

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

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**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.**

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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.

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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 be 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

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3 responses from the two groups to consider the extent to which degree level study has
4 eroded commitment to alternative conceptions. We will argue that our findings
5 suggest that the alternative conceptions commonly found among students in the topic
6 of ionisation energies are shared to a similar extent by their teachers, with the clear
7 implication that teaching may well be a major source of these ideas, and suggesting
8 that learners have a high level of commitment to the ideas once they are acquired, so
9 that they tend to form the 'hard core' for developing understanding about the topic.
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17 ***Background to the research***

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

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37 Despite this variation in terminology, most of the research into learners' ideas can be
38 seen as part of a coherent programme of research within science education (Gilbert &
39 Swift, 1985; Taber, 2006, 2009b). Although learners' ideas are often considered to be
40 of intrinsic interest, the prime rationale for initiating this research programme (RP)
41 was to inform the teaching of the scientific theories and models that are represented as
42 'target knowledge' in the school science curriculum (Driver & Easley, 1978; Driver &
43 Erickson, 1983; Gilbert, Osborne, & Fensham, 1982; Gilbert & Watts, 1983; Osborne
44 & Wittrock, 1983).
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53 As the RP aims to inform teaching, it is not limited to identifying students' alternative
54 ideas, and the frequencies with which they occur, but rather is also concerned with the
55 origins and nature of students' conceptions, and how they interact with teaching. The
56 various conceptions that have been identified vary along a range of dimensions
57 (Claxton, 1993; diSessa, 2002; Driver, 1983, 1989; Driver & Easley, 1978; Driver,
58 Guesne, & Tiberghien, 1985; Gilbert et al., 1982; Gilbert & Watts, 1983; Millar,
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3 1989; Pope & Denicolo, 1986; Pope & Gilbert, 1983; Solomon, 1992; Taber, 2000,
4 2008b). So, some ideas may be strongly committed to **and tenaciously retained**
5 **despite being contrary to teaching** (Taber, 2001a), where others seem to be readily set
6 aside (Claxton, 1993). Sometimes students can be very explicit about their ideas
7 (McCloskey, 1983), whereas other notions seem to be largely applied at an intuitive
8 level, and are identified only indirectly (diSessa, 1993). Some studies suggest that at
9 times an alternative idea will effectively block new learning (e.g. Chi, 1992), whereas
10 other research finds that alternative conceptions may act as intermediate conceptions
11 on conceptual trajectories leading to target knowledge (Driver, 1989). Yet other
12 studies suggest that in some circumstances learners can adopt manifold conceptions of
13 a topic with new ideas supplementing existing ways of thinking (e.g. Taber, 2000).
14 Sometimes identified alternative conceptions seem to be somewhat isolated ideas
15 (Claxton, 1993), whereas others seem to be integrated into theory-like conceptual
16 frameworks (Taber, 1998a).

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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**

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3 consider a *scientific* RP that seeks to explore the nature and conditions of learning in
4 science, and to inform the development of science pedagogy. The notion of scientific
5 RPs was proposed by the philosopher Imre Lakatos (1970), to show how individual
6 studies can contribute to developing knowledge within established research traditions.
7
8 In the Lakatosian model, a RP has ‘hard core’ assumptions and what Lakatos called
9 ‘heuristic’ apparatus guiding development of the programme. The hard core of a
10 research programme is in effect its *metaphysical* foundation – it is the set of
11 commitments that are *taken for granted*, and which are considered non-falsifiable
12 within the programme. New information about a topic is used to build up more
13 detailed understanding, but always consistent with the hard core. This more peripheral
14 body of ideas is known as the ‘protective belt’, because when new data are
15 inconsistent with the theoretical content of the RP, it is assumed that changes need to
16 be made within the protective belt (which thus ‘protects’ the hard core from
17 falsification).
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29 The Lakatosian notion of RP can be seen as an attempt to bridge Kuhn’s account of
30 science where scientists commit to ideas so strongly it becomes difficult to recognise
31 anomalies, and Popper’s prescription with its implication that scientists should readily
32 discard theories whenever apparently contradicted by experiments (Taber, 2009b). In
33 a Lakatosian RP anomalies are recognised, but largely tolerated (‘quarantined’) as
34 long as the overall RP is considered to be progressive, that is continuing to suggest
35 new directions for empirical investigation, and making predictions which are found to
36 be broadly consistent with empirical findings. Ultimately a RP may be discarded
37 when a more promising alternative is available, but this tends to be a more global
38 judgment about the potential of the programme for further progress, rather than
39 responding to individual falsifications. So, for example, the Newtonian programme,
40 with its hard-core commitment to absolute space and time, tolerated known anomalies
41 about orbital behaviour until Einstein offered the basis of an alternative RP
42 considered more fruitful.
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55 Hard core commitments of the constructivist RP would include the beliefs that a
56 student’s current knowledge and understanding is a major factor in subsequent
57 learning (Driver, 1989), and that more effective teaching can in principle be informed
58 by a better understanding of the origins, nature and development of learners’ ideas in
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3 science topics (Driver & Oldham, 1986; Leach & Scott, 2002; Russell & Osborne,
4 1993).

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8 These hard core commitments suggest general directions for research (e.g. exploring
9 student' ideas) that lead to particular theoretical constructs - such as the notion of
10 alternative conceptual frameworks (Driver & Erickson, 1983; Gilbert & Watts, 1983)
11 - and specific knowledge claims – for example, the octet framework represents
12 common features of how learners understand fundamental aspects of chemistry
13 (Taber, 1998a) – which are themselves open to further testing. Lakatos (1970) refers
14 to a RP developing a protective belt of auxiliary theory that offers 'refutable variants'
15 that are evaluated by the extent to which they help explain existing data, and suggest
16 useful directions for further research.
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24 25 **Considering learners as Lakatosian scientists**

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28 Indeed, one perspective that has been suggested to illuminate why some identified
29 alternative conceptions seem to be readily overcome whilst others are so tenacious, is
30 to consider that *a student learning science* can be understood to respond to new
31 information in much the same way as a scientist working within a Lakatosian RP
32 (Watts & Pope, 1982). Considering student thinking in terms of Lakatos' model of RP
33 has also informed one analytical scheme for exploring students' arguments about
34 socio-scientific issues (Chang & Chiu, 2008).
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42 Whilst comparisons between the progress of science and individual learning need to
43 be made with caution, Watts and Pope's (1982) suggestion that some ideas that a
44 learner develops may take on a hard-core status (attracting high levels of
45 commitment), whilst others can be considered to be more peripheral and so readily
46 shed, can have value for thinking about conceptual change among science learners.
47 We suggest that in the topic explored in this paper, ionisation energy, certain common
48 alternative conceptions reflect hard core commitments that are part of many learners
49 taken-for-granted ways of thinking about the topic.
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56 57 **Origins of alternative conceptions**

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60 There is no single source that can account for all of the reported learners' alternative

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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,

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

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

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25 **A range of studies report** subject knowledge deficiencies among trainee teachers
26 (‘pre-service’ teachers), for example in astronomy (Trumper, 2001); matter
27 conservation (Haidar, 1997); chemical equilibrium (Quilez-Pardo & Solaz-Portoles,
28 1995), redox reactions (De Jong, Acampo, & Verdonk, 1995), and behaviour of gases
29 (Lin, Cheng, & Lawrenz, 2000). It seems likely that *teachers’ own alternative*
30 *conceptions themselves make up one significant factor in the development of some*
31 *alternative conceptions among students, and so an important focus of the*
32 *constructivist RP should be the characteristics of alternative conceptions which*
33 *remain unchallenged by degree level study and initial teacher education courses, and*
34 *may be actually presented as target knowledge in science teaching.*
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44 ***Learning about the ionisation energy topic***

45 46 47 **Target knowledge about ionisation energies**

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50 In the Singapore context, students studying chemistry at senior high school
51 (university entrance) level take the Singapore-Cambridge GCE A Level (**General**
52 **Certificate of Education, Advanced Level**) examination (for which the Ministry of
53 Education, Singapore and the University of Cambridge Local Examinations Syndicate
54 are the joint examining authorities). The syllabus, sets out that
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3 “Candidates should be able to: explain the factors influencing the
4 ionisation energies of elements; explain the trends in ionisation
5 energies across a period and down a Group of the Periodic Table;
6 deduce the electronic configurations of elements from successive
7 ionisation energy data; interpret successive ionisation energy data of
8 an element in terms of the position of that element within the
9 Periodic Table...[for the third period (sodium to argon)] explain the
10 variation in first ionisation energy”
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16 (Singapore Examinations and Assessment Board, 2009: 8, 16)
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19 20 **Alternative conceptions of ionisation energies**

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22 Two particular alternative conceptions were identified in an interview study with UK
23 students studying A level chemistry in a Further Education college. The first of these
24 was that students tended to judge the neutral sodium atom as less stable than a
25 separated electron and Na^+ ion. This conception was one aspect of a common
26 conceptual framework, where students conceptualised chemistry at the
27 submicroscopic (molecular level) around an explanatory principle based on the
28 perceived stability, and desirability, of species with full **outer** shells or octets (Taber,
29 1998a). Attaining such a configuration was considered by students to be a sufficient
30 driver to explain chemical reactions. From this perspective, some students expected
31 the ionisation of sodium would be spontaneous, because the resulting cation would
32 have an octet of electrons in its outer shell.
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36 The second conception identified in the interview study concerned the way nuclear
37 charge interacts with the valence shell electrons. It was found that students considered
38 force to be *emanating from* the nucleus (rather than being an interaction between
39 charges), and being *shared between* the electrons present (Taber, 1998b). They would
40 explain the increase in successive ionisation energies as due to the nuclear charge
41 being shared among fewer electrons with each ionisation.
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45 **Subsequently**, a diagnostic instrument used to collect data from a sample of over three
46 hundred students in 17 institutions suggested that many UK A level chemistry
47 students would commonly agree with statements that were scientifically incorrect but
48 which were based on either the octet framework or the conservation of force
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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

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3 selected response combinations based upon alternative conceptions that had been
4 identified previously in interviews. This study has been reported in the literature (Tan,
5 Taber et al., 2005), and readers interested in the full findings are referred to the
6 published account.
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10 11 **Study 2: Singapore Pre-service teachers' thinking about Ionisation Energy**

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14 The IEDI was administered to 237 graduate pre-service chemistry teachers enrolled in
15 a chemistry pedagogy course during the period 2003 to 2006 in a teacher education
16 institution in Singapore. All the pre-service teachers who took part in the study had
17 chemistry as their first (main) teaching subject, and were being prepared to teach
18 chemistry up to A level. The majority of them had majored in chemistry as
19 undergraduates, while the rest had biochemistry, material science, material
20 engineering or chemical engineering degrees. The pre-service teachers were
21 forewarned of the testing session, and advised to prepare by reading the relevant A
22 level material on ionisation energy.
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32 As with the senior school students, this study showed that the pre-service teachers
33 commonly selected response combinations based upon alternative conceptions that
34 had been identified previously. Again readers are referred to the published account
35 (Tan & Taber, 2009) for the full findings.
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40 41 ***Research Question***

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43 The question we address here is *to what extent do graduate trainee chemistry*
44 *teachers in Singapore demonstrate alternative conceptions that have been found to*
45 *be common among A level chemistry students in Singapore?*
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50 This is based upon, what we consider, reasonable, assumptions about the validity of
51 comparing these two studies:
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55 1: that the two samples are reasonably representative of the wider populations of A
56 level chemistry students in Singapore (Study 1), and pre-service chemistry teachers
57 training in Singapore (Study 2).
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2: that a cross-sectional comparison between the two populations offers a meaningful

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3 insight into the influence of degree level study on thinking about this topic area.
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6 Our first assumption seems reasonable in view of the size of the samples: almost a
7 thousand A level chemistry students in Singapore drawn from almost half of the
8 institutions teaching A level; and all the specialist chemistry teachers-in-training in
9 Singapore (during the data-collection period) in the sample of pre-service teachers.
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13 Our second assumption is based on considering the pre-service teachers in study 2
14 (who would all previously have studied chemistry to A level or equivalent), as
15 representing a subset of A level students (i.e. similar to those in study 1) who have
16 subsequently undertaken degree level studies in chemistry or a related field. Whilst
17 some A level students may move abroad for undergraduate education, and some pre-
18 service teachers will have studied abroad, most of the pre-service teachers are
19 graduates from one of the two local universities with science/engineering
20 programmes, and the two samples may be considered to derive from substantially the
21 same educational context.
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31 Given that the IEDI diagnosed significant levels of alternative conceptions among the
32 graduate pre-service teachers, our purpose in the present study is compare the two
33 populations to ascertain the extent to which degree level education has challenged
34 common alternative conceptions. This comparison is complicated by the more
35 selective nature of the pre-service teachers. The subset of A level students who go on
36 to train to be teachers will be those (a) who were successful at A level, (b) chose to
37 study chemistry or cognate subjects at university, and (c) then made the career choice
38 of training to be chemistry teachers.
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46 A reasonable *prima facie* expectation, then, is that the pre-service teachers reflect a
47 subset of past A level students who were academically successful in, and especially
48 interested in, chemistry, so might be expected as a group to have demonstrated above-
49 average subject knowledge during their A level studies.
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54 ***Findings: comparing pre-service teachers' thinking with that of A level*** 55 ***students*** 56 57 58

59 In exploring the research question posed in this study, we will first offer a comparison
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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 than 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.

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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

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3 shows the distractors (incorrect response options) that reached this threshold.
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6 **Table 3: Popular distractors on the IEDI (%age selecting**
7 **response option, cf. %age of correct responses in parentheses).**
8 **[Figures in square parentheses provided for comparison across**
9 **studies.]**
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14 Table 3 shows 14 popular incorrect response combinations for the A level students,
15 and 14 popular incorrect responses for the pre-service teachers – with 11 of the
16 popular distractors being common across the two groups. Popular distractors were
17 selected *more often* than the correct response for five of the items for the A level
18 students, and for six of the items for the pre-service teachers (with two different
19 distractors proving more popular than the correct response in item 6). Of particular
20 note, four of the popular distractors were selected more than the correct response in
21 both studies (A2 in item 1; A3 in item 2; B4 in item 3; and A2 in item 6).
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29 The commonly selected response options reflected the alternative conceptions
30 identified in the original UK studies (the octet framework; the conservation of force
31 conception) as well as the additional factors that were discovered during the
32 development of the IEDI in Singapore (difficulty coordinating factors; confounding
33 Aufbau rules with nucleus-electron separation; stability of sub-shell configurations).
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40 **Coordinating conflicting factors**

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42 Items 5-10 concerned the learning objective that for the third period (elements sodium
43 to argon) “candidates should be able to explain the variation in first ionisation
44 energy”. This variation is shown in figure 2. Explaining this pattern requires
45 awareness of (a) the different factors at work; (b) whether they tend to increase or
46 decrease ionization energy, and (c) which factors dominate in particular comparisons.
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48 In the Discussion section (below), we consider the high level of intellectual challenge
49 faced in making such comparisons.
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56 **Figure 2: The pattern in the values of standard molar first**
57 **ionization enthalpies (SMFIE) across the elements of period 3**
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One of the findings from the study with A level students was that on a number of

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3 items students commonly selected the wrong options where several factors were
4 pertinent. There were six such examples that met our 10% threshold in Study 1.
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8 Two of these examples concerned the relative nucleus-electron separation in different
9 orbitals in the 'same' shell, where respondents selected options based on a 3p electron
10 in one atom being further from the nucleus than an electron in a 3s orbital in another
11 atom. Models predicting appropriate values for average electron-nucleus separation in
12 an atomic system are sophisticated (Dill, 2006), and not studied before university
13 level. However, students are expected to know that atomic radius decreases across
14 period 2 or 3 as nuclear charge increases (Singapore Examinations and Assessment
15 Board, 2009). In item 7, almost one quarter of the A level students selected a rationale
16 (response A4) based on the Al (aluminium) 3p electron being further from the nucleus
17 than the Na (sodium) 3s electron to justify sodium having a higher first ionisation
18 energy (which it does not); marginally more than selected the correct response. The
19 pre-service teachers as a whole performed considerably better; with about half the
20 frequency selecting this distractor, and twice the frequency selecting the correct
21 response (see Table 3).
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34 In Item 6 only a small proportion of the A level students selected what we consider
35 the canonical response, and this was also true among the pre-service teachers. Here
36 the most common response (A2) was that the first ionisation energy drops in going
37 from magnesium to aluminium because of the aluminium 3p electron being further
38 from the nucleus than the magnesium 3s electron. Nearly half of the A level students
39 selected this response, and a slightly *higher* proportion, just over half, of the pre-
40 service teachers made this choice.
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47 The other four examples in this category were:
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- 49 • in item 5, the popular distractor (A4) was based upon increased
50 repulsion between spin-paired electrons, where the more significant
51 factor was the increase in nuclear charge;
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- 53 • in item 7, the popular distractor (A3) was based upon a
54 consideration of additional shielding, where the more significant
55 factor was the increase in nuclear charge;
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- 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.

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3 From this perspective, the nuclear force is shared among the electrons in an atomic
4 system, and the removal of electrons allows those remaining to acquire a greater
5 share.
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9 Responses to two items in the IEDI suggest that this conception is common among
10 learners in Singapore. In item 4, almost one fifth of the A level students in Study 1
11 selected the response (A2) that the second ionisation energy of sodium is greater than
12 the first (which is true) because the same number of protons are attracting less
13 electrons (the alternative conception). The response patterns of the pre-service
14 teachers in Study 2 were very similar, with almost the same proportion selecting this
15 distractor.
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18 In item 2, very nearly half of all the A level students in Study 1 agreed with an
19 explicit statement of the conservation of force conception (response A3), referring to
20 the redistribution of the attraction for the nucleus when an electron is removed,
21 allowing remaining electrons to experience greater attraction. Less than a third of the
22 students selected the correct response based on Coulombic principles. In Study 2, we
23 again found that pre-service teachers responded in very similar ways, with just over
24 half of the respondents selecting the conservation of force based distractor, and a little
25 under a third the scientific response. Based on our samples, *therefore, there is no*
26 *evidence that the degree level study of the pre-service teachers had eroded the hold of*
27 *this alternative conception.*
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42 **Applying the octet framework**

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44 The octet framework is based on octets of electrons or full outer shells (sometimes,
45 but not always the same thing) being inherently stable, and offering a sufficient
46 explanation for chemical phenomena. Common responses to four of the items in the
47 IEDI reflected this way of thinking about ionisation processes (see Table 3).
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53 In item 1, over two fifths of the A level students in Study 1 responded **that** an electron
54 removed from Na would not return because the Na⁺ produced had a stable
55 configuration (response A2). This was slightly more than the proportion who selected
56 the scientifically acceptable option that the atom would reform because the cation and
57 electron would attract. In study 2 we found a very similar pattern among the pre-
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3 service teachers.
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6 In item 3, almost two thirds of the A level students in Study 1 considered that the
7 statement that the Na atom was a more stable system than the separated cation and
8 electron false because the cation had achieved a stable configuration (response B4).
9 The proportion selecting this response combination among the pre-service teachers in
10 study 2 was slightly less, but still a majority of the sample, and nearly twice the
11 proportion responding with the scientifically correct response.
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18 The responses linked to the octet framework were less popular in items 4 and 5, but
19 still attracted significant numbers of respondents. In item 4, about a sixth of the A
20 level students explained the second ionisation energy of sodium being greater than the
21 first in terms of disrupting the stable octet structure (response A1). Slightly more, a
22 little over a quarter, of the pre-service teachers chose this option. In item 5, one
23 available explanation (response B2) for the increase in **standard molar first ionisation**
24 **enthalpies** in Mg (**magnesium**) over Na was that Na could achieve a stable octet
25 configuration. In Study 1 the proportion of A level students selecting this option was
26 slightly below our (10%) threshold for being considered a common incorrect
27 response. However in Study 2, the proportion of pre-service teachers selecting this
28 option was slightly higher, just reaching our threshold. We do not read any
29 significance to this minor difference, but considering these four items together we
30 conclude that *degree level study has made very little difference to the use of the octet*
31 *framework as an explanatory principle.*
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43 44 **Extending notions of stable configurations**

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46 The octet framework is based on the perceived inherent stability of the noble gas
47 structures, which are commonly used by students to explain chemical phenomena, and
48 linked to the notion of 'full shells' (although only two of the noble gas elements
49 actually have full shells, and one of these, He, does not have an octet of electrons). A
50 number of common distractors in the IEDI are based on the commonly perceived
51 *inherent* stability of other configurations.
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59 In Study 1, three of these reached our threshold of being chosen by a tenth of the
60 sample. In item 5, a little over a tenth of the A level students selected a response

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3 based on the stability of a full 3s sub-shell (response B1). In item 8, about a quarter of
4 the A level students selected the option based on the stability of a half-filled 3p sub-
5 shell (response B2), and in item 9, almost one fifth of the A level students used this
6 rationale (response A3).
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11 These same response options were *more popular* among the pre-service teachers in
12 Study 2. So almost a fifth of the pre-service teachers selected the option based on
13 stable configurations in item 5; over a third in item 8; and over two-fifths in item 9. In
14 the latter two cases, these options were more popular than the correct responses.
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19 In addition, similar options were popular in two other items that had not met the 10%
20 response threshold in Study 1. So in item 6, an argument based on disrupting a full 3s
21 sub-shell (response A1) was selected by almost a fifth of the pre-service teachers, and
22 was more popular than the correct response. In item 10, an argument about a half-
23 filled sub-shell (response A1) was selected by almost a sixth of the pre-service
24 teachers. We found, then, that using perceived stability of filled and half-filled sub-
25 shells as explanatory principles *was considerably more popular among the graduate*
26 *pre-service teachers than among A level students.*
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34 35 **Discussion**

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37 In this paper we have compared the findings from two studies undertaken in
38 Singapore among **large** samples of A level chemistry students (Study 1), and pre-
39 service teachers preparing to teach chemistry at secondary/high school level (Study
40 2). Both studies used the two-tier IEDI that had been developed to follow up findings
41 from previous studies in the UK. Our key results here are that:
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- 48 1. understanding of ionisation energy is poor among both A level chemistry
49 students and graduate pre-service chemistry teachers;
- 50 2. whilst the **more highly selected** and more highly educated pre-service
51 teachers outperform the A level students over the ten-item test, they perform
52 equally poorly on half the items, and less well on one item;
- 53 3. pre-service teachers tended to make **fewer** mistakes when choosing the more
54 significant of competing factors that influence comparisons of ionisation
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3 energy;
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- 5 4. distractors based on alternative conceptions were popularly chosen by both
- 6 A level students and pre-service teachers:
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- 9 i. whilst the precise pattern of responses differs between the two groups,
- 10 the popularity of responses based on two common alternative
- 11 conceptions reported in the literature ('conservation of force'; 'the octet
- 12 rule explanatory principle') was similar among the pre-service teachers
- 13 and the A level students;
- 14
- 15 ii. in one area ('stability' of fully-filled and half-filled sub-shells), the
- 16 reliance on alternative conceptions was *more* prevalent among the pre-
- 17 service teachers than among the A level students.
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25 Figure 3 offers a schematic representation of the general trends found in these

26 categories of incorrect student response.

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29 **Figure 3: Schematic showing general trends in major categories**

30 **of respondent errors**

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34 As suggested in the results section (above), we consider the nature of common student

35 errors to fall into two categories: those that are primarily related to failures to

36 effectively coordinate a range of variables and concepts (where pre-service teachers

37 make less mistakes than the senior school students); and those that relate to the

38 adoption of alternative conceptions (where the pre-service teachers appear to be at

39 least as likely to hold the alternative conceptions).

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46 **Is the Singapore context unusual?**

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49 The research reported here is based on studies in one educational context, the city-

50 state of Singapore in South-East Asia. Undoubtedly there are unique characteristics of

51 any particular context. However, the Singapore studies built on earlier UK studies that

52 demonstrated how students commonly used the octet framework and conservation of

53 force conceptions in judging statements about ionisation energy.

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59 The topic of ionisation energies forms part of high school or college chemistry

60 courses in a number of countries. The administration of the IEDI (in translation where

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3 appropriate) to high school students or first year undergraduates in New Zealand,
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5 England, Spain, the US, and China has shown that similar results can be obtained
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7 across this range of educational contexts (Tan et al., 2008). We believe, therefore, that
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9 it is very likely that our findings are significant well beyond the specific context of
10
11 Singapore.

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13 It is clearly a concern for science education when common alternative conceptions
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15 found among school students remain unchallenged by further study of the subject area
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17 at degree level. The present study does not allow us to know to what extent our
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19 findings reflect a general trend rather than something specific about the topic of
20
21 ionisation energies. Further studies in other topics with known common alternative
22
23 conceptions would seem to be indicated.

24 25 **Contributing to the RP to inform teaching**

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27 It was suggested above that studies into aspects of student thinking and learning can
28
29 be understood as part of the **constructivist RP** into learning in science (Taber, 2009b).
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31 A RP has a hard core of central commitments (such as seeing learning as a process of
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33 step-wise personal construction of knowledge), and a 'protective belt' of auxiliary
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35 theory comprising 'refutable variants' of the RP – ideas consistent with and extending
36
37 beyond the hard core, but not themselves considered as irrefutable within the
38
39 programme. A range of concepts and models from research carried out in recent
40
41 decades have been identified as components of the constructivist RP's protective belt
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43 (Taber, 2009b).

44
45 It has been argued that as learning science is a complex, multi-faceted, phenomenon,
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47 it is appropriate to seek complementary insights by applying a range of distinct
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49 constructs as 'analytical lenses', provided that these different interpretive tools are
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51 considered to derive from a coherent set of underlying principles (Taber, 2008c).
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53 Here the authors draw upon constructs from the conceptual repertoire provided by the
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55 protective belt of the constructivist RP to interpret our results, and to indicate how our
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57 findings can inform science education.

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

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3 Assessment Board, 2009). We then consider student learning of this topic in terms of
4 a range of constructs from the theoretical repertoire of the RP: curriculum models;
5 learning demand; learning quanta; conceptual fossils; and finally Watts and Pope's
6 (1982) suggestion of considering student thinking itself to reflect Lakatosian RPs.
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10 **Drawing upon the progressive RP: The abstract nature of the subject matter**

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12 The constructivist perspective on learning science suggests that effective learning
13 depends upon subject matter being presented to learners in a form which is relatable
14 to, and comprehensible within, their existing 'cognitive structure' (cf. Ausubel,
15 2000). So teachers need to undertake conceptual analyses of topics that can facilitate
16 the identification of potential learning difficulties prior to planning teaching. We
17 therefore first set out the type of thinking about ionisation energies that would be
18 involved in demonstrating mastery of the target knowledge. Table 4 presents the
19 learning objectives from the A level chemistry course in Singapore (Singapore
20 Examinations and Assessment Board, 2009), alongside the patterns to be explained
21 and the conceptual basis used for offering explanations for those patterns.
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33 **Table 4: Conceptual requirements of meeting the learning**
34 **objectives for the ionisation energies topic in the Singapore A**
35 **level chemistry course**
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40 When the subject matter is analysed in this way, it becomes clear that meeting the
41 learning objectives involves selecting and applying a range of concepts to model
42 ionization processes. The learning objectives are underpinned by an underlying
43 assumption that something measured on a sample of gaseous substance on a
44 macroscopic scale can be understood by discussing processes occurring at the level of
45 individual atoms and electrons. This is known to be a major challenge for many
46 students learning chemistry (Gilbert & Treagust, 2009). Ionisation may be represented
47 by such formulaic representations as:
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56 Here $\text{Na}_{(g)}$ can refer to either a mole of atomized sodium (i.e. substance), or an
57 individual atom (i.e. theoretical model). Such representations are used in teaching as
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3 mediators between the molar scale phenomenon, and the theoretical, sub-microscopic
4 models used to explain so much of chemistry (Taber, 2009a).
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8 To achieve some of the learning objectives (i.e. Table 4: ii-iv), a model of the atom
9 considering electrons to be arranged in concentric spherical shells will suffice. Such a
10 model allows students to appreciate that moving across a period (Table 4: learning
11 objective ii) the electron to be ionized is subject to increasing core charge; and that in
12 moving down a group (Table 4: learning objective iii) the electron is initially further
13 from the same core charge (as the increase in nuclear charge and the additional shell
14 of shielding electrons can be considered to cancel in this model).
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21 However, this simple model would predict that *successive* ionisations from within the
22 same shell **remove** electrons subject to the same core charge, and **so** should be of
23 similar magnitude – which is not what is found. Although a shell model of the atom
24 *can* be used here, it is not sufficient to think purely in terms of the initial state of the
25 species to be ionized. On this model, it makes sense that the second ionisation energy
26 of sodium is very much greater than the first (Table 4: learning objective iv-b), as the
27 second electron to be removed begins closer to a much larger core charge. However,
28 it is not clear from this model why the third ionisation energy should be significantly
29 greater than the second (Table 4: learning objective iv-a), when both processes
30 involve removing an electron from the same shell and subject to the same core charge.
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40 The limitations of only considering the initial state of the species to be ionized (when
41 the electron is in an equilibrium conformation, and so actually initially subject to zero
42 net force) become important in making such comparisons. Rather, to attain learning
43 objective iv-a (Table 4), students need to adopt a dynamic model that allows them to
44 think about how the force on the electron varies as ionization occurs (see Figure 4).
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50 **Figure 4: Modelling a comparison of the second and third**
51 **ionisations of sodium based on a ‘shells’ representation of the**
52 **atom.**
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56 The final learning objective in Table 4, (v), cannot be achieved by using a shell model
57 of the atom, as the nature of the atomic orbital that an electron is removed from
58 becomes significant. Although increasing core charge, and diminishing atomic radius,
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3 lead to a generally increasing first ionisation energy across a period, electrons in p-
4 orbitals are inherently easier to remove than those in s-orbitals and this factor has a
5 greater effect (so there is a drop between Mg and Al on Figure 2). Moreover, where
6 the electron to be removed is spin-paired with another electron in a p-orbital, this also
7 reduces the ionization energy and is a greater effect (so there is a drop between P,
8 **phosphorus**, and S, **sulfur**, on Figure 2). Figure 5 shows how these three sets of factors
9 play out to give the pattern across the period.
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17 **Figure 5: Factors influencing the pattern of first ionisation**
18 **energies (SMFIE) across period 3. The figure shows the**
19 **respective 3rd shell electronic configuration beneath each**
20 **element symbol, and also indicates the orbital configuration**
21 **associated with the electron to be removed during ionisation – s**
22 **or p; singly occupied (s^1, p^1) or spin paired (s^2, p^2) – beneath the**
23 **data points.**
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30 **Drawing upon the progressive RP: student learning about multiple models**

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32 So to meet the learning objectives a range of abstract concepts needs to be applied and
33 coordinated to demonstrate understanding. Some comparisons students are asked to
34 make can be based on a 'shell' model of atomic structure, where others require the
35 application of notions about different types of orbitals. Furthermore, in the latter
36 cases, there are often several co-varying factors that may tend to produce opposing
37 effects, and students are expected to provide explanations that match the actual
38 comparisons of ionisation energy in different case (such as in items 5-10 on the IEDI).
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46 The **models** drawn upon are somewhat inconsistent: for example the notion of core
47 charge, whilst useful (learning objectives ii-iv in Table 4), assumes no
48 interpenetration of electrons into lower shells, and so is inconsistent with orbital
49 models needed for explaining other examples (learning objective v in Table 4). Justi
50 and Gilbert (2000) have criticised such models of atomic structure that draw upon
51 features that belong to distinct historical models that have been conflated without
52 consideration of temporal sequence or a concern for internal coherence within the
53 hybrid model itself.
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3 The constructivist RP developed in part in response to perceived limitations of the
4 Piagetian RP (Gilbert & Swift, 1985). The Piagetian perspective, based on
5 consideration of the general stage of intellectual development attained by students,
6 would suggest that the abstract and theoretical nature of the topic makes it generally
7 unsuitable for students who had not achieved the stage of 'formal operations' (Piaget,
8 1972). Such an approach has been used to offer a critique of secondary science
9 curriculum topics that would not be suitable for many 14-16 year olds (Shayer &
10 Adey, 1981).
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18 However, the present study concerns learning difficulties experienced by older
19 students who had been selected for studying science based on earlier success: where it
20 would be expected that these students have attained the highest Piagetian stage. A
21 neo-Piagetian approach might point to the need to shift between models in meeting
22 different learning objectives, and consider this to require a further stage of post-
23 formal operations (Kramer, 1983, cf. Finster, 1991). Being able to accept that several
24 inconsistent models may provide useful tools for thinking about the same topic
25 requires epistemological sophistication that is rare at secondary school level (Driver et
26 al., 1996), but which becomes more common during university study (Driver et al.,
27 1996; Perry, 1970).
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38 **Drawing upon the progressive RP: cognitive processing of new information**

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40 The constructivist RP moved beyond considering the general intellectual structures
41 available for learning, to consider a broader range of factors contingent in student
42 learning. Within the RP both cognitive and conceptual features of learner readiness to
43 learn material are considered. So, for example, how students need to process
44 information during learning and problem solving has been a key theme (Osborne &
45 Wittrock, 1983). The analysis above suggests that the subject matter places a high
46 cognitive load on students, as a range of concepts and considerations need to be
47 drawn upon and coordinated in demonstrating target learning (Tsaparlis, 1994).
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56 In items 6 and 7, distractors based on an argument that an Al 3p electron should be
57 considered to have a greater mean distance from the nucleus than a Na or Mg 3s
58 electron were commonly chosen. To make a comparison between the nucleus-3p-
59 electron mean separation in Al, and the nucleus-3s-electron mean separation in Na
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3 or Mg could be considered to imbue the models used with a degree of realism that
4 may not be justified.
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8 In part this could be the failure to realise that the characteristics of an orbital (3p)
9 depends upon the atomic environment **in which it is found** (so that comparing
10 different orbital types *in different atoms* is more complex than comparing different
11 orbital types *in the same atomic system*). High proportions of both groups selected
12 this response, which may in part be due to the way 3p (in a particular atomic system)
13 is commonly shown diagrammatically as being at a 'higher' energy level than 3s (see
14 Figure 1).
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21 The **pre**-service teachers made fewer mistakes than the senior school students when
22 choosing the more significant of competing factors that influence comparisons of
23 ionisation energy (items 5-10 of the IEDI). Both increased maturity, and several years
24 developing further familiarity with the knowledge domain, would have been
25 advantageous. The latter is likely to have helped in two ways. Increased experience
26 working with material allows it to be more effectively '**chunked**' so that it can be
27 treated as **fewer** 'items' in working memory (effectively increasing cognitive
28 processing capacity). In addition, greater familiarity with the phenomena to be
29 explained would make it easier to select from only those options that were logically
30 consistent with the actual patterns found in ionization energy. That is, a student who
31 remembered the pattern shown in figure 2 could exclude as viable answers those
32 distractors that were not consistent with the direction of the difference in the
33 ionisation energies of elements being compared.
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45 It is also possible that the higher performance here might be linked to better
46 visualisation processes that simply derive from greater familiarity with the atomic
47 models. Gilbert (2005) has emphasised the role of visualisation in learning science,
48 and this would seem to be one topic where developing mental models that can be
49 'run' to simulate chemical processes mentally (Georgiou, 2005) could be very
50 significant for effective learning (cf. Figure 4).
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57 Such considerations offer feasible explanations of the common errors in selecting the
58 more significant of competing factors that influence ionisation energy, where the pre-
59 service teachers generally made fewer errors. However, such arguments are
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3 insufficient to explain why in both studies our respondents commonly selected
4 responses based upon on alternative conceptions inconsistent with the chemistry they
5 studied.
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10 **Drawing upon the progressive RP: The development of alternative conceptions**

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12 We found that respondents, both among the high school students and the pre-service
13 teachers, commonly considered that nuclear forces were shared out among the
14 electrons in a shell (see Table 3). The chemistry topic of ionisation energies draws
15 upon prerequisite physics knowledge of the interactions between electrical charges
16 (i.e. Coulomb's law). However, work within the constructivist RP has shown that in
17 learning science students do not always apply the expected pre-requisite learning.
18

19 **Even assuming the pre-requisite concepts have previously been taught, this will not**
20 **ensure that learners have them available, and appreciate their relevance in new**
21 **learning contexts (Taber, 2005). Also,** many students are likely to bring to class
22 existing alternative notions about forces (Watts, 1983). Even when students
23 demonstrate scientifically acceptable ideas in studying one area of science (e.g. using
24 **Coulombic principles when studying electricity in physics**), they may not apply these
25 ideas where expected outside of that topic (Taber, 2008b).
26
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29 As we suggested above, understanding patterns in successive ionization energies
30 (learning objective iv-a in Table 4) actually requires appreciating a complex dynamic
31 model (Figure 4), that may be too challenging for many students at senior high school
32 level. The notion that the 'nuclear force' is shared out, so that each time an electron is
33 removed, the remaining electrons get a greater share of that force and so become
34 harder to remove offers an alternative (and much simpler) rationale for patterns in
35 successive ionization energies. It might seem surprising that degree level study does
36 not lead to this alternative conception being replaced by more scientifically acceptable
37 notions: however it is well known from studies within the constructivist RP that some
38 alternative conceptions are tenacious once acquired (McCloskey, 1983). The sharing-
39 out idea appears to be one of those conceptions that has intuitive appeal (diSessa,
40 1983), and so is firmly held. **Moreover, not only is it intelligible and plausible, but it**
41 **also appears fruitful (Posner, Strike, Hewson & Gertzog, 1982) in that it can be used**
42 **to offer an explanation for the pattern of successive ionisation energies.**
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3 We find a similar pattern with student responses based on the octet alternative
4 conceptual framework (see Table 3). Students readily adopt notions that octets or full
5 shells have some special intrinsic stability. Figure 5 shows this is not the case: if there
6 was some special inherent stability associated with the octet structure then the
7 ionization energy of Ar (**argon**) should be significantly higher than is shown. Figure 5
8 shows that Ar fits well with the pattern established by S and Cl (**chlorine**). The octet
9 rule is adopted by many school pupils as the basis for explaining bonding and
10 chemical reactivity, despite it not offering valid or logical explanations (Taber,
11 1998a). As the constructivist model would predict, this explanatory principle is then
12 used to interpret other chemical phenomena studied – such as ionisation energies.
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16 Moreover, in our sample we found evidence of the notion of full shells having
17 intrinsic stability being extended to full or even half-full sub-shells (see Table 4). In
18 these cases we found this alternative conception was *more* prevalent among the
19 graduate pre-service teachers than among the high school students. It would seem that
20 a form of explanatory principle that is intuitively attractive for students gets extended
21 to more nuanced cases. As chemistry students become more familiar with, and
22 experienced in applying orbital models of the atom, they come to apply a familiar way
23 of thinking to make sense of these new concepts. Again this would seem consistent
24 with constructivist perspectives on learning.
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27 **Drawing upon the progressive RP: identifying learning demand**

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29 Leach and Scott (2002) have talked about the notion of ‘learning demand’, i.e. the
30 discrepancy between a students’ current understanding and the target knowledge
31 being taught. Where this demand is significant, careful teacher scaffolding of learning
32 is needed to bridge the ‘gap’, otherwise students will have difficulty understanding
33 the target knowledge and may form alternative conceptions.
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37 Taber (2005) has used the notion of ‘learning quanta’ to draw attention to the way
38 complex scientific knowledge needs to be deconstructed into more manageable
39 components for effective construction of new learning. He has argued that there is a
40 time lag between initially learning new concepts, and being able to rely on them as
41 sound foundations for further learning. The process of consolidating new learning into
42 mental structures occurs over extended periods, and during this time teachers need
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3 to support students by reinforcing the ‘fragile’ learning, until it can be considered
4 ‘robust’ enough for students to apply it effectively and without support. Typically
5 learners are first introduced to an undifferentiated basic particle model early in
6 secondary education that is later differentiated into notions of atoms, molecules, ions
7 and so forth (Key Stage 3 National Strategy, 2002). Atomic structure is usually
8 introduced using a ‘shells’ model; that after a few years becomes supplemented, but
9 not necessarily substituted for all purposes, by more complex orbital models. Taber
10 has suggested that student difficulties in learning the models of the atom met in
11 school (Griffiths & Preston, 1992; Harrison & Treagust, 1996, 2000; Petri &
12 Niedderer, 1998) may in part be because students meet sequences of models of the
13 atom without there being sufficient consolidation of each model before the next is
14 introduced.

25 26 **The insidious nature of *some* alternative conceptions**

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

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

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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

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3 on the very alternative conceptions we would hope they could be challenging in their
4 own students.
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8 Indeed, our present study suggests this is not merely a matter of the A level context
9 reactivating notions that have been inert during university study – for the pre-service
10 teachers, having had more experience of working with orbital models of the atom,
11 actually showed *a greater tendency* to extend the desirability of a stable configuration
12 as an explanatory principle from octets/full shells to filled and half-filled sub-shells.
13 The graduate pre-service teachers were *more likely* to base explanations on these
14 alternative conceptions than the A level students they are preparing to teach.
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22 **Extending the progressive RP: applying the Lakatosian model to student** 23 **learning** 24

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26 Watts and Pope's (1982) suggestion of considering learners themselves as Lakatosian
27 scientists has received very limited attention within the RP. Here we will suggest that
28 our present study provides grounds for considering that this proposal is worthy of
29 further attention, as it may offer a useful way of thinking about the considerable
30 disparities found in student commitments to different alternative conceptions (Driver
31 & Erickson, 1983; Gilbert & Watts, 1983; Claxton, 1993). In other words, we can
32 consider that students' conceptual trajectories can be understood in terms of 'study
33 programmes' that are analogous to RP: that it a study programme is built around 'hard
34 core commitments' that are 'taken-for-granted' as the student looks to develop their
35 understanding (i.e. build up a protective belt of knowledge) of a topic around hard
36 core foundations. The reception of new information can be considered to be guided by
37 a negative heuristic (which ensures new information is interpreted to be consistent
38 with the hard core) and a positive heuristic (which seeks to extend understanding of
39 the topic in ways consistent with the hard core). These heuristics would not need to
40 applied consciously: rather it is the implicit commitment to the irrefutable nature of
41 the hard core assumptions which can often lead to teaching being reinterpreted in
42 unintended ways.
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57 In terms of our present study, the target knowledge is constructed around a
58 Coulombic model of atomic structure and ionisation processes, and so to be
59 successful in the topic a student would have to build their hard core for learning
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3 about the topic around such principles. Yet we have seen that the central assumptions
4 that students often make are quite inconsistent with such principles. Notions that
5 nuclear force is shared between electrons, and that full shells are desirable and
6 inherently stable, appear to derive from the application of deep-rooted intuitions about
7 the world, and so are strongly committed to: providing an alternative basis for the
8 hard core of many learners' study programmes.
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15 The differences between the response patterns of A level students and pre-service
16 teachers are consistent with such a model. The areas where pre-service teachers make
17 fewer errors concern less central principles, where alternative explanations can be
18 constructed within the 'protective' belt without bringing into question the core
19 commitments. The analysis above suggest differences may be understood in terms of
20 how greater intellectual maturity and familiarity with background knowledge allows
21 the pre-service teachers to work more effectively within the protective belts of their
22 understanding of the topic. Interestingly, the area where pre-service teachers make
23 more errors in the topic – by assigning inherent stability to a wider range of electronic
24 configurations – can be interpreted as the development of auxiliary theory through the
25 action of a programme's positive heuristic to extend understanding in ways consistent
26 with hard core assumptions: that is, the commitment to seeing certain types of
27 symmetry in electronic configurations as inherently stable being extended from full
28 shells to sub-shells.
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41 This Lakatosian interpretation offers an explanation of why some, but not all,
42 alternative conceptions have been found to be so tenacious. From this perspective,
43 certain conceptions are based on assumptions that are intuitively very convincing, and
44 to which a strong commitment is therefore implicitly made. Where these conceptions
45 are central to a topic studied in science, they naturally form the 'hard core' about
46 which the student looks to develop an understanding of the topic. The student
47 develops a conceptual framework of auxiliary conceptions around those core
48 commitments, and when faced with discrepant information the student is usually able
49 to protect the hard core by making adjustment within that protective belt of auxiliary
50 ideas.
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60 By analogy with RPs, such 'study programmes' are unlikely to be abandoned until

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3 they are recognised as no longer fruitful for developing new knowledge, and an
4 alternative with more promise is available to the student. So in our study, students
5 would be unlikely to switch to a programme based on Coulombic principles as long as
6 they are able to continue to interpret phenomena in terms of the sharing out of nuclear
7 force and the desirability of full shells.
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13 Quite why these particular conceptions appear to be so intuitively attractive, and
14 resistant to challenge during degree courses is not clear. Yet they clearly have
15 potential to be effective ‘memes’ (Blackmore, 2000): ideas that spread through a
16 population effectively because they are readily accepted, recalled and passed-on.
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18 What does seem clear, is that as long as high school teachers commonly hold these
19 alternative conceptions, they can use them in their own teaching explanations, and so
20 they are likely to be acquired by, or reinforced in, their own students.
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27 ***Conclusion: responding to the insidious nature of alternative***
28 ***conceptions***
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32 This study clearly highlights the issue of the extent to which insidious alternative
33 conceptions are **linked to hard-core commitments that are** retained by graduates as
34 they progress into professional roles (such as teaching) in science and technology. A
35 number of more specific directions for research are suggested by this study, such as
36 the extent to which respondents’ selection of distractors based on alternative
37 conceptions may be made almost instinctively without pause for analysis, and so
38 whether a different task (e.g. one that required the respondent to construct a more
39 explicit chain of argument themselves) would lead to a lower incidence of these ideas
40 being elicited among the graduate population.
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49 **The study also suggests that the largely neglected suggestion that student learning**
50 **might itself be fruitfully explored by considering learners as though they behave like**
51 **Lakatosian scientists (Watts & Pope, 1982) is worthy of further consideration. If it is**
52 **possible to develop this model to characterise which alternative conceptions tend to**
53 **become incorporated within the hard core of learners’ study programmes, and which**
54 **tend to only have protective belt status, then this will indicate those conceptions**
55 **where careful strategies and extended efforts are needed to encourage students to shift**
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3 to a new study programme.
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6 We also speculate that in this particular topic area, alternative conceptions are being
7 retained as elements of hard core understanding of chemistry and formally taught by
8 some teachers, rather than just formed when students interpret teaching, and it would
9 be useful to know the extent to which this is actually the case. If this is common,
10 suitable professional development inputs are indicated.
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16 Regardless of what further research may show, the present study would seem to have
17 clear implications for science education at three levels:
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- 22 • at secondary/ high level: given the tenacious and insidious 'hard
23 core' nature of the desirability of a full shell as an explanatory
24 principle; and the notion that nuclear attraction can be shared out; it
25 seems important that teachers (and textbook authors) are aware of
26 these common conceptions, and take care to make sure they do not
27 inadvertently (or deliberately) use phrasing and explanations which
28 can support the acquisition of these ideas;
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 - 33 • at initial teacher education level: work on auditing, diagnosing and
34 remediating subject knowledge in this topic area is important before
35 graduates are expected to teach the topic;
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 - 39 • at degree level: lecturers should be made aware of these common
40 ways of thinking and so they can hone their own teaching to avoid
41 reinforcing, and to challenge, such insidious alternative conceptions
42 - for example, by making explicit reference to the underlying
43 physical principles (such as Coulomb's law) that support the
44 chemistry.
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51 Considering the present results from the perspective of the constructivist RP has
52 allowed us to offer a feasible account of why learning in this topic is so problematic.
53 Successfully learning about ionization energy at senior high school level would seem
54 to involve being able to apply a range of concepts, and to coordinate different factors
55 that may be simultaneously active, whilst visualizing a dynamic hybrid model at the
56 sub-microscopic level. Given this analysis, learning difficulties in this topic should
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3 not be surprising.
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6 This leads us to question whether this material is appropriate in the curriculum at
7 senior high school level. If it *is* considered important that students should master this
8 topic before university level study, then the constructivist analysis (e.g. considering
9 pedagogic notions of 'learning demand' and 'learning quanta') suggests that this is
10 only likely to happen if much greater thought is given to sequencing and reinforcing
11 student learning of the prerequisite ideas through the secondary school years. Unless
12 that level of commitment is considered justified, it may be more sensible to
13 acknowledge that this is a topic that it is unrealistic to expect school students to
14 tackle. Delaying study until the undergraduate years could allow students to meet the
15 topic only after the necessary conceptual foundations have been consolidated, and
16 may break the cycle of generations of students developing the same alternative
17 conceptions.
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	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

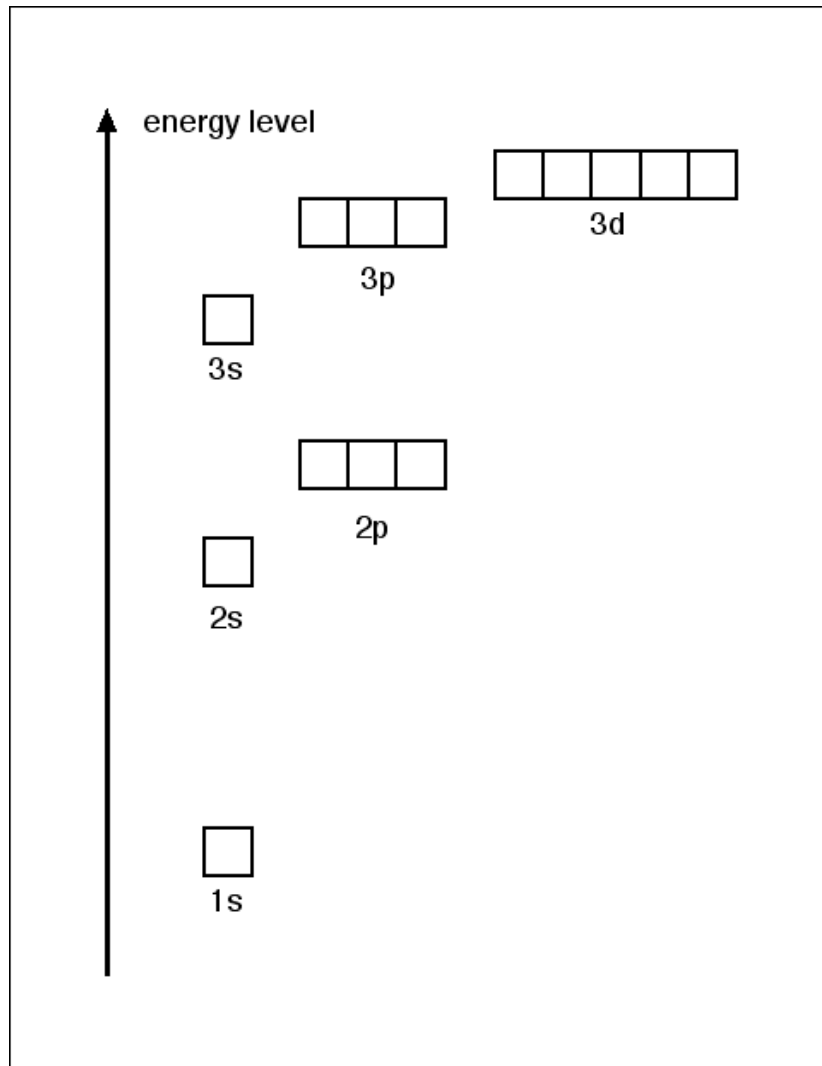
Table 2: Overall performance (% correct) on IEDI items

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 trend 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



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

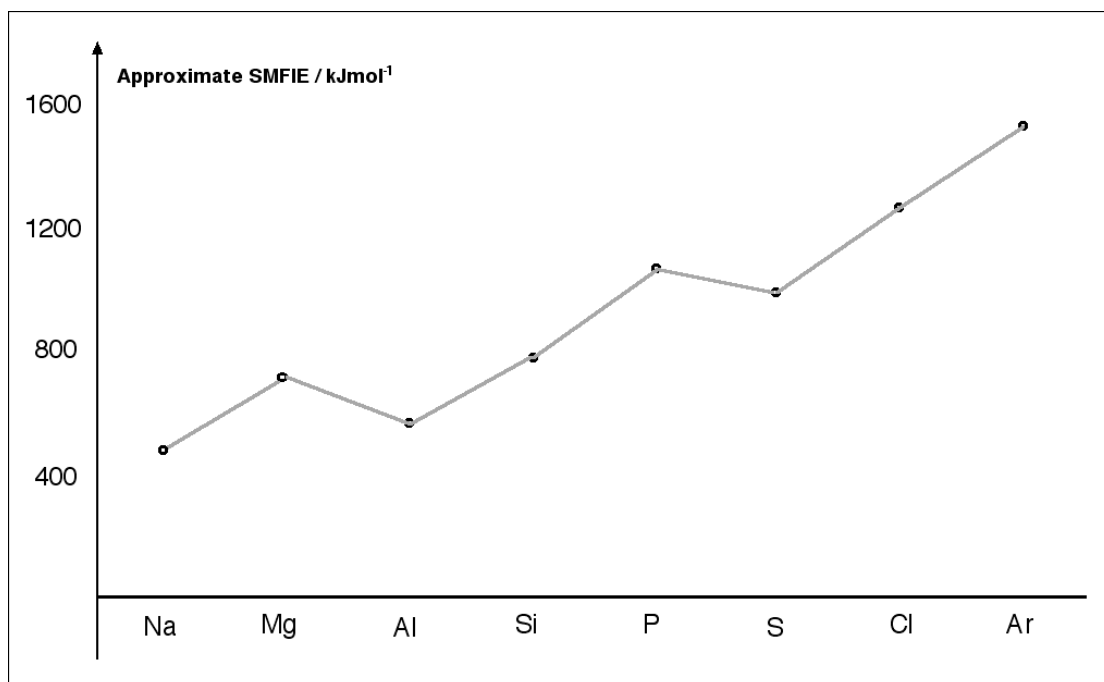


Figure 2: The pattern in the values of standard molar first ionization enthalpies (SMFIE) across the elements of period 3

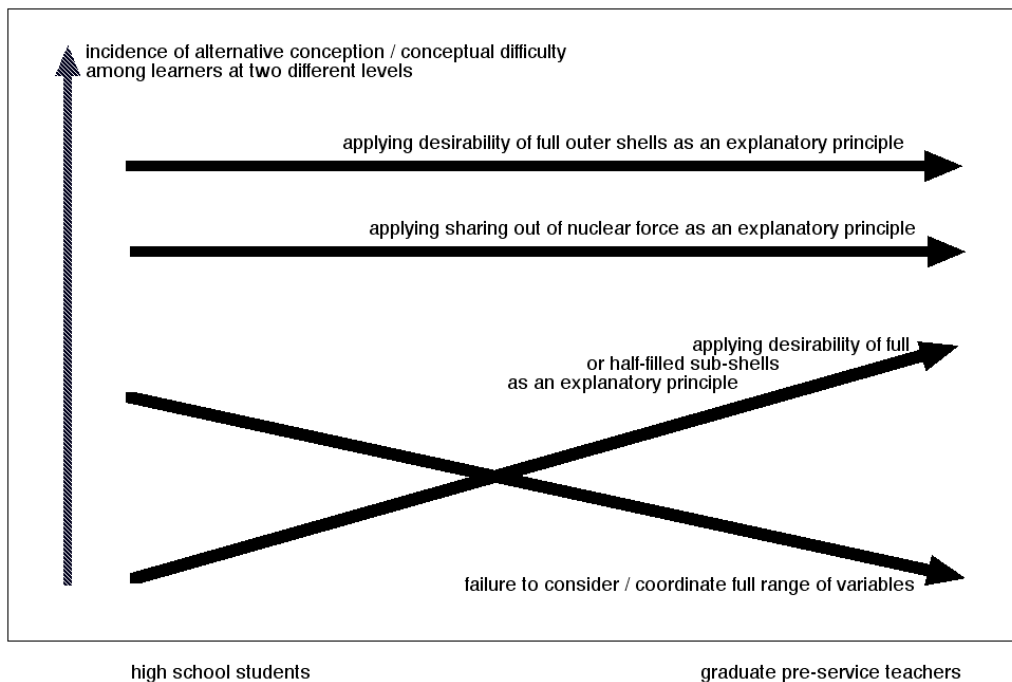


Figure 3: Schematic showing general trends in major categories of respondent errors

Review Only

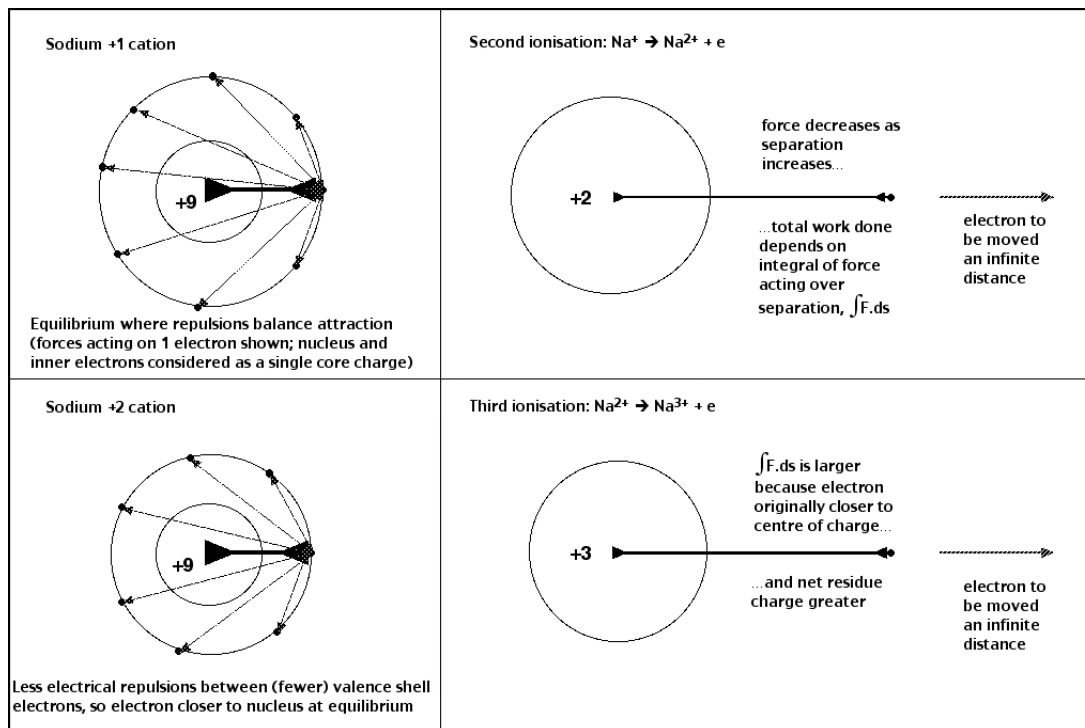


Figure 4: Modelling a comparison of the second and third ionisations of sodium based on a 'shells' representation of the atom.

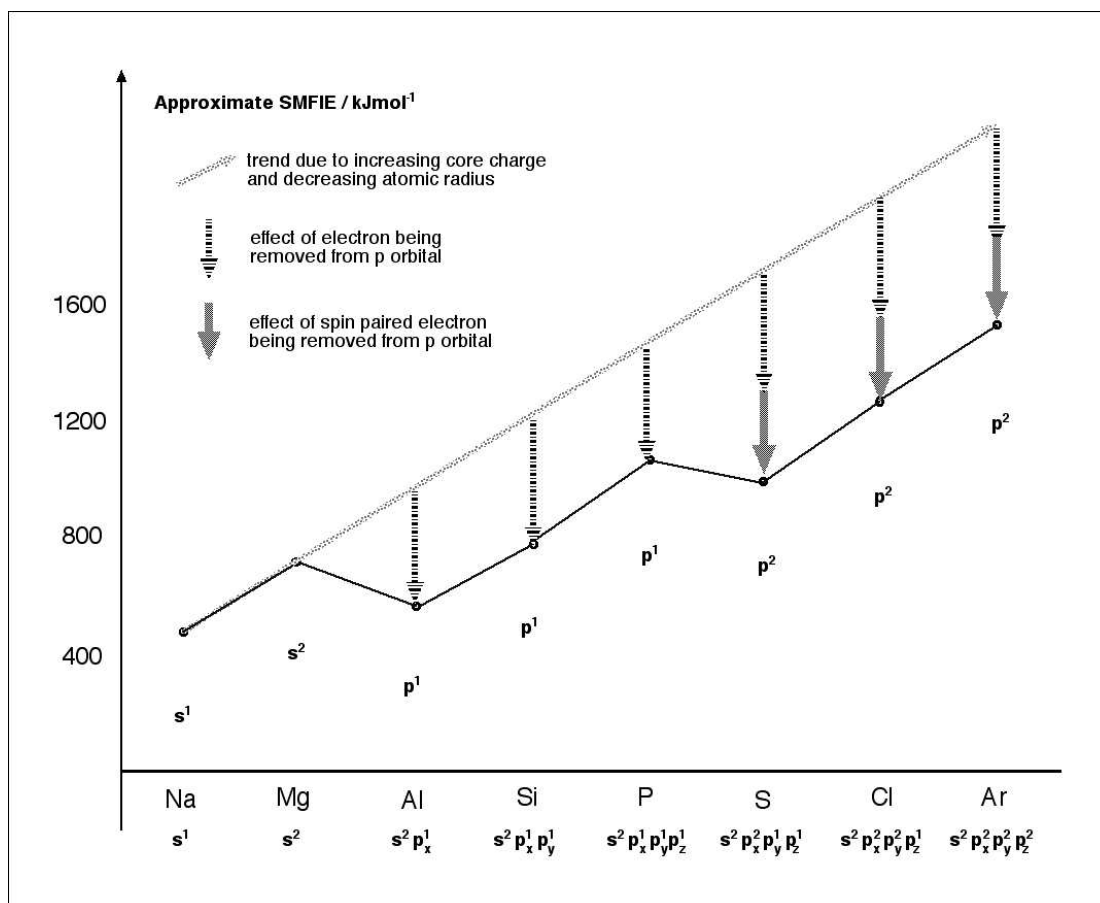


Figure 5: Factors influencing the pattern of first ionisation energies (SMFIE) across period 3. The figure shows the respective 3rd shell electronic configuration beneath each element symbol, and also indicates the orbital configuration associated with the electron to be removed during ionisation – s 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 all options given are inappropriate**, 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:



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.

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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.

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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.
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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.

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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.

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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.

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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.
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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.

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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.

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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.

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Reason

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- (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.
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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.

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Reason:

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- (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.

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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.

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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.
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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.

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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.

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