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The sharing-out of nuclear attraction: or "I can't think about physics in chemistry"

Abstract.

Pre-Univeristy chemistry students were found to consider that an atomic nucleus gives rise to a certain amount of attractive force which is shared equally among the electrons. Students used this 'conservation of force' principle in their explanations of such phenomena as patterns in ionisation energy. It is suggested that teachers of chemistry should be aware that although they may using conventional electrostatic principles in their presentations, their students may be reinterpreting their explanations through this alternative conception. The present research concerns the interface between two scientific disciplines (chemistry and physics) and suggests that learners do not readily integrate their knowledge across such domains. It is mooted that more research into how such demarcations encourage learners to compartmentalise their knowledge may prove fruitful.

Introduction - learners' alternative ideas in science.

It is well documented that learners of science may demonstrate ideas about natural phenomena that are not consistent with the accepted scientific models (Black and Lucas 1993, Driver and Erickson 1983, Driver, Guesne and Tiberghien 1985, Driver 1989, Gilbert, Osborne and Fensham 1982, Gilbert and Watts 1983). A vast literature shows that students come to classes with a wide array of alternative ideas about many scientific topics (Duit 1991). Indeed there is probably now sufficient evidence to advise that in any class there is likely to be a range of alternative conceptions concerning any basic science topic to be taught (Driver, Squires, Rushworth and Wood-Robinson 1994). The presence of these alternative conceptions suggests that much science teaching needs to be seen as an attempt to bring about conceptual change (Posner, Strike, Hewson, and Gertzog 1982, Strike and Posner 1985). Before the teacher can set out to bring about such change it is necessary to diagnose the alternative ideas it is intended to challenge.

One aim, then, of research into learners' ideas is to inform teachers of - and sensitise them to - the alternative conceptions and frameworks they may find among their students (Garnett, Garnett and Hackling 1995). Although each learner's cognitive structure is unique, researchers often find that explanations elicited from learners are similar enough to justify considering some conceptions as commonly held (Taber 1998).

As well as lists of common alternative conceptions teachers may benefit from being advised of the stability, context-dependence, and level of integration of learners' alternative thinking (Black 1989, Watts 1988) and research based on detailed case studies of individual learners has begun to explore these issues (Taber 1995b, Taber and Watts 1997).

There is a principle in folk-wisdom as well as public health-care that 'prevention is better than cure', and therefore the origins of learners' ideas are also of interest. It certainly seems worthwhile to identify any alternative thinking that largely derives from the way subjects are taught, and to distinguish this from ideas that develop without reference to formal instruction (Taber 1995a).

Alternative conceptions about such topics as mechanics may be understood to develop as learners impose meaning on their experiences of the world. The spontaneous development of a belief in an impetus being imparted to an object certainly seems more likely than an intuitive grasp of Newtonian laws (Gilbert and Zylbersztajn 1985). It seems likely there is little that science educators can do in the way of 'preventative' work to avoid learners developing alternative schemes in these areas. As Wolpert (1992) has pointed out, scientific orthodoxy is often far from 'common sense'.

The research discussed in this paper, however, was focussed on a concept area - the chemical bond - that is far from everyday experience. Although chemical bonds are ubiquitous and of central importance to all aspects of our lives, we do not experience them directly - and learners are unlikely to be party to much informal learning about the topic. For most people chemical bonding is not a major topic of everyday conversation. A naïve expectation might therefore be that learners will not demonstrate alternative conceptions in such topics. Research shows this is far from the case (Butts and Smith 1987, Peterson and Treagust 1989, Taber 1994a, 1995b, 1996, 1997a, 1997c, 1998, Taber and Watts 1996, 1997).

This leads us to consider the origins of alternative conceptions in such topics. A number of - relatively - distinct possibilities may be considered:

(a) that such alternative conceptions are actually misconceptions - simple misunderstandings of what the learner has read or been told (Hapkiewicz 1991, Zoller 1990);

(b) that the language used to teach the topics is loaded with unintentional meanings (Watts and Gilbert 1983) - so for example perhaps the teacher uses the term 'bonding' to mean a physical interaction whereas the learner construes 'bonding' to imply a social interaction;

(c) that the learner constructs an understanding of the topic upon alternative versions of the prerequisite knowledge;

(d) that the learner has some in built perceptual/conceptual bias which leads to an unorthodox interpretation of curriculum material presented.

A documented example of option (c) would be the case of the student who commenced A level (i.e. pre-University college) chemistry having no knowledge of the conventional meaning of positive and negative charges, but having an alternative scheme for the '+' and '-' symbols used to label ions. This learner made sense of her chemistry classes, but it was often a different sense to that intended by her teachers (Taber 1995b).

The final option in the list refers to the presence in cognitive structure of certain fundamental - and perhaps largely tacit - tendencies to see the world in particular ways, so that even completely novel information may be interpreted through deep-seated biases. Piaget referred to the "system of mental tendencies and predilections of which the child himself has never been consciously aware and of which he never speaks" (1973, p.14). Such features have been discussed in the literature, for example Andersson's experiential gestalt of causation has been suggested as a framework through which new examples of causality may be interpreted (1986). The learner expects to identify an agent and an instrument through which an effect may be produced. Similarly, di Sessa has referred to phenomenological primitives, or p-prims which are considered to be basic principles such as closer means stronger which are potentially widely applicable (Hammer 1996). The extent to which such features are idiosyncratic and result from unique individual experience, or may reflect those cognitive structures which have an evolutionary basis, and are triggered through normal cognitive development (Pinker 1995, LeVay 1993) is an open question.

Although the topic of chemical bonding is part of the A level chemistry syllabus, it is of particular interest as a concept area requiring prerequisite knowledge from physics, and this was one key concern of the study. There has been little research into the interface between areas of science presented to learners as distinct disciplines, and relevant work that has been undertaken has highlighted the need for more attention to this issue (de Posada 1997). However, much has been written about the importance of context in determining which conceptual frameworks learners bring to bear at any time (Hennessey 1993, Solomon 1992). This present paper may be considered as providing evidence of students not applying basic physics knowledge in the context of what they perceived as the subject matter of chemistry - or being limited to "thinking about chemical things in chemistry" in the words of one of the learners in the study.

Methodology

This paper reports results from research into A level students' developing understanding of chemical bonding. The main research technique was in-depth interviews with 15 volunteer students at various stages of their A level chemistry course in a single Further Education college (Taber 1997c). These informants are referred to as colearners: a term that recognises both their contribution to the research process and the ethical responsibilities owed to them by the teacher-researcher (Taber 1994b, 1997c). Interviews were supplemented by a range of other data collected, including samples of student work and test responses, and a limited use of survey instruments. The principles of a grounded theory approach were used to work from case studies of individual learners to develop a model of conceptual development of more general application (Taber 1997b, 1997c).

The research interviews were based around a deck of simple line diagrams - a standard technique in science education research (Gilbert, Watts and Osborne 1985, Osborne and Gilbert 1980) Most of these figures represented simple structures such as atoms, molecules and sections of lattices. Some diagrams representing macroscopic situations (such as a falling apple, a projectile being thrown and so forth) were also used to elicit colearners' ideas about how forces operate on an 'everyday' scale (Taber 1997c).

Some of the ideas uncovered through the research interviews were used to inform the design of simple paper-and-pencil instruments that could survey larger numbers of learners. Of relevance to this present account is the 'truth about ionisation energy diagnostic instrument' which presented respondents with a simple figure of a sodium atom (reproduced as figure 1) and thirty statements which were to be evaluated as either true or false. This instrument was presented to over a hundred (110) A level chemistry students (Taber 1997c).

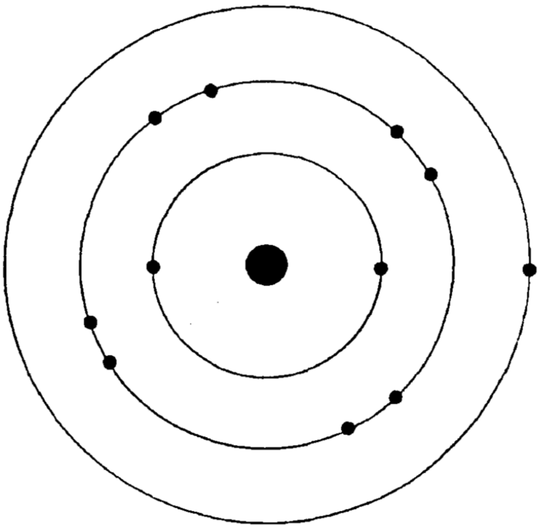

Figure 1

Context of the findings

Analysis of the interviews suggested that these A level students exhibited a range of alternative conceptions. Of particular interest was the common occurrence of a range of related ideas that are considered to make up an alternative conceptual framework for explaining chemical processes based around the importance of electronic configurations (Taber 1997c, 1998). It was found that chemical reactions were often conceptualised in terms of the perceived desirability of full electron shells, rather than being considered the result of physical interactions.

Common alternative conceptions of mechanics already widely reported in the literature were also found in the research (Taber 1997c). So some colearners believed that throwing a projectile involved imparting a force that would continue to act after the projectile was in free flight, and some colearners believed that a net force was needed for an object to continue to move, or even to continue to remain stationary on the ground. As these ideas have been widely found in other research (Gilbert, Watts and Osborne 1982, Gilbert and Zylbersztajn 1985, Watts and Zylbersztajn 1981, Watts 1983) they will not be detailed here, but these findings reiterate that the basic principles of physics that a college teacher might expect to be able to take for granted may not be shared by the learners.

The 'conservation of force' conception

One result that was considered to be of particular interest was the use by colearners of an alternative explanatory principle - the 'conservation of force' conception - that might be paraphrased:

> a charged body gives rise to a certain amount of force, which is available to be shared amongst oppositely charged bodies

For example, in an interview at the end of his first year of A level study one of the colearners, referred to as Tajinder, suggested that all eleven electrons in a sodium atom would be attracted towards the nucleus with equal "forces of attraction",

> "each electron has the same amount of force between the nucleus and itself, no one electron has more force to it than another. It's like this nucleus doesn't attract that electron more than that electron, it attracts all electrons, like the same."

The 'conservation of force' explanatory principle was first identified, and labelled, during an earlier interview with Tajinder. Tajinder thought that the electronic energy levels in the helium atom, and the helium cation would be different "because in the ion, the two proton's are only attracting one electron, but in [the atom] they've got two electrons to attract, so therefore like sort of their attraction is like spread out over two instead of one". In another interview he repeated this idea, that "the protons only have … one electron to attract, in helium ion, [whereas in] helium atom they've got two electrons to attract". The term 'conservation of force' was coined by the interviewer (KST) as the interpretation of Tajinder's words was checked. Tajinder explained that the force from the nucleus was "spread over the number of electrons there are", and that no additional force would be available to attract an additional electron - at least "not if the [nuclear] charge hasn't gone up by one".

> I: So a certain charge on the nucleus, implies there's a certain amount of force available?
>
> T: Yes.
>
> I: And if you increase the number of electrons, you therefore … decrease the amount of force each one gets?
>
> T: Yes.
>
> I: A kind of conservation of force principle?
>
> T: Yes.
>
> (I: interviewer (the author); T: colearner Tajinder)

Tajinder was interviewed on over twenty occasions during his A level course, and his explanations were analysed in some detail (Taber 1997c, Taber and Watts, 1997). The unorthodox nature of Tajinder's explanation was discussed with him, and compared with the accepted scientific arguments (where the repulsion between electrons must be considered as well as the attraction between electron and nucleus). Tajinder still sometimes argued from the 'conservation of force' principle in subsequent interviews,

> "you need more energy to remove the second electron, because the charge on the nucleus is still the same, and there's one less electron to attract, so the nucleus has more attraction to these [remaining] electrons"

Even near the end of his A level course Tajinder suggested that "the nucleus has a certain amount of attraction to electrons, and when there's a pair of electrons it's … attracting both equally, but if one is removed then the other one would be attracted more".

This was not an isolated example, as similar ideas were elicited from a number of the colearners interviewed. So Mike explained that he thought that the size of the attraction between an atomic nucleus and an electron depended upon, "whether there was enough electrons to fulfil the attraction of the positive" as "a single proton attracts a single electron, a one-on-one basis, … when you've got two electrons to one proton, they're both attracted, but not as much".

Kabul thought that in the hydrogen molecule the force on an electron due to one nucleus was less than the force it would have experienced in a single hydrogen atom "because the nucleus [is] attracted to a cloud of two electrons, so the force, you know, divides". So Kabul thought there was "less force going towards [sic] that electron" as although the total force due to the nucleus was unchanged, it was shared amongst two electrons. Another colearner, Umar came to the same conclusion, as in the atom the nucleus "would have more effect on the single electron because one plus can be for the one minus electron", whereas in the molecule "the nucleus, the same charge, one plus, is acting on two electrons, each of one minus, so it'd be less".

The corollary to this idea would be that when there are less electrons than protons the electrons should experience extra attraction. So according to Umar when a sodium atom was ionised, the electrons would

> "be attracted more, because the same positive charge pulling on less electrons, so, it's more on each electron [as] the amount of energy [sic] that that nuclear charge used in pulling that outer electron which is one plus, is like distributed across the other remaining electrons, that same energy."

So according to Umar's understanding, when one electron was removed from the sodium atom the nucleus attracts the remaining electrons more, as "what it would have used to attract the [eleven] electrons it uses to attract the remaining ten". If a second electron was removed "then there'll be the same nuclear charge pulling on the remaining nine electrons so it'd be stronger even more". Each time an electron was removed "there's a stronger nuclear charge on the electrons", until when only one electron remained "it'd be attracted much more stronger, 'cause there'd be plus-eleven charge pulling on only one electron".

Applications of the 'conservation of force' explanatory principle to ionic size

Students used the 'conservation of force' principle to explain various physical phenomena. So for example Jagdish suggested in a test that the aluminium cation was smaller than the atom "because the core charge has less electrons to pull in, it can pull in more tightly", and in an examination some months later she wrote that the greater size of the fluorine anion compared to the atom was partly "because of the extra electron" as "the core charge cannot pull on the electrons as tightly". In an interview Lovesh explained that in a potassium ion the potassium had "lost an electron and so the effective nuclear charge … attracts the electrons in more closer". Umar suggested that because an anion had more electrons than protons "each electron's got less charge on it overall from the core charge".

Applications of the 'conservation of force' explanatory principle to ionisation energy

The topic that provided the richest evidence of colearners applying the 'conservation of force' explanatory principle was that of patterns in ionisation energies. Jagdish explained how with each ionisation, as "there is one less electron the positive nuclear charge can pull on the [remaining] electrons a little more", so "the core charge can pull in more tightly each time an electron is removed".

Kabul comments that "as we start removing the electrons, you know the net nuclear charge acting on the remaining electrons will increase". In his final interview Kabul explained that when the outermost electron was removed from a sodium atom the force acting on the remaining electrons

> "would be more compared to before because there are eleven protons in the nucleus, you know, holding ten electrons, so there would be more force, but before there were, you know, eleven protons and eleven electrons, so the force divides".

Some colearners attempted to quantify the notion of nuclear attraction being shared out amongst electrons. Rhea's explained that when a magnesium atom had been ionised ten times,

> "you have an ion with +10 charge, holding 2 electrons. So the nucleus has the two protons keeping the electrons attracted to the nucleus, and also a spare 10 protons left over from the 10 electrons removed, to hold the 2 electrons very tightly."

She went on to explain that there was

> "a +6 charge for each electron that is to be removed, so a lot of ionisation energy is required to remove the final two electrons".

Similarly, Umar describes how on successive ionisation, "once each previous electron is removed there is greater attraction by the nuclear charge on the remaining electrons". In a Na9+ ion "there's an eleven plus charge, on two electrons" and so "effectively five and a half positive to one minus electron", and in the Na10+ ion "they'd be eleven plus on the one electron" and so a "much stronger force".

The ‘conservation of force’ explanatory principle as a common notion

Although the ‘conservation of force’ conception was identified among colearners volunteering themselves for research interviews, it does not seem to be an artifact of the clinical setting. Indeed some of the most explicit references to the ‘conservation of force’ explanatory principle have been collected from test and examination responses of A level chemistry students who were not involved in the interview study.

The following explanations of relative atomic and ionic sizes reflect those presented above from research interviews,

> “the radius will become smaller when an electron is taken away from outer shell because the nucleus’s attraction will have more effect, i.e. it’s force will be distributed amongst less”
>
> “As the ion has an extra electron in its valent shell, the core charge, which remains the same, has to spread its attractive forces equally to each electron thus resulting in less attractive forces on each valent electron and larger atomic radius.”

The following examples concern the ionisation of magnesium, and are quite explicit in suggesting that the force of the nucleus is shared amongst the electrons present,

> “When an electron is removed the effective core charge is shared out between one less electron therefore increasing the energy needed to remove another electron.”
>
> “The loss of one electron has meant the remaining electrons receive the lost electron[’]s share of the attraction to the centre so the valence shell is pulled more tightly in to the centre.”
>
> “Once the first electron is removed, the nuclear charge is no longer shared amongst two valence electrons, but one. There is a stronger attraction which means more energy is needed to remove it.”

Five items in the ‘truth about ionisation energy diagnostic instrument’ (Taber, 1997c) were written from the perspective of the ‘conservation of force’ conception. These statements were judged to be true by a majority of A level chemistry students asked to complete the instrument (see table 1).

Statement reflecting 'conservation of force'	Respondnts judging statements as 'true' (%)
The 11 protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons'	72
If one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus'	69
The third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus'	70
After the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus'	79
'The force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed'	74

Table 1. Support for 'conservation of force' statements in the diagnostic instrument

As the diagnostic instrument was used within one college these results cannot be considered as representative of the wider population of A level chemistry students. However this response pattern is considered as indicative that the 'conservation of force' notion may be widely applied when students attempt to explain atomic level phenomena such as patterns in ionisation energies.

Contextual dependence of the alternative conception

The 'conservation of force' conception was elicited from students when they were asked to consider atomic and related systems. Due to the nature of the research reported (focussing on the concept of the chemical bond) there was little attempt to explore whether the learners would have applied the same principle in different contexts. However there were a few indications in the data collected that the 'conservation of force' conception is an explanatory principle that may be seen as particularly relevant to the molecular world.

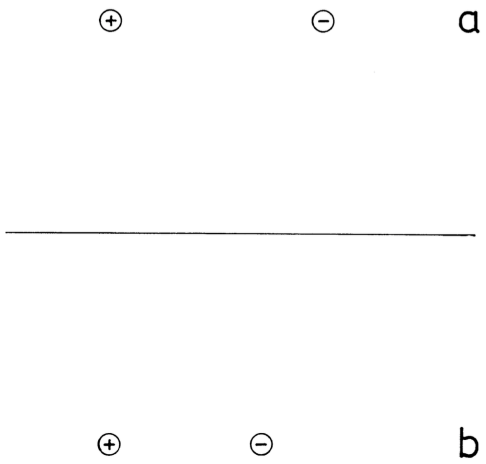

Figure 2

When Tajinder considered figure 2 he recognised that there would be a stronger force of attraction between the charges in part (b), than in part (a), because the distance between the positive and negative particles is smaller. When he was subsequently shown figure 3, however, he thought that all the electrons would be attracted equally despite some clearly being shown as further from the nucleus. It would seem that Tajinder’s recognition that charge separation is important was not elicited in the more complex atom-like structure perceived as a nucleus attracting many electrons.

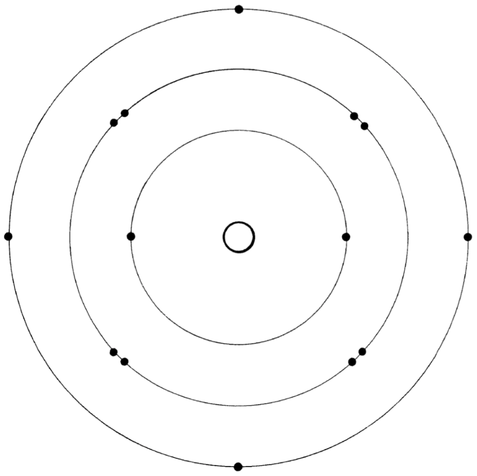

Figure 3

When Kabul was explaining about successive ionisations of a sodium atom he suggested that each time an electron was removed, the remaining electrons experienced more force, and that if all but one electron was removed from an atom the force on that one electron would be "much more". He thought that he could work out the force on an electron using "Coulomb's law, and … measure the distance, and … just bung it in the formula and you know the force". Kabul thought he could carry out the calculation for the electron when in a sodium atom, and repeat the calculation for the situation when it was the only electron (in an Na^{10+} ion), and he would get a bigger answer. It would appear that even when Kabul had available the appropriate curriculum science tools to analyse such a situation, his 'conservation of force' notion took precedence in his thinking.

Here we see two intriguing examples of student thinking. In one case a learner applies a simple physical principle (force diminishes with increasing separation) in one context, but then does not apply this in an atom-like system. In the second example the learner attempts to justify his 'conservation of force' notion by appealing to the authority of a mathematical relationship that actually undermines his belief. Although neither Kabul nor Tajinder studied physics to A level, both had obtained high grades in physics in their school-leaving examinations. One of their classmates - who was studying A level physics and chemistry concurrently - made a telling remark after a class discussion of ionisation energies,

> "I can't think about physics in chemistry, I have to think about chemical things in chemistry"

Discussion

Clearly the work that has been reported here is in some sense provisional, being based on a small scale study in one College. However, the data discussed show that:

- some A level students interviewed applied the 'conservation of force' conception in their explanations of physical phenomena (relative sizes of ions, patterns in ionisation energies);
- similar arguments were found in the written work both of these students, and their peers who were not involved in the interview study;

- a simple diagnostic instrument then revealed that something like three quarters of a larger sample of learners would judge statements based on the 'conservation of force' conception as true rather than false.

There seems to be sufficient evidence to suggest that the 'conservation of force' conception may be widely used by chemistry students at this level.

This finding is of considerable significance to chemistry teachers. Students of chemistry are expected to be able to produce explanations for such phenomena as patterns in ionic radii and in ionisation energies. The 'conservation of force' conception allows learners to make the correct predictions in many cases. However, inappropriate reasoning will be penalised in examinations. Anions are larger than their atoms, which are larger than their cations - but not because of the number of electrons sharing the available nuclear attraction. Successive ionisations do require increasing energy, but not because there are 'spare' protons in the nucleus which can redistribute their force between the remaining electrons.

Chemistry teachers will base their own presentations of these topics on the principles of Coulombic electrostatics. Some teachers may be very explicit about this underpinning knowledge, whilst others may just assume their students share this very basic physics background. It may well be that many students either do not share their teacher's knowledge of electrostatics, or - like Tajinder and Kabul - apply alternative assumptions in the context of the interactions in atoms and molecules.

What the present research has not been able to address is the origin and scope of the 'conservation of force' alternative conception. Without such investigation it is not possible to be sure how significant this alternative conception is in other areas of the science curriculum, nor whether it might be avoided by making changes to the teaching of science at an earlier stage of science education. The evidence presented shows that many learners use this alternative explanatory principle in the particular context of nuclei and electrons. Kabul referred to Coulomb's law, yet when applying it to the force between a nucleus and an electron he seemed to only admit an individual electron's 'share' of the nuclear charge into the calculation. It is clear that Tajinder accepted the Coulombic principle that the force between two charges diminishes with separation, but for some reason he did not apply this to atoms. Research certainly shows that learners commonly apply an alternative conceptual framework for understanding chemical bonding (Taber 1997c, 1998) - a framework that provides learners with an alternative rationale to the electrostatic principles underpinning curriculum science (Taber 1997a). This octet rule framework has been found to be a very stable aspect of learners' cognitive structures, and to be applied by students long after they have acquired more sophisticated tools for explaining the same aspects of chemistry (Taber 1997c, Taber and Watts, 1997). One feature of the framework is its anthropomorphism - with atoms owning electrons, having needs, and entering into 'social' arrangements (Taber and Watts, 1996). It is possible to speculate that the notion of sharing the nuclear charge fairly (i.e. equally) between the electrons may be related to this way of thinking about atoms. Perhaps even students who study physics as well as chemistry may compartmentalise atoms as part of their chemical knowledge, where physics is not seen to apply. This certainly seems to be a worthwhile theme for future research.

One of the advantages of using interviews - as in the present study - is that the interviewer has the flexibility to follow-up interesting responses, and to probe the informant's ideas in as much detail as is desired. In the introduction to this paper it was suggested that alternative conceptions that do not derive from direct experience of a phenomena might originate in a number of ways. Where a learner's conception is based upon a simple misunderstanding, or on alternative conceptions of prerequisite knowledge, or on unintentional nuances of the teacher's words one might expect to gain insight into this through the interview process. However the other option suggested - the influence of the "system of mental tendencies and predilections" - depends upon what Polanyi (1962) has described as the ineffable domain, "where the tacit predominates to the extent that articulation is virtually impossible" (p.87). In an interview it is possible to 'peel' away the layers of an explanation by asking a series of "but why?" questions: but a point is reached where the only answer forthcoming will be "it just is, it's natural, that's the way the world is" (Watts and Taber, 1996). None of the colearners exhibiting the 'conservation of force' conception attempted to justify the principle as something they had been taught - rather they seemed to just make the assumption spontaneously.

The results presented here flag up an apparently common alternative conception, which influences aspects of A level chemistry students' understanding of atomic phenomena. Teachers discussing the forces acting between nuclei and electrons should be aware that their students may construe the interactions in terms of the nucleus giving rise to a certain amount of force to be shared-out, and be prepared to elicit and challenge such beliefs. There is clearly scope for further research to explore whether the 'conservation of force' principle is applied in other contexts, and by other groups of learners - by students studying for degrees in the physical sciences for example. There is also the intriguing question of why learners seem to abandon familiar physical principles and apply a different set of rules once they perceive a series of charged particles as an atom. As always research leads to interesting data, and even more interesting questions.

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