Taber, K. S. (2013). Upper Secondary Students' Understanding of the Basic Physical Interactions in Analogous Atomic and Solar Systems. Research in Science Education, 43(4), 1377-1406. doi:10.1007/s11165-012-9312-3

Upper secondary students' understanding of the basic physical interactions in analogous atomic and solar systems

Abstract:

Comparing the atom to a 'tiny solar system' is a common teaching analogy, and the extent to which learners saw the systems as analogous was investigated. English upper secondary students were asked parallel questions about the physical interactions between the components of a simple atomic system and a simple solar system to investigate how they understood the forces acting within the two systems. A sample of just over one hundred students across the 15-18 age range responded to a pencil-and-paper instrument that asked about four aspects of the two systems. It was found that for both systems about four-fifths of students expected forces to decrease with increasing distance; but that only a little over half expected there to be interactions between the minor constituents (electrons; planets). Most students failed to apply Newton's third law to either system. There was a considerable difference in the extent to which respondents were able to identify the type of force acting in the systems (nearly all for the solar system, but only a small proportion in the case of the atom). The findings are considered in terms of both the limitations of student understanding of the basic physics, and possible implications for the use of the teaching analogy.

Upper secondary students' understanding of the forces acting in analogous atomic and solar systems

Introduction

A key aspect of teaching is 'making the unfamiliar familiar', that is helping learners to understand novel material by finding ways to link to their existing personal knowledge of the world (Ausubel, 2000). Indeed, Piaget's (1972) model of development suggests that we must understand learning in terms of an iterative process that starts with the interaction between innate mental structures and the experienced world, leading to the modification of available mental structures which then allow qualitatively different experiences - which in turn allow further modifications of the mental structures, etc. Whilst the details of Piaget's scheme have faced extensive critical review (e.g., Sugarman, 1987), this central 'constructivist' perspective on learning has been widely adopted in science education (Driver, Asoko, Leach, Mortimer, & Scott, 1994; Gilbert & Watts, 1983), and continues to be reflected in research exploring teaching and learning in science (Taber, 2009b).

Indeed, Lakoff and Johnson (1980a, 1980b) have argued of the centrality of metaphor in human thinking and language. They suggest that concepts used to refer to abstract ideas are understood by analogy with basic concepts which themselves relate to fundamental distinctions we can make about the environment. So a basic discrimination we might make based on our perceptions of our orientation in the environment is between up (the sky is up) and down (the ground is down). Rockets go up, and old buildings fall down: however *by analogy* popular songs go *up* (and down) the music charts, sports teams 'sit' on *top* of their leagues, other people can bring us *down* (or lift us *up*), a '*rising* star' (in whatever field) is said to be *on-the-up*, and it is sometimes said that the *higher* such stars climb, the harder they *fall* (and that that one should behave well to people one passes on the way *up*, as one may well pass them again on the way *down*).

Such metaphorical language is ubiquitous, and can be found in science as well as in everyday usage (Muldoon, 2006). Perhaps physicists intended irony in naming the ‘top’ and ‘bottom’ quarks (which are also known as ‘truth’ and ‘beauty’), but in chemistry there are elements that are found at the top of their groups, or ‘higher’ than others in the electrochemical series. Of course, these descriptions become literal when referring to particular representations, but only because those representations themselves inherently use an analogy between physical space and conceptual ‘spaces’. In biology, too, we find this: so a predator is said to be at the ‘top’ of a food web.

We are dealing here with metaphors, because the analogies are not made explicit, and indeed the initial adoption of such usage may well have occurred without any conscious attempt at analogy: rather, as Lakoff and Johnson would argue, the nature of our cognitive apparatus is such that using such analogies is totally natural for us.

Metaphor and analogy in teaching

Teaching involves helping learners expand their personal stores of knowledge and understanding. We hope that learners who were not previously familiar with Newton’s laws, or a model of the structure of atom, or the role of the mitochondria in cells, and so forth, will have become familiar with these ideas after teaching.

It is much easier to help pupils become familiar with some ideas than others, as some referent phenomena can be demonstrated directly. There are still substantial logical issues concerning how a learner being shown something new knows where the boundary of the phenomenon is; and how a learner can understand group membership by being shown a few examples of set members (Rutherford, 1934). Despite these very real issues, in practice we can often get across the idea of colour mixing, combustion, or Coleoptera by showing students examples of colour mixing, combustion, or Coleoptera. However, there are many other scientific concepts – such as conservation of energy, covalent bonding and codons – that are much less easy to demonstrate directly.

Teaching then often involves finding analogues from students’ own experience that can be used as conceptual hooks (sic) that can anchor (sic) new learning to something that is already understood (Harrison & Coll, 2008; Sjøberg, 2000). Richard Feynman developed a teaching analogy of energy being like a child's building bricks "which are absolutely indestructible, and cannot be divided into pieces" (Feynman, Leighton, & Sands, 1963: 4-1), which might get dissipated during use but were conserved. At the end of the day we would always have the same number of bricks as there were to start with, as long as we were careful to check in all the places they may get dropped or thrown. This particular example was adopted in teaching guidance offered to English secondary school science teachers (The National Strategies Secondary, 2009).

Covalent bonding is commonly described as being the 'sharing' of a pair of electrons between two atoms (Coll & Treagust, 2001). This is an interesting example as it is an analogy between the interactions between tiny inanimate particles of matter and the familiar social behaviour of people, relying upon learners finding reasonable an underlying anthropomorphic comparison between atoms and sentient beings. That is, atoms are considered to 'want' or 'need' to obtain octets or full shells, and that one way that they can satisfy such needs is being entering into arrangements to share electrons between them. The sharing metaphor seems to be readily accepted by learners, reflecting the widespread adoption of the 'needs' of atoms for full electron shells as an explanatory principle in learning chemistry (Taber, 1998a). However, although this is a readily adopted metaphor, it is less clear whether the use of anthropomorphic metaphors for submicroscopic processes is ultimately counter-productive in impeding learning progression (Taber & Watts, 1996).

In the biological example, the reference to there being a 'genetic code' is so well established as part of everyday language, that the metaphor may readily be missed, and again there is an underlying current (another metaphor) of teleology associated with the notions of anything being 'coded in the genes'. Again this raises an issue for science education, as such teleology is sometimes considered 'taboo' in science, despite being detected in some scientific works (Swanson, 2011).

Traditionally the term 'dead metaphor' has been used for "a linguistic expression that had once been novel and poetic, but had since become part of mundane conventional language" (Lakoff, 1987, p. 143). However, in teaching we may often have the situation where scientists and science teachers have become blind to the metaphorical origin or terms and phrases, in which case they may not appreciate how learners interpret such language when they are introduced to it. The physics educator Andrea diSessa noted in one of his papers how he had failed to notice the obvious way in which the term 'resistance' may be understood in electrical circuits, as for him it had become "a thoroughly dead metaphor" (diSessa, 1993, p. 212). That is, for the physics teacher, resistance may simply be a way of labelling how much p.d. is required to produce a certain amount of current flow, rather than having potential implications of being an active opposition to that flow.

Schmidt (1991) has described how the labels we used in science teaching may act as 'hidden persuaders', such as when students assume (not unreasonably) that the product of a neutralisation reaction will *necessarily* be neutral. Another example concerns the notion of quantum-mechanical spin. When students are taught that electrons have spin, this refers to an inherent abstract property named by analogy to our everyday notion of spinning objects: however, students are likely to simply assume that electrons spin in the same literal sense as a spinning basketball or planet (Taber, 2005). Where habitual use of such terms by teachers leads to the metaphorical nature of their origins to become invisible (so to speak), they are unlikely to think to make it explicit to learners how such terms are intended to be understood.

Analogies as teaching models

Given Lakoff and Johnson's (1980a) ideas about the centrality of metaphor in human thought and language, it is likely that teachers often use analogy in teaching spontaneously, without explicitly considering the analogical nature of the process. However, teachers also adopt deliberate and planned teaching models in order to represent curriculum material in ways they feel will be understood and appreciated by their students (Clement, 2008; Harrison & Coll, 2008). This can be undertaken both to aid conceptual understanding, and to engage learners by making links with topics of interest to them. So, for example, analogies are often used to help students appreciate features of the electrical circuit-as-system which are not readily appreciated (Leach & Scott, 2008; Samaras, 2010; Singh, Sabella, & Rebello, 2010; Society, 2011). Similarly, the counter-intuitive idea that supports (the ground, a table) exert an upwards force on bodies resting on them may be taught through a sequence of demonstrations acting as bridging analogies (Brown & Hammer, 2008; Roth & Tobin, 2009; Singh et al., 2010).

There are many teaching analogies which are in common use, such as considering the nucleus of a cell to be like the brain (Roth & Lucas, 1997); or the camera to be like the eye (Schraw, Wadkins, & Olafson, 2007; Society, 2011), or considering the change of direction of light when it moves between materials with different refractive indices to be akin to a vehicle or marching band passing from a tarmacadam surface to a graveled area (Samaras, 2010; Sjøberg, 2000).

One such common teaching analogy takes the form that '*an atom is like a tiny solar system*' (Rutledge & Warden, 2000; Spitz, 1993; Stake, 2000), and it is that comparison that motivated the work reported in this paper. The analogy was actually used by Rutherford, who "advanced atomic physics by drawing an analogy between the structure of the solar system and the structure of an atom" (Spector & Gibson, 1991, p. 120), for example referring to "planetary electrons, as they have been termed from analogy with our solar system" (Stake, 1978, p. 17).

The structure of analogy

The basis of analogy is an explicit comparison between two systems that share some level of structural similarity. Such analogies can be highly fruitful in science itself as well as in science learning (Nersessian, 2008; Schraw et al., 2007; Singh et al., 2010; Sjøberg, 2010; Society, 2011). So when Lise Meitner and her nephew Otto Robert Frisch considered that if an atomic nucleus was *like* a liquid drop it might under some conditions divide into two smaller drops (Stein & Kaufman, 2010), that helped them understand the results of Meitner's research team (Otto Hahn and Fritz Strassmann) in terms of the possibility of the fission of heavier nuclei (Meitner & Frisch, 1939).

Similarly, helping physics students appreciate the structural similarities between analogous quantities can help bring three disparate sets of phenomena under a common pattern. For example, analogies can be drawn between physical processes that demonstrate exponential decay (e.g. cooling, capacitor discharge, equilibration of water in two connected columns, radioactive decay), which can all be modelled with simple negative feedback loops (Taber, 2011).

The process of analogy involves a mapping of features between the analogue and the target to demonstrate the structural similarities in the two systems (Stake, 1995). As the similarities occur at the level of relationships within a structure, such an approach compares *systems* rather than discrete entities. So in saying that an atomic nucleus is like the brain of the cell, the implication is that the nucleus *is to* the cell, as the brain *is to* the body.

Sometimes a distinction is made between positive, negative and neutral aspects of an analogy. In the nucleus – brain comparison, a positive feature of the analogy would be how the signals from the nucleus can influence activity in the rest of the cell (akin to how signals from a brain influence activity elsewhere in the body). However, there are negative aspects to the analogy (the brain uses electrical signals as well as chemical signals: the nucleus just the latter). There are also features of a brain that might be considered irrelevant, and so neutral: such as its hemispherical specialisation. Arguably, the distinction between neutral and negative aspects of an analogy is rather arbitrary: if students are expected to learn about the structure of the nucleus as well as its function, then the hemispheres of the brain might be considered a negative, rather than a neutral, feature.

The atom and the solar system

Both atoms and solar systems are commonly part of secondary school science. Students are usually expected to learn about 'our' solar system: our sun, Sol, and its system of planets with their moons, planetoids and comets. Various models and representations are commonly used in teaching, and the level of detail presented will vary with age/grade level. Students will be expected to understand how spatial and dynamic features of the solar system leads to the phenomena of day and night, and the seasons on earth, and to the phases of the moon and occasional eclipses. Learning in this topic has been well studied in a variety of cultural contexts, and common learning difficulties have been found widely reported (Brewer, 2008). Students will also be taught that the stars in the night sky are other suns, and that many of these will also have their own systems of planets and other associated bodies.

The atom is a somewhat different notion. Whereas the 'reality' of the solar system is doubted by few (the sun, the moon, and a number of the planets can be seen directly), and we now have extensive data that allows us to describe much of that system in great detail, the atom has somewhat different ontological status. That is not to suggest that atoms are fictitious: but rather that they are perhaps best conceptualised as useful notions for thinking about matter at submicroscopic scales rather than 'what is there'. Producing models of the atom involves more than selecting a suitable scale, and considering the level of detail needed (cf., in the case of the solar system, do we include the asteroid belt, what about the rings around the major planets?). Modelling the atom requires making choices about forms of representation that go beyond deciding upon the appropriate degree of simplification, that is choices regarding which details can be omitted in the model.

This is because the nature of matter at the submicroscopic scale at which the atom concept is useful is very different from how it appears macroscopically. Atoms, molecules, ions, electrons and so forth are fuzzy balls of fields that do not have distinct surfaces or definitive volumes, quite unlike the plastic balls glued together, or connected by springs, in our structural models. It has been suggested it is best not to refer to them as particles (the term 'quanticles' has been mooted). These entities are not like familiar particles of matter, but are subject to significant quantum effects. Quantum theory applies to everything, but elephants, jets, people and indeed salt grains have wave-like properties that are usually negligible. Where nucleons can 'tunnel' their ways out of nuclei, people tend to not be able to walk through walls, and need to use doors. Indeed where there are several available doors, people have to walk directly through one specific doorway, unlike the way that electrons can diffract through crystals.

In learning about atoms in school science a series of models that is commonly met. This often starts with the undifferentiated 'particle' of kinetic theory (where no distinction is made between atoms, ions and molecules), considering the atom as like a tiny ball. Later a Bohr-like model of the atom having a central nucleus and concentric shells of orbiting electrons is met. For those students who study physical science in the higher grades, this type of model will be supplemented by more nuanced models with electrons understood as occupying orbitals and/or being considered in terms of clouds (another metaphor) of electron density (Harrison & Treagust, 2000; Petri & Niedderer, 1998).

Much has been written about student learning difficulties in this whole area (Harrison & Treagust, 2002), and the limitations of the models that inform curriculum and teaching (Justi & Gilbert, 2000; Taber, 2003a). Despite this, the model of the atom as a central nucleus surrounded by shells of orbiting electrons is commonly used in secondary science, and indeed provides the basis for much of the chemistry taught at upper secondary level.

Making the unfamiliar, familiar

The logic of the teaching analogy, then, is that the atom, an abstract, and assumed unfamiliar, entity - too small to be directly demonstrated in class - is like a tiny version of the more familiar solar system. When Nicoll undertook a study of undergraduate's conceptions of chemical bonding in a US university, she found that "students at all levels invoked a solar system analogy when describing the interaction of electrons and the nucleus within atoms" (Nicoll, 2001, p. 718). She reported how one sophomore (second year undergraduate) responded to being asked what he thought atoms 'looked' like:

> "I kind of picture, like…the solar system, I guess is what I'm thinking of. Planets would be similar to the electrons. Except that… orbitals aren't really all, all shaped the same way as, as, ah, as the orbits of planets. But, but you can kind of picture the, that the distance of, of each shell…from the nucleus as being similar to the distance of each planet from the sun. And the sun is like the nucleus. So, so the outer shell would be, like, Pluto is to the sun"
>
> (Nicoll, 2001, p. 718)

For at least some students, then, the 'atom is like a tiny solar system' analogy seems to provide an effective way of imagining a structure for the atom.

The nature of the atom-solar system analogy

Using the analogy that 'the atom is like a tiny solar system' as a teaching model can be understood as based on the (perhaps often implicit) premises that:

1. Secondary age students are generally familiar with the general form of the solar system;

2. The atom is an abstract theoretical entity, and atomic structure is generally unfamiliar to students at the start of secondary school;

3. There are structural similarities between the two systems such that students can be introduced to atomic structure by comparison with their existing knowledge of the solar system.

Given such premises, this teaching analogy seems quite reasonable. Where the target knowledge here is the particular 'planetary' model for the atom - and the explicit nature of this being a model should be emphasised during teaching (Taber, 2010) - then it is possible to identify some clear positive features of the analogy:

- the atom (like the solar system) has a central body, and more peripheral bodies;
- the peripheral bodies in the atom (as in the solar system) move around the central body;
- forces act to maintain the peripheral bodies in their orbits around the nucleus (cf. around the sun);
- the central body in the atom (as in the solar system) is more massive/larger than the peripheral bodies;
- the central body of the atom and the peripheral bodies are given different denotations and considered ontologically distinct: the nucleus; the electrons (cf. the sun; the planets)

Despite these similarities, there are clearly many differences between the systems (Taber, 2001). That need not undermine the potential usefulness of the comparison: but does suggest that teachers should be careful to explain that not all features are analogous (Smardon, 2009). Among the major differences (leaving aside scale) are the nature of the forces involved (attractive and repulsive electrical cf. attractive gravitational), the variations between planets (size, shape, colour, rotation, material composition, mean temperatures, mean density etc.), the lack of shells in solar systems, the presence of other bodies (asteroids, comets), the peripheral bodies having their own companions (moons), the near planar arrangement of the solar system; and the uniqueness of the solar systems (there are plenty of other solar systems, but it would be unlikely to find one that astronomers could not tell apart from our own).

Gentner (1995, p. 159) defined an analogy as "a comparison in which relational predicates, but few or no object attributes, can be mapped from base to target" and in the example of "the hydrogen atom is like our solar system" suggested:

> Intended inferences concern chiefly the relational structure: e.g., "The electron REVOLVES AROUND the nucleus, just as the planets REVOLVE AROUND the sun," but not "The nucleus is YELLOW, MASSIVE, etc., like the sun." …The hearer might map "The fact that the nucleus ATTRACTS the electron CAUSES the electron to REVOLVE around the nucleus" from "The fact that the sun ATTRACTS the planets CAUSES the planets to REVOLVE AROUND the sun".
>
> (Stake, 1995, p. 159)

Learners' notions about the analogous systems

The motivation for exploring students' perceptions of the similarities of atomic and solar systems derived from consideration of the teaching analogy in the light of research into student thinking about these areas of science. Thagard has suggested that "beginning physics students are taught the Bohr model of the atom by analogy to the solar system, but the model of orbits that is acquired gets in the way of later acquisition of quantum-mechanical notions" (Southerland, Abrams, Cummins, & Anzelmo, 2001, p. 542). There is indeed research to suggest that once students had adopted a model of electrons in orbits, they are resistant to give up this notion when taught orbital models (Taber, 2005). However, the present research was intended to explore how students understood the forces acting in the solar system, and within an atom modelled as a planetary system.

Physicists understand the dynamics of solar systems largely in terms of Newtonian physics (with some relativistic tweaks to explain some details, such as the rate of the advance of the perihelion of mercury), but it is known that Newtonian physics is counter-intuitive to many learners (Gilbert & Zylbersztajn, 1985; Watts & Zylbersztajn, 1981). Even when students accept and can apply Newtonian physics in cases of linear motion, they may have difficulties with orbital motion (McCloskey, Carmazza, & Green, 1980). For example, one student that the author worked with "identified unbalanced forces with acceleration, [but] apparently considered orbital motion to be the result of balancing centripetal and centrifugal forces, which kept the orbiting body moving round". 'Alice' defined "acceleration as a change in speed [i.e., not velocity], and so did not seem to consider a change of direction alone as sufficient criterion for an acceleration" (Taber, 2008). It seems quite possible that where the solar system is offered as an analogue to introduce the atomic structure model, it may not be that well understood in physical terms by many of the learners exposed to the teaching analogy.

Moreover, research into student thinking about chemistry at the submicroscopic level has long been recognised as a major area of difficulty for learners (Gilbert & Treagust, 2009). Students often readily adopt talk of charges in chemistry, but they may not transfer across the associations of charge that operate in physics classes. One student was found to maintain an idiosyncratic meaning for positive and negative charges throughout most of her college chemistry course (Taber, 1995). Secondary students commonly consider such non-viable ions as C^{4+}, Na^{7-} or Cl^{11-} as being especially stable where they would have full outer electron shells or octet structures (Taber, 2009a). So teachers need to be aware that student references to electrical charges do not necessarily cue thinking in terms of conventional electrical interactions in atomic and molecular systems.

Student thinking about atoms in terms of their 'needs' and 'desires' often seems to operate in place of consideration of the physical interactions that scientists use to explain chemical properties and behaviour (Taber & Watts, 1996). Moreover, when forces are invoked, they may be considered to operate in ways at odds with scientific principles. So, for example, increases in successive ionisation energies may be explained in terms of the nuclear force being 'shared out' among less electrons each time one is removed from an atom or ion (Taber, 1998b).

Research question

So teachers should not assume that students will conceptualise the atomic structure model in electrical terms without this being made explicit in teaching. This raises the question of whether using the 'atom is like a tiny solar system' teaching analogy could be compromised where students hold non-canonical ideas about the solar system. It follows from the pedagogical rationale for using teaching analogies discussed above that in deciding whether to use such an analogy with a particular group of students, the teacher should be informed by the students' current level of understanding of both the target concept and the analogue to be used.

The hypothesis underpinning the present study is that given the findings of previous research into students' ideas in both the topics of forces and atomic structure, many school-age students are likely to hold alternative conceptions about the interactions in both atomic and solar systems. The question explored in the present study was: *how would a sample of students understand the forces acting within the solar system, and the analogous planetary model of the atom.*

Methodology

The present paper reports an analysis of student responses to a diagnostic probe designed to be suitable for use by teachers undertaking formative assessment in their classroom teaching, and which was administered by teachers to a sample of secondary age students from several English schools.

A diagnostic probe

A simple diagnostic probe was designed to allow teachers to elicit students' thinking about atomic and solar systems, with a format that allowed ready comparison between the two types of system (Taber, 2002a). The probe was informed by a reading of the literature on student thinking, and interviews previously carried out by the author with

16-19 year old students studying science subjects in an English further education college (Taber, 2000). The probe (see the Appendix) asked 8 closed questions, supplemented by asking for reasons in some cases, and then asked students to list the similarities and differences between the two systems. The present paper considers the first 8 questions, which concerned aspects of the pattern of physical forces in the two systems (see table 1). The details of the questions are reported below, where the student responses are considered.

Focus	Atomic system	Solar system
type of force	gravitational (Q1)	electrical (Q5)
effect of distance on force	outer electron attracted with less force (Q2)	more distant planet attracted with less force (where planet masses are comparable) (Q6)
reciprocity of forces	same magnitude force between nucleus and electron (Q3)	same magnitude forces between sun and planet (Q7)
force between peripheral bodies	force between electrons (i.e. repulsion) (Q4)	force between planets (i.e. attraction) Q8

Table 1: Structure of the diagnostic probe

The probe included exemplar figures to illustrate the two systems (see figures 1 and 2), which were designed to be superficially similar.

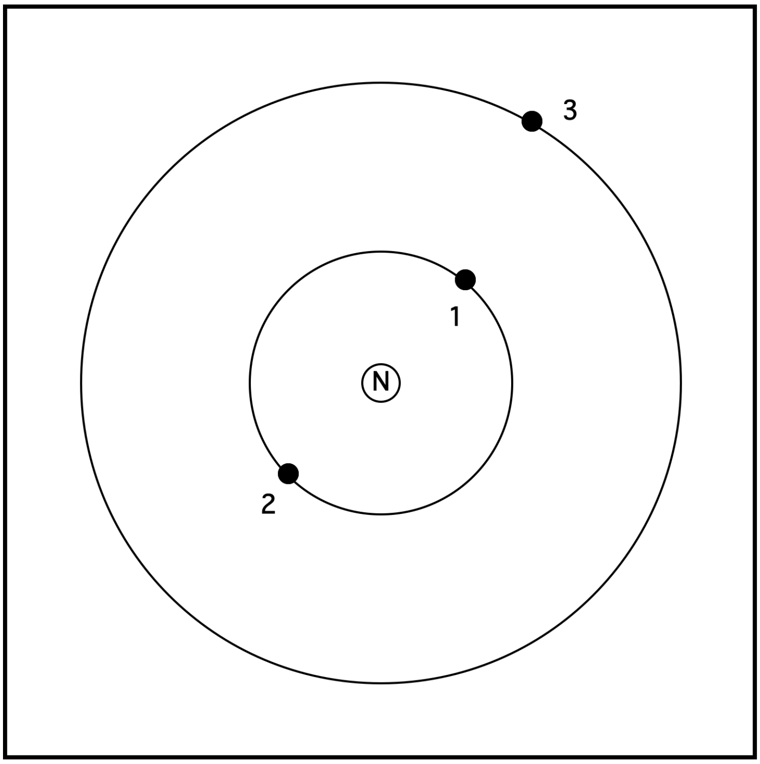

Fig. 1 Focal figure - atomic system

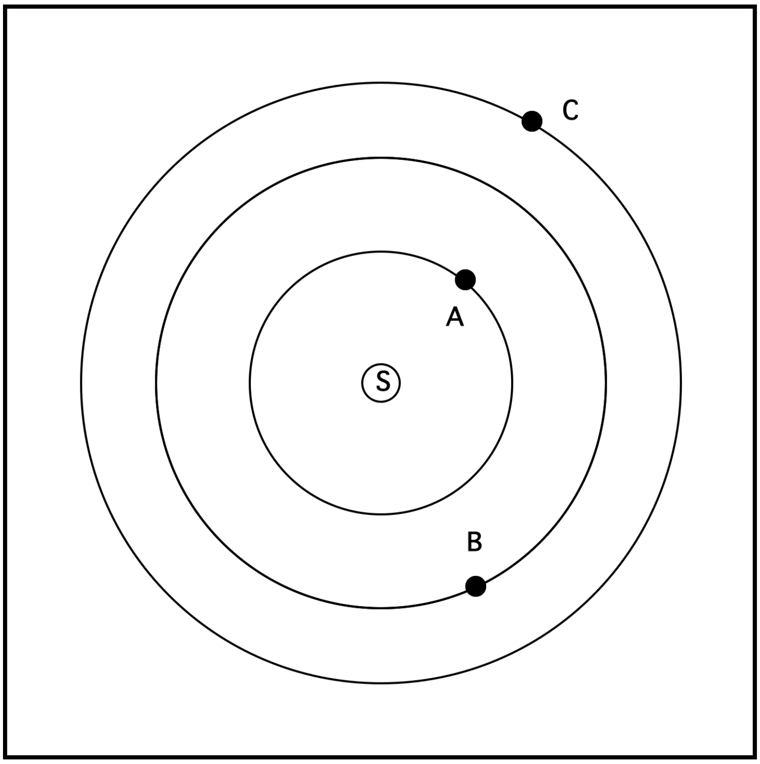

Fig. 2 Focal figure - solar system

Respondents

The probe was designed as part of a project to support teachers in challenging chemical misconceptions in the classroom, set up by the UK's Royal Society of Chemistry in 2000-2001. As part of the project, a series of classroom probes were designed, informed by research into student conceptions, and tested in classrooms under normal classroom conditions. Teachers expressing an interest in the project administered probes relevant to teaching topics to their own classes, and returned the completed probes for analysis. Teachers were provided with the rationale for a probe; and suggestions on debriefing the students. The outcome of the project was a volume containing classroom probes on different topics aimed at different age groups (11-14, 14-16 or 16-19) with teachers' notes (Taber, 2002a), accompanied by a guide to the research background and general 'constructivist' teaching approach (Taber, 2002b).

Data from the atom/solar system probe was returned from six teaching groups, as shown in table 2.

Class group	School	School Year (age)	n
Gp. 1	School A	10 (14-15 year olds)	18
Gp. 2	School B	11 (15-16 year olds)	11
Gp. 3	School B	11 (15-16 year olds)	19
Gp. 4	School C	11 (15-16 year olds)	19
Gp. 5	School C	12 (16-17 year olds)	28
Gp. 6	School D	13 (17-18 year olds)	10

Table 2: Sample of respondents

The respondents make up a convenience sample. The project was announced in the professional periodicals aimed at science teachers in the UK, and data was collected where teachers who were interested enough to volunteer to take part, and committed enough to return completed instruments. It is quite likely that such teachers may in some ways be unrepresentative of science teachers nationally. Moreover, with so few classes involved, little can be inferred from comparisons between classes or schools.

Indeed there is good reason to assume that the sample of students discussed here is *not* fully representative of the national population. Schools A and D were independent (fee-paying) schools which are only attended by a minority of students in England. Students at these schools are usually from the more prosperous sections of society, or have won competitive scholarships. Schools B and C were both state schools, but both were Grammar schools, which unlike schools in most areas of the UK admit students based on selective ability testing. Broadly, then, all four schools involved may be considered to be more ‘academic’ in nature, tending to produce students who perform well on national examinations. The central point for the present study was that the same sample of students answered questions about both the atomic and solar systems.

Analysis

The eight questions varied according to the amount of structure imposed upon student answers, and the analytic process therefore varied according to the question. In particular, the extent to which responses were coded according to pre-determined categories, or using categories derived from the data, depending upon the particular question (Taber, 2007).

Questions 1 and 5 asked students to identify a type of force, and here the categories used were determined by the responses students gave, but grouped according to the extent to which they would be considered acceptable from the curriculum (scientific) perspective. The first part of each of the other questions (2-4, 6-8) were analysed as if closed response questions. Although questions 2, 4, 6 and 8 had the appearance of open ended questions, their wording implied that one of a limited number of responses was expected (‘stronger’, ‘weaker’ or ‘the same’ in Q2 and Q6; ‘yes’ or ‘no’ in Q4 and Q8) and most responses were unproblemtatically classified accordingly. The second parts of questions 2-6 and 6-8 asked students for the reasons for their answers to the first part of those questions. Pupils did not always give responses to these parts, but where they did, their answers were assigned to response categories derived from the data itself, i.e. open coding. It is in the nature of open responses that they do not always fit readily into a limited set of categories. However, common categories are reported with some illustrative examples of student responses.

Findings: student perceptions of forces in the two systems

The findings will be presented initially in the order in which questions were presented, first for the atomic system, and then for the solar system. Then the responses across the two systems are compared.

Forces in the atomic system

Question 1 asked 'what type of force attracts the electrons towards the nucleus?' The responses to this question are shown in Table 3. This shows there was a wide range of suggestions for the type of force acting in the atom. Accepting a range of terms (electrical, electromagnetic, electrostatic, static, electricity) for electrical forces gives a total of 20 correct responses across the six classes – from a total of 105 students.

A larger proportion of respondents gave answers that were considered vague, i.e. references to charges or field strength or simply paraphrasing the question (attraction, pull). An even larger proportion of the respondents made suggestions that were clearly wrong from the perspective of curriculum science: the most popular categories of response being gravity or magnetism. Indeed more of the students suggested gravitational forces than electrical forces; and if references to poles were considered to imply magnetic poles, magnetism was suggested as often as electrical forces.

The student [TF128/6] who responded 'no' (see table 4), justified this response on the basis "because it [electron 3] is further away from the nucleus ∴ [therefore] the pull is less", and it would seem this student only read part of the question, and probably also considered the force on this electron to be weaker than on electrons 1 and 2.

Question 2 asked students 'is **electron 3** attracted to the nucleus by a *stronger* force, a *weaker* force, or the *same size* force as **electron 1**? (and 'why do you think this?'). The responses to the first part of this question are summarised in table 4.

A clear majority of respondents in each class responded that the outer electron would be subject to a *weaker* force, in line with the conventional Coulombic scheme. Of course, as most of these students did not recognise the forces were electrical (i.e. Q1), they were presumably applying a more general schema for how force depends upon separation (see below, where the responses to Q2 and Q6 are compared).

Type of force	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6	Overall
electromagnetic	0	1	0	0	1	2	4
electricity/ electrical	0	0	0	6	1	0	7
electrostatic	0	0	0	3	2	3	8
gravity + static	0	0	0	0	1	0	1
correct	*0*	*1*	*0*	*9*	*5*	*5*	*20*
pull	8	0	0	0	0	0	8
attraction	0	2	0	0	2	1	5
positive	0	0	1	0	3	0	4
negative	0	0	0	1	0	0	1
charge	0	0	0	0	7	0	7
field strength	0	0	0	0	1	0	1
vague	*8*	*2*	*1*	*1*	*13*	*1*	*26*
gravity	3	6	9	2	4	0	24
magnetism/ magnetic	3	2	5	3	3	0	16
pole force/polar	2	0	0	0	0	1	3
magnetism/gravity	1	0	0	0	0	0	1
internuclear	0	0	0	0	0	1	1
interatomic	0	0	0	0	0	1	1
nucleophilic	0	0	0	0	0	1	1
incorrect	*9*	*8*	*14*	*5*	*7*	*4*	*47*
sub-total	***17***	***11***	***15***	***15***	***25***	***10***	***93***
no response	1	0	4	4	3	0	12
total	***18***	***11***	***19***	***19***	***28***	***10***	***105***

Table 3: Student suggestions for the type of force attracting the

increasing distance leads to	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6	Overall
stronger force	4	1	0	1	1	0	7
same size	1	2	2	7	3	1	16
weaker force	13	7	17	11	24	9	81
subtotal	***18***	***10***	***19***	***19***	***28***	***10***	***104***
no	0	1	0	0	0	0	1
total	***18***	***11***	***19***	***19***	***28***	***10***	***105***

Table 4: Student perceptions of how force changes with separation in the atomic system

Of the 81 students who thought that the force attracting the outer electron was weaker that than attracting an inner electron, all but two offered reasons. In 75 (95%) of these cases their reason, or part of it, was that the electron was further way from the nucleus. So typical responses were that electron 3 "is further away so there is a weaker force than electron 1" and "electron 1 is much closer to the nucleus than electron 3 and the force is much stronger for these electrons which are much closer." Nine of the students referred to electron shielding (seven of these were from one class, group 6), although most of these gave this as an additional feature and also mentioned the electron being further form the nucleus: e.g. "because of electron shielding and it is further away ∴ [therefore] less force".

Only a small minority of respondents thought that the outermost electron would be subject to a *stronger* force than the other electrons in the atomic system. The logic here was that a stronger force would be needed to hold an electron at such distance: e.g., "because it is further away from the nucleus, so needs a stronger force to attract it."

Where students felt the electrons would be subject to the *same* magnitude of force, there was variety in the nature of the explanations. One student suggested that "this is same force because the waves of strength are being transmitted as and equal force all along the wave". Another suggested that this was "because all electrons have a charge of -1". A couple of the students seemed to distinguish between the force and its effect (“the force being given out is the same, but seems weaker”), for example suggesting “electron 3 is further away from the nucleus than [electrons] 1 + 2 so it will feel a weaker force, but the nucleus will exert the same size force on them”.

Question 3 asked students to select one of 4 statements relating to the force between the atomic nucleus and electron 2 (as well as give their reasons). The students' responses to this question are summarised in table 5.

	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6	Overall
the force attracting the nucleus to electron 2 is larger than the force attracting electron 2 to the nucleus	0	0	0	0	1	0	1
the force attracting the nucleus to electron 2 is the same size as the force attracting electron 2 to the nucleus	1	2	7	12	15	6	43
the force attracting the nucleus to electron 2 is the smaller than the force attracting electron 2 to the nucleus	3	6	5	1	7	3	25
there is no force acting on the nucleus attracting it to electron 2	14	3	7	5	5	1	35
sub-total	***18***	***11***	***19***	***18***	***28***	***10***	***104***
no response	0	0	0	1	0	0	1
total	***18***	***11***	***19***	***19***	***28***	***10***	***105***

Table 5: Student perceptions of the reciprocity of force between nucleus and electron in an atomic system

Table 5 shows that the most popular response was that which reflected the scientific principle (i.e. Newton's third law) although this was only selected by about two-fifths of the sample. It is also clear that this response was much less popular in some classes than others. The notion that the force only acted in one direction – from nucleus to electron – was chosen by about a third of the students, whilst almost a fifth thought that the nucleus would attract an electron more strongly than the electron would attract the nucleus.

Reasons for considering that the nucleus did not experience a force were that if it did “the nucleus would either drift away from the electron or drift towards the electron” and that “the nucleus is the only thing that can apply a force”. Those considering the nucleus to experience a smaller force included that “the nucleus has a far greater mass than electron 2 and therefore has a lot more gravity” and that “the nucleus is more charged than the electron so the electron is more attracted to the nucleus”.

It is interesting to consider here the reasons students offered for the *correct* response that the forces were equal. Of the 43 correct respondents, only 37 offered reasons for their choice of answer. Two of these explicitly referred to action and reaction, and two others made references to equal forces. One of these responses reiterated that “the nucleus has a positive charge acting on the electron and the electron has a [sic] equal force acting on the nucleus”; and the other was the vague “because all forces equal each other”. These were the only responses that could readily be considered to match target knowledge.

There were six references each to the mutual attraction between opposite charges (which did not inherently indicate equal magnitude forces) and six references to the size or charge of the electron and nucleus being equal: “because the proton has a positive force [sic] and the electron is negative but the size is the same”, although the nuclear charge would actually have been +3 in this atom.

Of particular note, half of the explanations (19/37) given for this correct response were based on the incorrect reasoning that the forces must be balanced as the distance between the nucleus and electron was not changing. One respondent explained that “the electron does not get closer to the nucleus, nor the nucleus get closer to the electron, however they do not get further apart”. So it would seem that although about two fifths of the sample correctly indicated that the forces on the electron and nucleus would be equal, this was in most cases supported by flawed reasoning.

Question 4 asked ‘is there any force between **electron 1** and **electron 3**?’ (and ‘why do you think this?) The responses to this item are summarised in table 6.

It can be seen from Table 6 that a small majority of the respondents considered there was a force acting between the electrons. Most of these offered a reason for their response, and for the majority (31 students) this was that the electrons repelled each other (e.g., “because the electrons try to repel each other”). However, seven other students who responded that there was a force, suggested this would be gravity (e.g., “they both have gravity and react with each other”).

Force between electrons	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6	Overall
yes	8	6	5	3	24	10	56
no	10	4	14	13	3	0	44
subtotal	***18***	***10***	***19***	***16***	***27***	***10***	***100***
no response	0	1	0	3	1	0	5
total	***18***	***11***	***19***	***19***	***28***	***10***	***105***

Table 6: Student perceptions of the interactions between electrons in an atomic system

Among the students who did *not* consider there would be a force between the electrons, six pointed out that the electrons would have the same charge (e.g., “because they have the same electric charge), and five that electrons would not attract each other (e.g., “because electrons do not attract”). 15 students in this category explained that any force acting would be the electrons being attracted *by* the nucleus (e.g. “they are only attracted to the Nucleus”).

Forces in the solar system

The questions asking about the solar system were structured similarly to those about the atomic system (see Table 1). Question 5 asked ‘what *type of force* attracts the planets towards the sun?’ The responses to this question are shown in Table 7. Table 7 shows that nearly all of the students recognised that the force acting as gravitational in nature.

	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6	Overall
gravity/gravitational	15	11	19	16	22	9	92
weight	0	0	0	0	1	0	1
correct	*15*	*11*	*19*	*16*	*23*	*9*	*93*
field strength	0	0	0	0	1	0	1
attraction	0	0	0	0	0	1	1
vague	*0*	*0*	*0*	*0*	*1*	*1*	*2*
pole force	2	0	0	0	0	0	2
positive	0	0	0	0	3	0	3
incorrect	*2*	*0*	*0*	*0*	*3*	*0*	*5*
sub-total	***17***	***11***	***19***	***16***	***27***	***10***	***100***
no response	1	0	0	3	1	0	5
total	***18***	***11***	***19***	***19***	***28***	***10***	***105***

Table 7: Student suggestions for the type of force attracting the planets to the sun in the solar system.

Question 6 asked students 'is **planet C** attracted to the sun by a *stronger* force, a *weaker* force, or the *same size* force as **planet A**?' (and 'why do you think this?'). The responses to the first part of this question are summarised in Table 8.

increasing distance leads to	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6	Overall
stronger force	1	3	0	3	1	0	8
same size	1	1	1	6	4	1	14
weaker force	16	7	18	9	23	9	82
subtotal	***18***	***11***	***19***	***18***	***28***	***10***	***104***
no response	0	0	0	1	0	0	1
total	***18***	***11***	***19***	***19***	***28***	***10***	***105***

Table 8: Student perceptions of how force changes with separation in the solar system

It should be noted that (unlike in the parallel question about the atomic system) strictly the students were not given sufficient information to offer a definitive response in this question. If the planets were of similar masses, then the forces acting on them due to the gravitational attraction to the sun would decrease with the distance of the orbit to the sun. However, a more distant plant that was more massive could *in principle* be subject to a greater force than a closer less massive planet. Respondents did not appear to recognise this complication: only one student failed to offer an unambiguous response, and about four-fifths of the students adopted the scientific view that (subject to the assumption of similar planetary masses) force on the closer planet was greater.

Of the 82 students who though that the outermost planet was subject to a weaker force, 80 gave justifications that related to the planet being furthest from the sun, including 6 who referred to additional considerations. One student offered a different reason and one gave no reason. Common responses, parallel to the atomic system case, were along the lines that the force was weaker "because it is further away from the sun" and "because planet A is closer to the sun, so the force acting on the planet will be very strong, but as planet C is further away from the sun, the force will be weaker as it is further away".

Where reasons where offered for the minority view, that a stronger force acted on the furthest planet, these reflected the reasons given for the parallel item about the atom. So one student who in the case of the atomic system had explained the outer electron was subject to a stronger force "because it is further away and so will need a stronger force acting on it", similarly explained in the case of the solar system "because it is further away, and so will need a larger force acting on it."

In parallel with responses to question 2, some students argued that each planet would be subject to the same force "as the sun gives out the same amount of force for each planet", although again for some students the forces and its effect at distance were distinguished: "the sun gives out a force. Depending on how far away the planet is this force will be more/less effective on it."

Question 7 asked students to select one of 4 statements relating to the force between the sun and planet B (as well as give their reasons). The students' responses to this question are summarised in Table 9.

	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6	Overall
the force attracting the sun to planet B is larger than the force attracting planet B to the sun	1	0	0	4	3	0	8
the force attracting the sun to planet B is the same size as the force attracting planet B to the sun	2	2	4	6	14	4	32
the force attracting the sun to planet B is the smaller than the force attracting planet B to the sun	3	6	8	2	6	6	31
there is no force acting on the sun attracting it to planet B	12	3	7	4	5	0	31
sub-total	***18***	***11***	***19***	***16***	***28***	***10***	***102***
no response	0	0	0	3	0	0	3
total	***18***	***11***	***19***	***19***	***28***	***10***	***105***

Table 9: Student perceptions of the reciprocity of force between sun and planet in a solar system

Table 9 shows that there were three fairly evenly popular response categories in this question. Almost a third of the sample thought that the sun and planet would experience equal force (the canonical response, as required by Newton's third law). However, the options that associated a lesser force, or indeed no force, acting on the sun from the planet were nearly equally as popular.

Common reasons for considering the force on the planet to be smaller were along the lines that "the sun has a far greater mass than planet and therefore has a lot more gravity". Similar reasoning was used to argue that the planet experienced no force (e.g., it [the sun]'s bigger so draws things in"), although another common reason was that if the sun was subject to a force then "the sun would move towards the planet and it doesn't" (although of course this logic should imply that the planet was moving towards the sun, whereas they both orbit the system centre of mass).

Of the 32 students who gave the correct response from the curriculum perspective, 26 were able to offer reasons. One of these responses made an explicit reference to "Newton's 3rd law", but then added "the forces must be balanced or they would move closer to each other", suggesting the law was being incorrectly understood. Another student suggested that "the same force is experienced between two bodies which are gravitationally attracted to each other". A third student from the same class (Group 6) argued that "the force attracting mass to itself is dependent on its own mass and mass of the object. As this is the same when at planet or at sun. This force is always the same also." Whilst the grammar was dubious, the suggestion that the same terms were involved whichever way round the force was calculated (i.e. force depends upon $m_{sun} \cdot m_{planet} = m_{planet} \cdot m_{sun}$) was sound.

However these were the only responses reflecting target knowledge. Most of the explanations offered (19/26) reflected the main reasoning given for equal magnitude forces in Q3, i.e. that *the distance between the sun and planet was not changing*: "the planets are staying the same distance from the sun at all times." Some respondents actually phrased their answers in terms that "they aren't moving", although presumably they were thinking in terms of their separation.

Question 8 asked 'is there any force between **planet A** and **planet C**?' (and 'why do you think this?) The responses to the first part of this item are summarised in table 10.

Force between planets	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6	Overall
yes	8	6	5	6	20	10	55
no	9	5	14	10	7	0	45
subtotal	***17***	***11***	***19***	***16***	***27***	***10***	***100***
no response	1	0	0	3	1	0	5
total	***18***	***11***	***19***	***19***	***28***	***10***	***105***

Table 10: Student perceptions of the interactions between planets in a solar system

Table 10 shows that the respondents were fairly evenly split over whether the planets exerted a force over each other, with a small majority favouring such an interaction.

The most common type of explanation (30 instances) for why there would be any force, related to there being gravitational force, although often phrased as if the planets ‘had’ gravity (e.g., “because both have gravity so both have forces between them”). Other types of response were much less frequent, with four students simply referring to an attraction between them, but there were three references to orbits as the basis of an explanation (e.g., “Planet B’s orbit provides a force”). A couple of students suggested that the planets would repel each other (e.g. “they repel each other”), and one indicated that the attraction between the planets was somehow due to the presence of the central mass in the system (“bound by force from central mass”).

Among those students who did not think there was a force between the planets, the most common type of explanation (14 instances) was that any attraction would be to the sun (e.g. “as the force is being generated by the sun and not planets A + C”). Eight students explained that the planets would not attract each other (“e.g. “planets don’t attract”). Five commented on them being in different orbits, or too far apart (e.g., “because they are on different orbits”). Three students justified there not being any force on the basis that such a force would lead to a collision or similar event, for example the student who wrote “the planets would collide and if the force was to [sic, too] strong in the opposite repelling way then planet ‘B’ and ‘A’ would collide or ‘C’ would disappear [sic] into distant space”. Interestingly, one of the students who did not think there was any force, nonetheless explained that “they repel each other”.

Comparing responses across the two systems

Considered in isolation, these findings offer a mixed picture of the extent to which these upper secondary students understood the physical interactions in the two systems: with the proportions offering the scientifically most acceptable responses varying considerably from item to item. It is important to reiterate that findings from a modest convenience sample that cannot be considered statistically representative of the wider national population.

It should also be noted that since the data were collected, there have been changes in curriculum and assessment procedures in England (QCA, 2007a, 2007b). However, the results from these six upper secondary classes, from four different selective schools, can be seen as indicating that *teachers cannot be confident that their students have a full understanding of the physical basis of the interactions in either the solar system or the atom*.

The present paper was however motivated by a more specific focus: that being the common teaching analogy of the atom being a tiny solar system. In this context the present data is informative: as despite any limitations in the representativeness of the sample, the data does reflect *the same students responding to structurally similar questions across the two different physical systems*.

By comparing between questions 1 and 5, it is clear that these students tended to have a much better awareness of the nature of forces involved in the solar system than in the atomic system (see figure 3). The findings reiterate the suggestions from previous work that students do not readily appreciate that the interactions between components of the atomic system are basically electrical in nature. (Given this, it us perhaps not so surprising that many students do not tend to think about the interactions *between* atoms and molecules in electrical terms.)

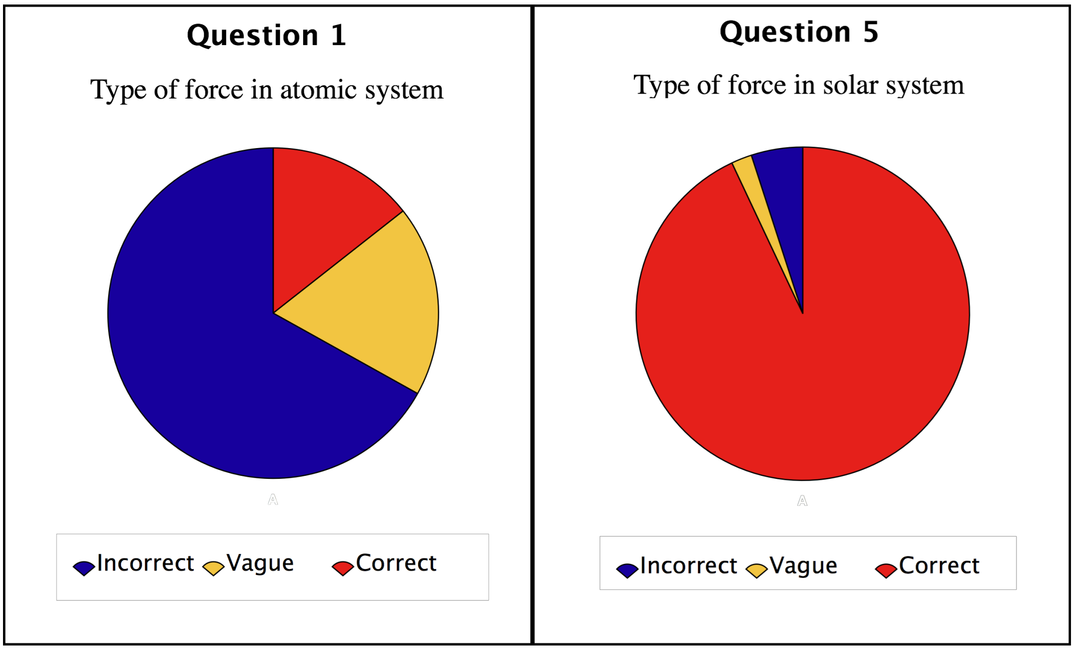

Figure 3: Students identifying type of force in the two physical systems

It is not known whether the students in the sample were themselves introduced to the atom in terms of the 'tiny solar system analogy'. However, these findings do suggest that where teachers use this teaching analogy, they should take special care to emphasise the different nature of the forces in the two systems: especially as students in the present study commonly suggested gravitational forces were at work in the atom. (There are such forces of course, but their magnitude is negligible compared with the electrical forces).

Questions 2 and 6 asked pupils about the effect of separation on the magnitude of force experienced by an electron / planet due to the nucleus / sun. Here students responded in very similar ways in terms of both systems (see figure 4), generally expecting an increase in separation to be associated with a smaller force: which is appropriate in both cases an inverse square law applies (Coulomb's law, or Newton's law of Universal Gravitation).

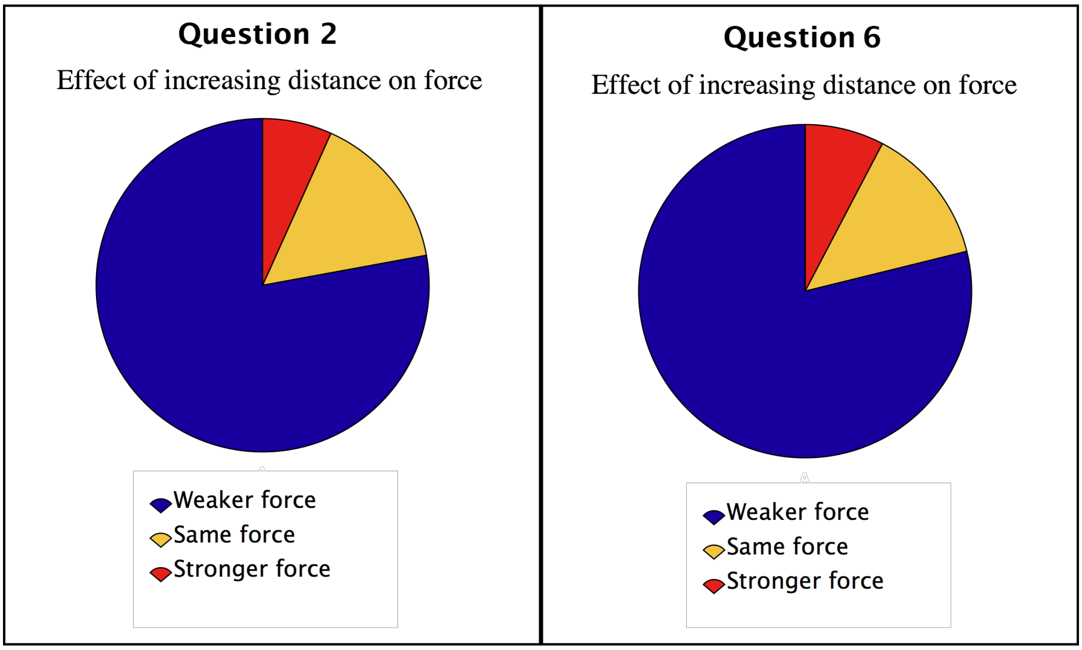

Figure 4: Students' expectations of the effect of increasing separation

Questions 3 and 6 both relate to the application of Newton's third law (N3), which tells us that forces always act between two bodies, and equally on both. Transposed to the specific question contexts, applying N3 would lead us to believe:

- the force attracting the nucleus to electron 2 (in figure 1), is equal in magnitude, opposite in direction, and acts along the line of action as the force attracting electron 2 to the nucleus
- the force attracting the sun to planet B (in figure 2) is equal in magnitude, opposite in direction, and acts along the line of action as the force attracting planet B to the sun

So the correct response in each case would the second option, i.e. that the force attracting the nucleus (or sun) to electron 2 (or planet B), is the *same size* as the force attracting electron 2 (or planet B) to the nucleus (or sun). Figure 5 offers a comparison between the responses on these two questions.

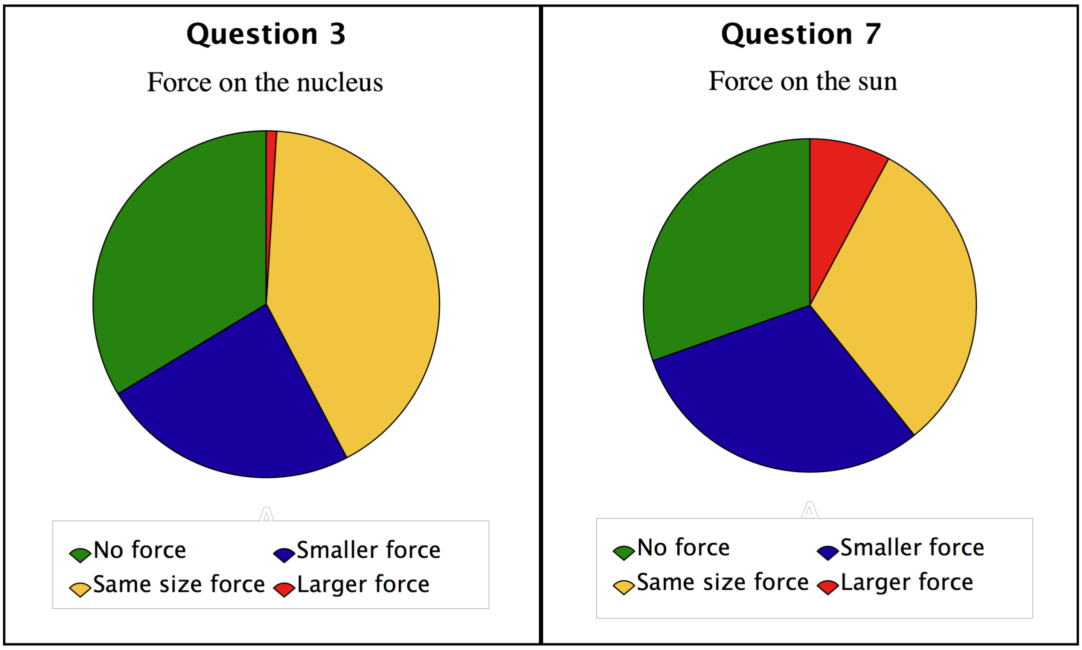

Figure 5: Students' perceptions of the 'reaction' force acting on the central body due to interaction with an orbiting body

As figure 5 shows, responses were quite spread across the response options on these two questions, so that in both questions the canonical physics response (of equal force acting) was selected by a minority of the students. The response patterns for the two systems are not precisely the same. In the case of the atomic system, the suggestion that the nucleus might be subjected to a larger force from an electron than it was exerting on the electron was only selected by one student, and the correct N3-based response attracted more support than the other options. However, in the case of the solar system, there was a greater (though still modest) frequency for the option that the sun might be subject to greater force from a planet than vice versa. However, the distribution across the other three options was nearly identical (Table 5 cf. Table 9). So in thinking about a solar system, pupils were just as likely to select one of two apparently convincing alternatives as the response reflecting accepted physics.

The suggestion that the sun, or nucleus, experiences less force than a planet, or electron would seem to reflect a common-sense idea that bigger bodies can have more effect than smaller bodies, whereas in science we distinguish the size of the force, from its effect: i.e. the same size force brings about less change in a larger body. The other popular option, along the lines that *only* the larger body has an effect, may well relate to aspects of the geometry of these two systems. In both cases the central body is considered as fixed (when considering atomic and solar systems we tend to chose such a frame of reference, although in teaching we may not always be explicit about such choices, cf. Adbo & Taber, 2009). As the sun, or nucleus, does not seem to be effected by the planet, or electron, then it might seem that no force could have been acting.

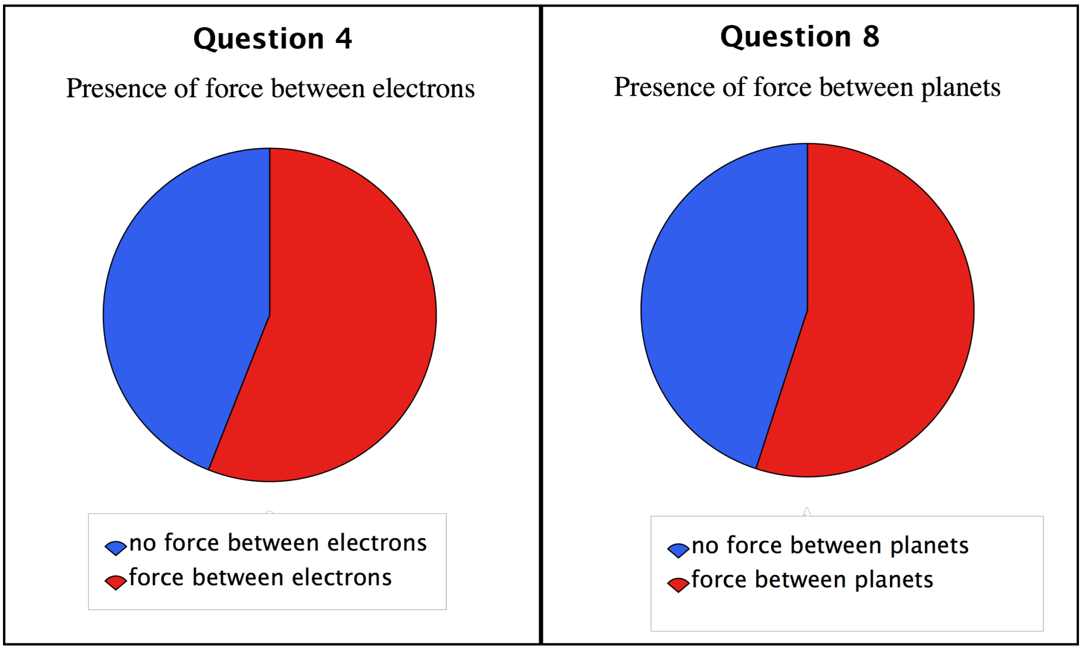

Figure 6: Students' perceptions of the whether orbiting bodies (electrons/planets) exert force on each other in the two systems

Finally, questions 4 and 8 both asked about possible interactions between the orbiting bodies in the two systems, i.e. specifically whether there would be any force between either two of the electrons, or two of the planets. The responses for these two questions are compared in figure 6.

Figure 6 suggests that among this sample of students there were very similar responses across the two systems. In both cases a slight majority of those responding did recognise there would be forces (between any two electrons in the atomic system; between any two planets in the solar system), but in each case nearly a half of respondents (44%, 45% respectively) did not think such forces would act. From the canonical physics perspective, all massive bodies are subject to gravitational force between them; and all charged bodies are subject to electrical force between them: that so many senior secondary students did not recognise that such forces would act is of some concern.

Discussion

This study has reflected upon the teaching analogy of considering the atom as like a tiny solar system, and has explored how a sample of secondary level students in England understand the physical forces in atomic and solar systems.

Key findings are that:

- although students were generally aware that solar systems were bound by gravitational forces, there was a relatively low level of awareness of the nature of the forces acting in atomic systems: with a broad range of vague and specific and incorrect suggestions being made;
- almost half of the sample did not recognise forces acting among the peripheral (orbiting) components of the systems (i.e. force between planets; force between electrons);
- although there was generally a strong recognition that forces decreased with separation of the interacting bodies, only a minority of students recognised that the same magnitude of

force acted on two interacting bodies (as per Newton's third law);

- the pattern of responses was very similar across the two systems when considering both these principles (forces decreasing with separation; equal 'action' and 'reaction' forces).

Studies reporting from samples of learners can only be considered to be statistically representative of wider populations when respondents are selected using a specified sampling frame. For example, if students can be randomly selected from the full population, then it is possible to draw inferences about the likely limits on the error that would be made in assuming the sample results can stand for the responses that would have been obtained from all members of the population. Random sampling from full populations is seldom viable in educational research, and convenience sampling, such as in the present study, is a common approach. Studies based on approaches to sampling that do not support statistical inferences strictly only report on the thinking of *the particular* study participants. However, by providing information about the data collection contexts, such studies allow readers to make judgements about the likely relevance of findings to other educational contexts, i.e. what is known as 'reader generalisation' (Kvale, 1996).

The present study presents findings from a sample of secondary students giving responses to questions with a particular wording and sequence, and highlighting symmetry across the two systems. Whether such strong similarities would have been found using very different formats of questions and representations must remain a moot point, and is worthy of further attention. The present results are based on the researcher's interpretation of student responses to a written instrument, assuming that the respondents made reasonable sense of the questions, and made serious efforts to answer the questions according to their understanding. Items were informed by previous research; and the administration of the instrument was undertaken by the students' usual classroom teachers - who were given the opportunity to comment on both the appropriateness of the instruments and any student responses to completing the probe (Taber, 2002a). These safeguards provide some assurance of the 'content validity' and 'face validity'.

However, it is well known that student thinking about scientific topics may often be nuanced, and shows considerable variation in terms of such issues as stability and commitment (Taber, 2009b). There was no attempt in this study to either test reliability in terms of a re-application of the instrument to the same learners, or to ask learners to rate their confidence in their responses. The probe was intended as part of a suite of resources that teachers could use for formative assessment within classroom teaching, to diagnose potential alternative conceptions and to provide feedback on student learning. In that context, it was suggested teachers follow-up the administration with a classroom discussion of students' ideas, highlighting the canonical responses, therefore providing participants the opportunity to benefit from their contribution to the study, and making the administration an authentic test of the potential of the probe to support teaching. It is considered that ecological validity is afforded by designing an instrument likely to fit within students' expectations of the normal range of lesson tasks, and which can be incorporated into the teacher's usual classroom practices.

Appreciating the nature of interactions in atomic systems

A very basic concept in teaching and learning about the atom, is that negatively charged electrons are attracted to a positively charged nucleus. Indeed, this idea is so basic to the atom concept that the finding that *only a minority of the sample could offer an appropriate label (such as electrical, or electromagnetic) for the type of force* involved may seem surprising. If the findings from this sample are indicative of what might be found more widely, this would be a matter of some concern. This might well be the case, as this finding is actually consistent with research into student understandings in such areas as chemical reactivity and stability, chemical bonding, and patterns in ionisation energies; where phenomena that are largely explained canonically in chemistry in terms of electrical interactions, are often considered by students in terms of alternative explanatory principles (Taber, 1998a, 2003b, 2009a). This finding is in keeping with a good deal of research evidence suggesting that learning about the submicroscopic models of atoms and molecules so central to modern science is found challenging by many students (Gilbert & Treagust, 2009).

That so many students assumed there were no interactions between planets in solar systems or electrons in atoms is again something that may seem surprising. Such ideas are needed to make sense of ideas commonly discussed in astronomy (perturbations of orbits) and especially chemistry (shapes of molecules, ionisation energies). For these students the salient idea appears to be that the electron/planet orbits the nucleus/sun because which is explained by a force from the central body – and reaction forces (acting on the central body) and interactions with other orbiting bodies have no role as part of the explanatory scheme. This is yet another reminder of just how counter-intuitive some of the most basic ideas about forces taught in school physics are to many learners (Gilbert & Zylbersztajn, 1985; Watts & Zylbersztajn, 1981), and student responses in the present study reflect comments elicited in earlier interviews (Taber, 2000) where students did not appreciate the mutual nature of forces acting on interacting bodies.

Intuitive understandings of forces

One striking feature of the study is that students in the sample saw similar patterns of force interactions in the very different systems, presumably related to their similar overall geometries (at least as represented). It is conjectured that the perceived similarity between these systems likely relates to intuitive understandings that may be applied. So diSessa has described primitive cognitive elements labelled p-prims (phenomenological primitives) that seem to be highly influential in naive physics (diSessa, 1993). These act as implicit knowledge elements, involved in 'pattern-recognition' during pre-conscious processing of sensory information. Perceptions presented to consciousness are already interpreted in terms of these intuitive understandings, which reflect general abstractions of the way the world seems to work.

A general (and often sound) principle that an influence gets weaker with greater distance may be readily acquired from experience in the world, and both focal figures may be perceived in these terms, so that despite the different perceived natures of the forces acting in the systems (table 3 cf. table 7), there is a common patterns of largely correct responses to questions 2 and 5 (see tables 4 and 8; figure 4).

However, other commonly experienced patterns may lead to other aspects of these two systems being perceived in ways at odds with canonical science. Larger bodies influence smaller ones more than vice versa; movement of a body is (in common experience) the outcome of some kind of action on that body: and this may lead to majority of respondents considering the forces acting on the larger (apparently fixed) bodies in the these two systems being either smaller than the forces acting on the mobile smaller bodies, or even being non-existent. Again, across the sample, the two systems are perceived in largely similar ways (tables 5 & 9; figure 5), with most respondents failing to select the canonical scientific responses. The distinction some students make between the force associated with a body, and how that force is experienced by another body reflects the scientific distinction between a force and its effect, but seems to parse the world, and use terms, different from the scientific model (Watts & Gilbert, 1983). A tentative interpretation here (perhaps worthy of following up on in future research) is that these students use 'force' to refer to something more akin to potential (related to the mass or charge of one body), and references to how that force is felt are akin to the field strength at the second body. The proportions of students who do not expect the peripheral bodies to interact is again very similar across systems, with almost half apparently unaware of the universal nature of gravitations or electrical interactions.

Some researchers into student ideas in science have suggested that rather than focus on where students form alterative conceptions, it may be more productive to concentrate research on those intuitive ideas that students commonly form, with a view seeing how the construction of canonical understanding may be encouraged from the commonly available starting points (Hammer, 2004; Smith, diSessa, & Roschelle, 1993). The present study would suggest that common intuition that effect diminishes with distance (something readily abstracted from a range of common experience) is readily applied in two contexts where learners have no direct experience: atomic and solar systems.

However, the present study also suggests that the common experience that when unequal bodies interact it is the larger one has greater effect, seems to act as an impediment to adopting Newton's third law. A key issue here is that students seem to *directly* associate the magnitude of force with its effect (rather than seeing it as one factor, along with mass). In this case, the student intuitions are not in themselves inappropriate, but rather are being inappropriately mapped to components of the scientific scheme, offering potential for research exploring how such intuitions may be better channeled towards a canonical understanding.

Conclusion

This study set out to investigate how a sample of students understood the forces acting within the solar system, and the analogous planetary model of the atom. What seems very clear is that despite its centrality to the teaching of the atom concepts, students seem to be largely ignorant of the electrical nature of interactions in the atom, and perhaps this needs to be emphasised much more strongly. In the English system, there is focus on teaching about simple electrical circuits early in secondary education, but often limited focus on electrostatics, and it may well be that teachers are often wrongly assuming students appreciate the significance of the charges on electrons and nuclei. Given that gravitational forces were just as likely to be mooted as electrical forces, this is one area where the teaching analogy (of the atom as being like a tiny solar system) should be used with care: with the negative aspect of the analogy here emphasised. Had the questions about the solar system been presented first, it is possible even more students might have nominated gravitational forces in the atomic system.

The poor performance of students in understanding key aspects of Coulomb's law in relation to the atom (the requirement for force between a nucleus and an electron to act equally on both; and especially the presence of forces between electrons) is consistent with research showing that students commonly fail to understand chemical phenomena and models (reactivity patterns, stability, bonding, ionisation) in terms of electrical interactions (Taber, 1998a, 2003b, 2009a). The teaching analogy has potential to reinforce alternative conceptions here: the pattern of common non-canonical responses about electrical interactions in the atom closely reflected similar non-canonical responses about gravitational interactions in solar systems.

It would clearly be useful to know how closely the findings of the present study would be reflected in other populations, especially in other educational curriculum contexts. If some of the patterns found here do indeed reflect the influence of common implicit knowledge elements (diSessa, 1993), then it would seem likely that broadly similar findings would be obtained in other national contexts.

It is not suggested here that the teaching analogy should necessarily be avoided. The teaching analogy may well be useful where students already have a good appreciation of the physical interactions in the solar system, and teaching is explicit about how these features map onto the 'planetary' model of the atom (including focusing on the differences between the systems). The diagnostic instrument discussed in this paper could be usefully administered by teachers who wish to inform their own use of the analogy by better understanding their own students' prior knowledge about the forces acting in these systems. What *is* suggested by the present study is that in teaching both of these systems, more focus is needed on the nature of the forces acting. Given the parallels found in student perceptions across these two types of system, the analogy may potentially be very useful if teachers are able to challenge the common alternative conceptions in one of these systems and then use the analogy both as a starting point for addressing the second system, and reinforcing conceptual change in the original context.

Acknowledgements: The work reported here is based upon materials developed during the Royal Society of Chemistry's Teacher Fellowship project on Challenging Chemical Misconceptions in the Classroom https://science-education-research.com/projects/challenging-misconceptions-in-the-classroom/). Thanks are due to the teachers who administered the probe, as well as the students who completed it.

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Appendix: The diagnostic instrument

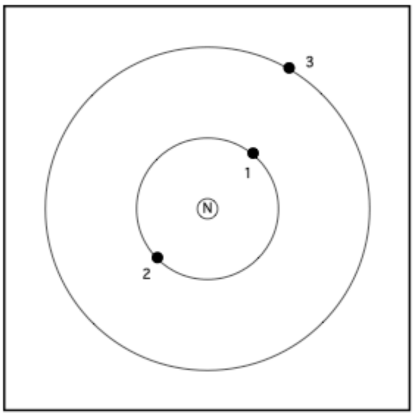
The atom and the solar system

The diagram on the right shows a simple model of an atom.

N is the nucleus, and there are three electrons, labelled 1, 2 and 3.

The electrons are attracted to the nucleus.

Below are some questions about the atom shown in the diagram.



1. What *type of force* attracts the electrons towards the nucleus?	

2. Is **electron 3** attracted to the nucleus by a *stronger* force, a *weaker* force, or the *same size* force as **electron 1**?	

Why do you think this?	

3. Which statement do you think is correct (☑) ?:

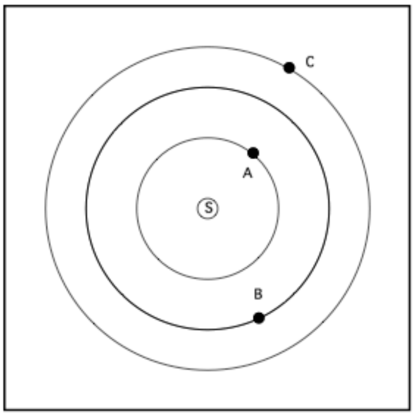
☐	the force attracting the nucleus to electron 2 is *larger* than the force attracting electron 2 to the nucleus.
☐	the force attracting the nucleus to electron 2 is the *same size* as the force attracting electron 2 to the nucleus.
☐	the force attracting the nucleus to electron 2 is the *smaller* than the force attracting electron 2 to the nucleus.
☐	there is *no force* acting on the nucleus attracting it to electron 2.

Why do you think this?	

4. Is there any force between **electron 1** and **electron 3**?	

Why do you think this?	

The atom and the solar system



The diagram on the left shows a simple model of a solar system.

S is the sun, and there are three planets, labelled A, B and C.

The planets are attracted to the sun.

Below are some questions about the solar system shown in the diagram.

5. What *type of force* attracts the planets towards the sun?	

6. Is **planet C** attracted to the sun by a *stronger* force, a *weaker* force, or the *same size* force as **planet A**?	

Why do you think this?	

7. Which statement do you think is correct (☑) ?:

☐	the force attracting the sun to planet B is *larger* than the force attracting planet B to the sun
☐	the force attracting the sun to planet B is the *same size* as the force attracting planet B to the sun
☐	the force attracting the sun to planet B is the *smaller* than the force attracting planet B to the sun
☐	there is *no force* acting on the sun attracting it to planet B

Why do you think this?	

8. Is there any force between **planet A** and **planet C**?	

Why do you think this?	