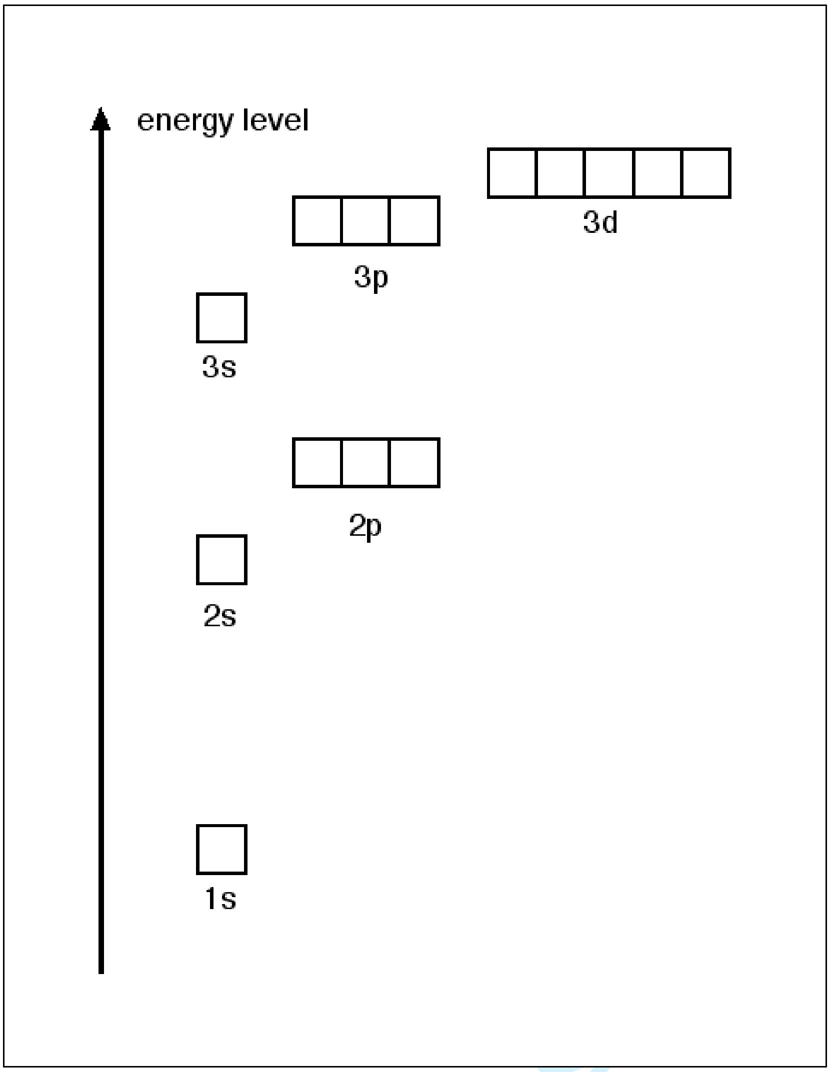

Figure 1. Typical schematic representation of relative energy levels associated with orbital types in isolated multi-electron atom.

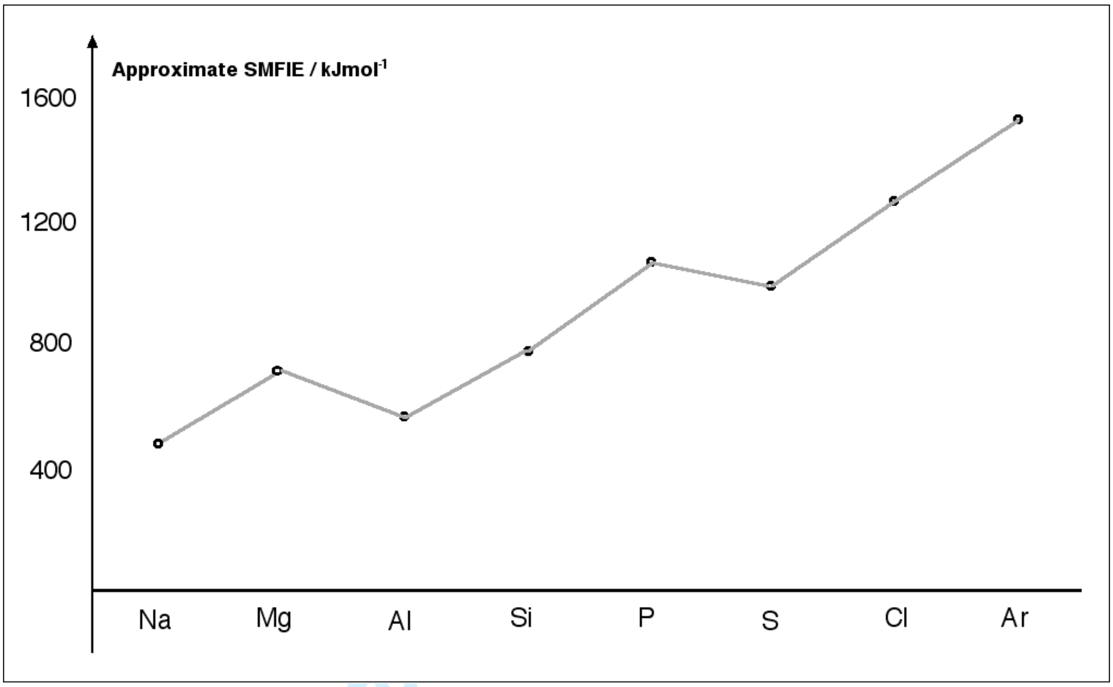

Figure 2: The pattern in the values of standard molar first ionization enthalpies (SMFIE) across the elements of period 3

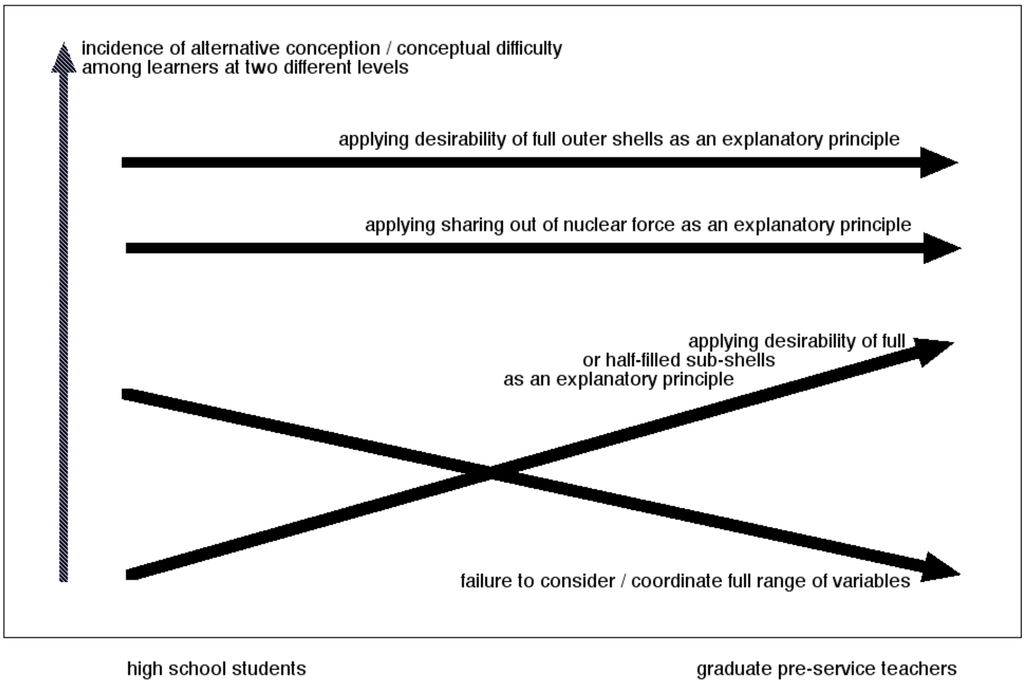

Figure 3: Schematic showing general trends in major categories of respondent errors

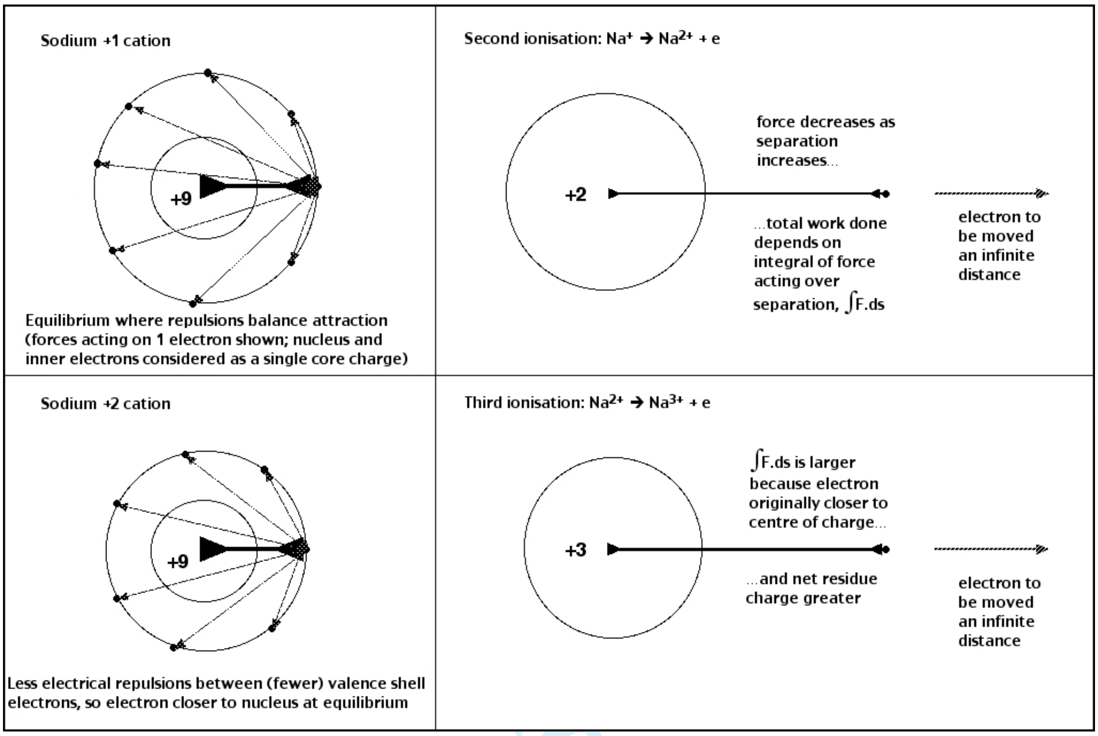

Figure 4: Modelling a comparison of the second and third ionisations of sodium based on a 'shells' representation of the atom.

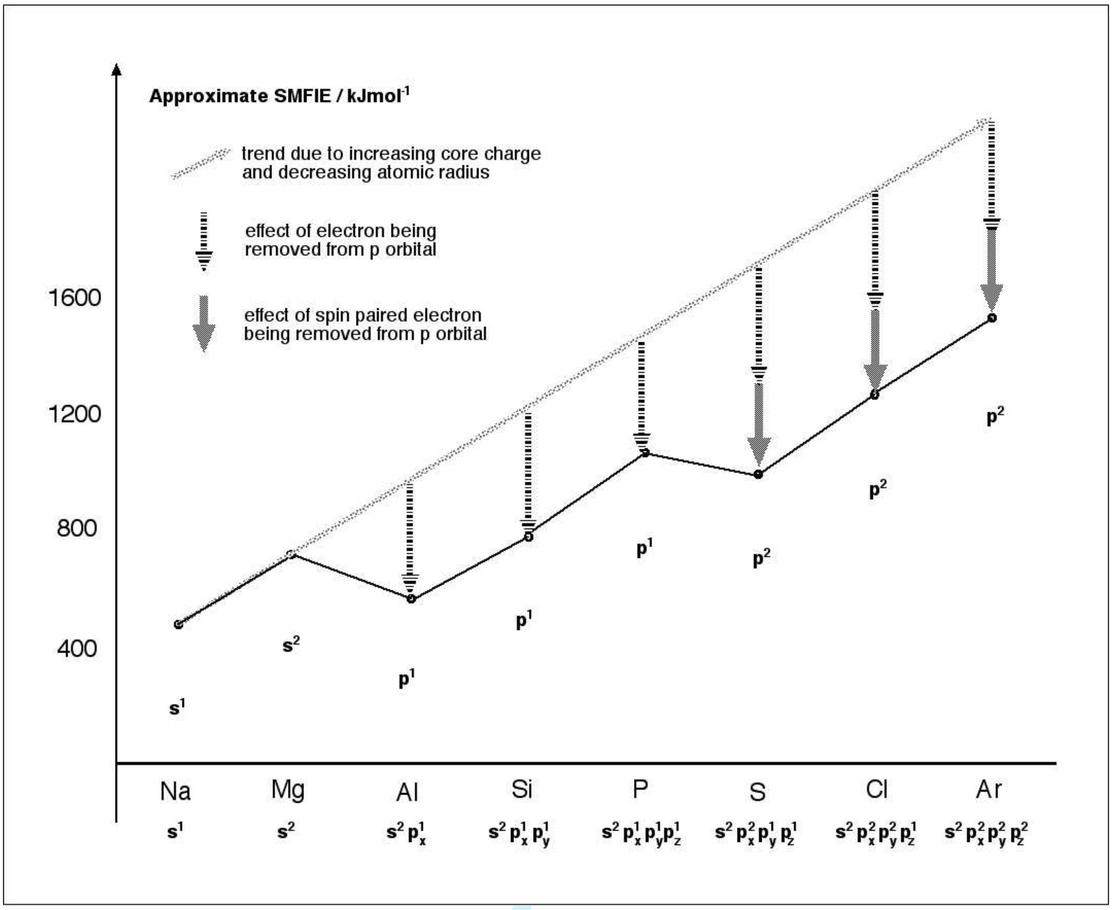

Figure 5: Factors influencing the pattern of first ionisation energies (SMFIE) across period 3. The figure shows the respective 3rd shell electronic configuration beneath each element symbol, and also indicates the orbital configuration associated with the electron to be removed during ionisation – s or p; singly occupied (s^1, p^1) or spin paired (s^2, p^2) – beneath the data points.

Appendix **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 at the back of 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.

   Reason:
   - (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 sulfur 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 sulfur ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^4$)?
   A. The first ionisation energy of phosphorus is greater than that of sulfur.
   B. The first ionisation energy of phosphorus is less than that of sulfur.
   C. I do not know the answer.

   Reason
   (1) More energy is required to overcome the attraction between the paired 3p electrons in sulfur.
   (2) 3p electrons of sulfur 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 sulfur is greater than the repulsion between its 3p electrons.
   (5) In this situation, the effect of an increase in nuclear charge in sulfur 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 sulfur ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^4$)?
   A. The first ionisation energy of silicon is greater than that of sulfur.
   B. The first ionisation energy of silicon is less than that of sulfur.
   C. I do not know the answer.

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

References

Ausubel, D. P. (2000). *The Acquisition and Retention of Knowledge: a cognitive view*. Dordrecht: Kluwer Academic Publishers.

Banerjee, A. C. (1991). Misconceptions of students and teachers in chemical equilibrium. *International Journal of Science Education, 13*(4), 487-494.

Blackmore, S. (2000). The power of memes. *Scientific American* (October 2000), 52-61.

Chang, S.-N., & Chiu, M.-H. (2008). Lakatos' Scientific Research Programmes as a Framework for Analysing Informal Argumentation about Socio-scientific Issues. *International Journal of Science Education, 30*(13), 1753-1773.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: examples from learning and discovery in science,. In R. N. Giere (Ed.), *Cognitive Models in Science* (Vol. XV, pp. 129-186). Minneapolis: University of Minnesota Press.

Claxton, G. (1993). Minitheories: a preliminary model for learning science. In P. J. Black & A. M. Lucas (Eds.), *Children's Informal Ideas in Science* (pp. 45-61). London: Routledge.

Dal, B. (2006). The Origin and Extent of Student's Understandings: The Effect of Various Kinds of Factors in Conceptual Understanding in Volcanism. *Electronic Journal of Science Education, 11*(1), 38-59.

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

Dill, D. (2006). Penetration and sheilding [Electronic Version]. *Supplementary Notes: Quantum Mechanics*. Retrieved 28th December 2007, from http://quantum.bu.edu/notes/QuantumMechanics/

diSessa, A. A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. L. Stevens (Eds.), *Mental Models* (pp. 15-33). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

diSessa, A. A. (1993). Towards an epistemology of physics. *Cognition and Instruction, 10*(2&3), 105-225.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limón & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29-60). Dortrecht: Kluwer.

Driver, R. (1983). *The Pupil as Scientist?* Milton Keynes: Open University Press.

Driver, R. (1989). Students' conceptions and the learning of science. *International Journal of Science Education, 11*(special issue), 481-490.

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., & Erickson, G. (1983). Theories-in-action: some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education, 10*, 37-60.

Driver, R., Guesne, E., & Tiberghien, A. (1985). Children's ideas and the learning of science. In R. Driver, E. Guesne & A. Tiberghien (Eds.), *Children's Ideas in Science* (pp. 1-9). Milton Keynes:: Open University Press.

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., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994). *Making Sense of Secondary Science: research into children's ideas*. London: Routledge.

Duit, R. (1991). Students' conceptual frameworks: consequences for learning science. In S. M. Glynn, R. H. Yeany & B. K. Britton (Eds.), *The Psychology of Learning Science* (pp. 65-85). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Duit, R. (2007). *Bibliography - Students' and Teachers' Conceptions and Science Education*. from http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html

Fensham, P. J., Gunstone, R. F., & White, R. T. (1994). *The Content of Science: a constructivist approach to its teaching and learning*. London: Falmer Press.

Finster, D. C. (1991). Developmental instruction: part 2. Application of Perry's model to general chemistry. *Journal of Chemical Education, 68*(9), 752-756.

Georgiou, A. K. A. (2005). *Thought Experiments in Physics Learning: On Intuition and Imagistic Simulation.* MPhil Thesis, Faculty of Education, University of Cambridge, Cambridge.

Gess-Newsome, J., & Lederman, N. G. (1999). *Examining pedagogical content knowledge*. Dordrecht: Kluwer.

Gilbert, J. K. (2005). Visualization: a metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in Science Education* (pp. 9-27). Dordrecht: Kluwer Academic Publishers.

Gilbert, J. K., & Boulter, C. J. (Eds.). (2000). *Developing Models in Science Education*. Dordrecht: Kluwer Academic Publishers.

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., & Swift, D. J. (1985). Towards a Lakatosian analysis of the Piagetian and alternative conceptions research programs. *Science Education, 69*(5), 681-696.

Gilbert, J. K., & Treagust, D. F. (Eds.). (2009). *Chemical Education: Linking the representational levels of chemistry*. Dordrecht: Springer.

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

Goodwin, A. (2002). Teachers' continuing learning of chemistry: some implications for science teaching. *Chemistry Education: Research and Practice in Europe, 3*(3).

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.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*(9), 799-822.

Haidar, A. H. (1997). Prospective chemistry teachers' conceptions of the conservation of matter and related concepts. *Journal of Research in Science Teaching, 34*(2), 181-197.

Hammer, D. (2004). The variability of student reasoning, Lecture 3: Manifold cognitive resources,. In E. F. Redish & M. Vicentini (Eds.), *Research on Physics Education* (pp. 321-340). Bologna/Amsterdam: Italian Physical Society/IOS Press.

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.

Justi, R., & Gilbert, J. K. (2000). History and philosophy of science through models: some challenges in the case of 'the atom'. *International Journal of Science Education, 22*(9), 993-1009.

Key Stage 3 National Strategy. (2002). Framework for teaching science: years 7, 8 and 9. London: Department for Education and Skills.

Kramer, D. A. (1983). Post-formal operations? A need for further conceptualization. *Human Development, 26*, 91-105.

Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrove (Eds.), *Criticism and the Growth of Knowledge* (pp. 91-196). Cambridge: Cambridge University Press.

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.

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.

McCloskey, M. (1983). Intuitive Physics. *Scientific American, 248*(4), 114-122.

Millar, R. (1989). Constructive criticisms. *International Journal of Science Education, 11*(special issue), 587-596.

Osborne, R. J., & Wittrock, M. C. (1983). Learning Science: a generative process. *Science Education, 67*(4), 489-508.

Perry, W. G. (1970). *Forms of intellectual and ethical development in the college years: a scheme*. New York: Holt, Rinehart & Winston.

Petri, J., & Niedderer, H. (1998). A learning pathway in high-school level quantum atomic physics. *International Journal of Science Education, 20*(9), 1075-1088.

Piaget, J. (1972). *The Principles of Genetic Epistemology* (W. Mays, Trans.). London: Routledge & Kegan Paul.

Pope, M. L., & Denicolo, P. (1986). Intuitive theories - a researcher's dilemma: some practical methodological implications. *British Educational Research Journal, 12*(2), 153-166.

Pope, M. L., & Gilbert, J. K. (1983). Personal experience and the construction of knowledge in science. *Science Education, 67*(2), 193-203.

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

Quilez-Pardo, J., & Solaz-Portoles, 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.

Russell, T., & Osborne, J. (1993). *Constructivist Research, Curriculum Development and Practice in Primary Classrooms: Reflections on Five Years of Activity in the Science Processes and Concept Exploration (SPACE) Project*. Paper presented at the Third International Seminar on Misconceptions in the Learning of Science and Mathematics.

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

Shayer, M., & Adey, P. (1981). *Towards a Science of Science Teaching: Cognitive development and curriculum demand*. Oxford: Heinemann Educational Books.

Singapore Examinations and Assessment Board. (2009). *Chemistry Higher 2 (Syllabus 9647)* Singapore Examinations and Assessment Board.

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

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

Taber, K. S. (1998b). 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, K. S. (2000). Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science Education, 22*(4), 399-417.

Taber, K. S. (2001a). Shifting sands: a case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education, 23*(7), 731-753.

Taber, K. S. (2001b). When the analogy breaks down: modelling the atom on the solar system. *Physics Education, 36*(3), 222-226.

Taber, K. S. (2003). Understanding ionisation energy: physical, chemical and alternative conceptions. *Chemistry Education: Research and Practice, 4*(2), 149-169.

Taber, K. S. (2005). Learning quanta: barriers to stimulating transitions in student understanding of orbital ideas. *Science Education, 89*(1), 94-116.

Taber, K. S. (2006). Beyond Constructivism: the Progressive Research Programme into Learning Science. *Studies in Science Education, 42*, 125-184.

Taber, K. S. (2008a). Conceptual resources for learning science: Issues of transience and grain-size in cognition and cognitive structure. *International Journal of Science Education, 30*(8), 1027-1053.

Taber, K. S. (2008b). Exploring conceptual integration in student thinking: evidence from a case study. *International Journal of Science Education, 30*(14), 1915-1943.

Taber, K. S. (2008c). Of models, mermaids and methods: The role of analytical pluralism in understanding student learning in science. In I. V. Eriksson (Ed.), *Science Education in the 21st Century* (pp. 69-106). Hauppauge, New York: Nova Science Publishers.

Taber, K. S. (2009a). Learning at the symbolic level. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple Representations in Chemical Education* (pp. 75-108). Dordrecht: Springer.

Taber, K. S. (2009b). *Progressing Science Education: Constructing the scientific research programme into the contingent nature of learning science*. Dordrecht: Springer.

Tan, K.-C. D., Goh, N.-K., Chia, L.-S., & Taber, K. S. (2005). *Development of a Two-Tier Multiple Choice Diagnostic Instrument to Determine A-Level Students' Understanding of Ionisation Energy*. Singapore: National Institute of Education, Nanyang Technological University.

Tan, K.-C. D., & Taber, K. S. (2005). What comes after stable octet? Stable sub-shell! *Journal of Science and Mathematics Education in Southeast Asia, 28*(1), 81-102.

Tan, K.-C. D., & Taber, K. S. (2009). Ionization Energy: Implications of Pre-service Teachers' Conceptions. *Journal of Chemical Education, 86*(5), 623-629.

Tan, K.-C. D., Taber, K. S., Goh, N.-K., & Chia, L.-S. (2005). The ionisation energy diagnostic instrument: a two-tier multiple choice instrument to determine high school students' understanding of ionisation energy. *Chemistry Education Research & Practice, 6*(4), 180-197.

Tan, K.-C. D., Taber, K. S., Liu, X., Coll, R. K., Lorenzo, M., Li, J., et al. (2008). Students' conceptions of ionisation energy: A cross-cultural study. *International Journal of Science Education, 30*(2), 263-283.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate student's misconceptions in science. *International Journal of Science Education, 10*(2), 159-169.

Trumper, R. (2001). A cross-college age study of science and nonscience students' conceptions of basic astronomy concepts in preservice training for high-school teachers. *Journal of Science Education and Technology, 10*(2), 189-195.

Tsaparlis, G. (1994). Blocking mechanisms in problem solving from the Pascual-Leone's M-space perspective. In H.-J. Schmidt (Ed.), *Problem Solving and Misconceptions in Chemistry and Physics,* (pp. 211-226). Dortmund: International Council of Association for Science Education.

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

Watts, M. and M. L. Pope (1982). A Lakatosian view of the young personal scientist. Paper presented at the *British Conference on Personal Construct Psychology*, Manchester: University of Manchester Institute of Science & Technology, September 1982.

White, R. T. (1985). Interview protocols and dimensions of cognitive structure. In L.

H. T. West & A. L. Pines (Eds.), *Cognitive Structure and Conceptual Change* (pp. 51-59). London: Academic Press.