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# The atom in the chemistry curriculum: fundamental concept, teaching model or epistemological obstacle?

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by

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# Abstract:

*Research into learners' ideas about science suggests that school and college students often hold alternative conceptions about 'the atom'. This paper discusses why learners acquire ideas about atoms which are incompatible with the modern scientific understanding. It is suggested that learners' alternative ideas derive - at least in part - from the way ideas about atoms are presented in the school and college curriculum. In particular, it is argued that the atomic concept met in science education is an incoherent hybrid of historical models, and that this explains why learners commonly attribute to atoms properties (such as being the constituent particles of all substances, or of being indivisible and conserved in reactions) that more correctly belong to other entities (such as molecules or sub-atomic particles). Bachelard suggested that archaic scientific ideas act as 'epistemological obstacles', and here it is argued that anachronistic notions of the atom survive in the chemistry curriculum. These conceptual fossils encourage learners to develop an 'atomic ontology' (granting atoms 'ontological priority' in the molecular model of matter); to make the 'assumption of initial atomicity' when considering chemical reactions; and to develop an explanatory framework to rationalise chemical reactions which is based on the desirability of full electron shells. These ideas then act as impediments to the development of a modern chemical perspective on the structure of matter, and an appreciation of the nature of chemical changes at the molecular level.*

keywords: atomic theory; chemical education; epistemological obstacles; chemical ontology; teaching models

# The atom in the chemistry curriculum: fundamental concept, teaching model or epistemological obstacle?

## Introduction: the ‘problem of the atom’ in chemistry teaching.

The purpose of this paper is to explore the notion of ‘atom’ as it is met in chemical education, and particularly at upper secondary level (e.g. 14-16 years) . This is important because of the centrality of the atomic concept, both in modern chemistry *and* in school and college curricula, and because it will be suggested that the idea of the atom in chemical education is problematic. In particular, it will be argued that ‘the atom’ of school chemistry (as far as such a nebulous concept can be specified), may be a very different entity to ‘the atom of modern chemistry’ (ditto), and may *also* be significantly different from the teaching model of the atom that would be likely to be most fruitful when viewed from a pedagogic perspective.

In order to make this case, the concept of atom will be looked at from three perspectives. Firstly, in order to provide a basis for meaningful discussion, a brief vignette of the modern particle model of matter will be presented. This is *not* intended to be a thorough presentation, but rather to provide a ‘bench mark’ for what we might understand the atom to be (at a depth, say, appropriate for commencing University study of chemistry), with which other conceptions of the atom may be compared. It is offered as the ‘common ground’ (Johnson and Gott, 1996) that readers would hopefully share with the author: if we can agree on what the ‘chemical atom’ might be understood to be, then we are in a position to consider whether the ‘curricular atom’ is the same sort of ‘beast’. The presentation offered is *not* intended to be a traditional text-book presentation, but *is* intended to be scientifically valid: *i.e.* I offer a model of the atom that I consider to be consistent with the way the atom concept is used in modern chemistry.

The second perspective that is offered is that of chemical education, at secondary school and college level. The key question that will be asked here is ‘what do learners understand an atom to be?’. It will be shown that the notion of atom acquired by many learners (e.g. by age 16) is significantly different from the model of the ‘chemical atom’ offered as a benchmark, and it will further be argued that the differences can *not* be explained in terms of learners acquiring a basic conceptualisation that is evolving towards the target concept. The differences are not just matters of simplification, but of the ‘learner’s atom’ being a different type of entity to the ‘chemical atom’.

If the case for seeing the ‘learner’s atom’ as being a distinct entity to the ‘chemical atom’ is accepted, the key question becomes *why should this be?* One feasible answer might be that the atom, as presented in chemistry curricula, is *intentionally* different to the ‘chemical atom’ for sound educational reasons. In this case, it could be argued, that the ‘learner’s atom’ does not match the ‘chemical atom’, but may be much closer to the *intended* target (the ‘curricular atom’). In other words, it could be that in chemistry teaching, it is considered appropriate to teach a model of the atom which is designed to meet educational objectives, rather than be scientifically accurate. If this were the case, it should be possible to find evidence both that

(a) the model of the atom that is taught ('the curricular atom') is *substantially different* to 'the chemical atom' in ways which match 'the learner's atom'; and that

(b) this teaching approach is rationalised within the educational literature.

In this paper it will be suggested that there is some evidence that (a) is the case. There is certainly evidence from documentation such as text books, although this is not currently supported by substantial data from classroom observation as the studies have not been undertaken. However, no evidence has been found to support (b). In other words, learners seem to be deliberately taught about atoms in a way which does not match the scientific use of the idea, but this practice does not seem to derive from any explicit policy!

This would seem to present a paradox - for why should teachers deliberately teach something that is scientifically dubious *unless* there are educational reasons for doing so? One possibility, of course, is that teachers teach according to their own conceptions of the atom, which may not match 'the chemical atom' either. This may well be possible, but the suggestion that many, if not most, school and college chemistry teachers hold an alternative understanding (or 'misconception') of the atomic concept solves one mystery, at the cost of opening up a new one. The explicandum is simply moved back a generation.

In order to suggest a feasible explanation of this conundrum, a third perspective is introduced: that of historical models of the atom. It is argued in this paper that the approach to understanding the atom that is inherent in much school and college chemistry derives from historical ideas that no longer have currency in chemistry research, but which have left their imprint in the way the subject is taught and learnt. *At least some aspects of 'the learner's atom' that do not match 'the chemical atom' derive from 'the curriculum atom' being an anachronism*. Whilst this may seem a bold claim, it is little more than a recognition that the types of 'epistemological obstacles' that have been recognised as impeding the thinking of scientists (Bachelard 1968), *also* operate in science education. As teachers are further from the 'cutting edge' of science, and therefore have less opportunity to see their ideas refuted, we should not be surprised if this is the case. It will also be suggested that ideas which act as learning impediments to novice chemists can also be useful approximations for expert chemists when they can be seen as one option among alternative ways of conceptualising chemical systems. Consequently, learners and professional chemists may sometimes speak about atoms in ways which are superficially very similar, which therefore makes the problematic aspects of the learner's ideas less obvious.

## Models and generalisation.

Before proceeding to consider the issues raised above, it is appropriate to comment on two aspects of the discussion presented here. Firstly, it should be noted that all of 'the atoms' discussed in this paper are considered to be models. (The nature of these models is considered in the section on 'Teaching models and historical models' later in this paper.) There are, of course, valid philosophical questions concerning the status of ‘atoms’: whether they ‘really exist’, and if they do, to what extent we could be considered to have true knowledge of them.

Most chemistry teachers (certainly at secondary and college levels) probably consider that the atomic models they teach approximate to some extent to ‘real atoms’ that exist in nature. Without in any sense wishing to dismiss the issue, the extent to which any atomic model may, or may not, reflect ‘reality’, or even the extent to which such a statement *could* be meaningful, are not questions that are examined here.

The atoms discussed in this paper have their existence as models. This is *not* to imply that because they are Popperian world 3 objects they exist - in the sense that unicorns may be said to exist once someone has thought of them (Popper, 1979). Rather, the atomic model (or models, see below) used by scientists exists *as a tool* which is used to plan experiments, interpret results, discuss findings etc. This atomic model exists as a social construct (which has real consequences in the practice of chemical research) regardless of questions of its correspondence to ‘reality’.

In the same way, the models of the atom used in teaching have consequences for students, and the models constructed by learners have consequences when their ideas are assessed, and when they are faced with subsequent related learning tasks. This latter point is considered especially significant in view of some of the research findings that are considered below.

The second point that needs to be made is that there is no *one* model of the atom used by scientists in their work; no *one* model of the atom taught in schools and colleges; and no *one* model of the atom constructed in the minds of learners.

When I discuss ‘the chemical atom’ I am presenting *a model* (or a *meta*model?) of key aspects of the atomic models which are used in chemistry, that might be considered a suitable level of understanding on entering university study. My presentation of ‘the curricular atom’ and ‘the learner’s atom’ are generalisations to an even greater extent, intended to show key aspects from the constellations of models used by teachers and constructed by learners. It should be borne in mind in what follows that these ‘models of models’ are useful generalisations, but they necessarily ignore the wide variety of individual mental models used by individuals teaching and learning chemistry.

## The chemical atom.

Readers of this paper will doubtless hold a sophisticated understanding of the concepts of atoms and molecules. However, in order to establish our ‘benchmark’ by which to judge learners’ ideas and the models used in teaching, it is important to make explicit the level of understanding which would be expected after studying the topic in school science and then college chemistry. My discussion is ground in the U.K. education system (where learners typically follow their study of the national curriculum to age sixteen by taking a two year college level course before commencing university study), but *in broad outline* it is not tied to any particular educational system.

It seems appropriate at this point to alert readers that the presentation that follows may not represent the way that they would typically conceptualise this topic. However, the reasons for this form of presentation will be made clear, and it is certainly intended to provide a formalism that readers would recognise as technically correct, at a level of approximation that is appropriate for students at university entrance level.

A student commencing university level of study of chemistry would normally be expected to have some familiarity with the molecular model of matter from school and college level courses. In the U.K., for example, it would usually be expected that the student would already be aware of the following aspects of the particle model of matter:

(1) many substances comprise of a large number of (to a first approximation, or t.a.f.a.) identical particles, or molecules;

(2) the molecules are attracted to each other by forces, which are electrical in nature;

(3) the molecules have internal structure, being comprised of smaller particles still, which are bound together by stronger forces;

(4) these smaller particles are electrons, which have a negative electrical charge, and nuclei, which have a positive electrical charge with magnitude some multiple of the electronic charge. The forces holding the molecules together may be considered to be due to the electrical attraction between the nuclei and the electrons.

(5) The molecular structure may be described - and the molecule, and therefore the substance defined - (t.a.f.a.) in terms of the configuration of nuclei and electrons.

(6) the nuclei are further comprised (t.a.f.a.) of two types of particle: protons (each with a positive charge of equal magnitude to the electronic charge, and each having approximately two thousand times the mass of an electron) and electrically neutral neutrons (which are marginally heavier than protons). The nuclei are held together by an even stronger 'nuclear' force which counters the repulsion between the protons.

(7) Not all substances consist of discrete molecules, but these other types of substance (metals, ionic crystals, giant covalent structures) are *also* comprised of the same basic units - nuclei (containing protons and neutrons) and electrons. These structures may be considered to be made up of a repeating pattern of these units.

(8) Both molecular and non-molecular substances are (t.a.f.a.) neutral, as the nuclear charge balances the electronic charge: *i.e.* the number of electrons and protons in a sample are (t.a.f.a.) equal.

(9) The arrangement of electrons and nuclei in both molecular and non-molecular substances is usually such that *some* of the electrons may be considered (t.a.f.a.) to be associated with only one nucleus, and most of these electrons are usually in 'shells' around the nucleus. These electrons may be considered as 'core' electrons, and the nucleus and surrounding core electrons are sometimes referred to as *atomic cores*.

(10) Electrons in a structure that are not part of an atomic core are referred to as valency electrons. In some substances some valency electrons are (t.a.f.a) associated with only one atomic core ('non-bonding' or 'lone pair' electrons), but in many cases valency electrons must be considered to be associated with two or more atomic cores ('bonding' electrons) and they may be delocalised over larger parts of the structure.

(11) The simplest molecules comprise of a single nucleus with one or more ‘shells’ of electrons, but only a small number of substances are considered to have such a structure (*i.e.* the monatomic molecules of the noble gases). Most molecules have two or more atomic cores shrouded by valence electrons.

(12) A neutral system of a single nucleus with electrons is called an atom - the molecules of the noble gases are atoms.

(13) A system of a single nucleus and electrons which are (t.a.f.a.) only associated with that one nucleus, and which is charged (ie *not* neutral) is called a (simple) ion. Molecular ions consist of several atomic cores shrouded by a cloud of valence electrons such that the overall entity is charged. Many substances comprise of a repeating arrangement of two or more types of ion. The ratio of ions in such systems is such that (t.a.f.a.) the substance is neutral even though individual ions are charged.

(14) As well as molecular substances and ionic substances, two other common types of arrangements are a repeating pattern of (t.a.f.a.) identical cores embedded in a field (or ‘sea’) of delocalised electrons (*i.e.* metals); and an extensive lattice of cores with localised pairs of electrons between them (giant covalent structures).

This presentation is not very sophisticated, and it is certainly not complete. For example the existence of isotopes provides one way in which the ‘t.a.f.a. identical cores’ may *not* always be identical, and students would be expected to know something about the details of the electronic structures of cores, atoms and some molecules in terms of orbitals, energy levels and quantum numbers. This latter area provides much room for debate. For example, there are serious issues around what learners should be taught about the significance of discrete hydrogen-like electron orbitals in multi-electron systems (e.g. Scerri 1991), or the meaning of rehybridisation (Gillespie 1996). Luckily these issues do not impinge upon the central theme of this present paper, and one's position on these issues has no bearing on the thesis being mooted.

## Change and constancy in chemical systems.

What I would like to emphasise about the presentation here, which - albeit incomplete - I believe to be one which has scientific validity, is the limited role of the atom. This is the aspect of the presentation which I accept may seem idiosyncratic to some readers, as chemists may commonly conceptualise much of chemistry at the molecular level in terms of atoms. However, my argument here is that thinking in terms of atoms may be largely due to habit, and that the presentation above is valid, albeit perhaps somewhat distinctive. This argument is developed further below.

If it is possible to identify a level of 'fundamental' particles most appropriate for discussing chemistry, then I suggest that this would be at the level of protons, neutrons and electrons. Although physicists may work with 'particle zoos' at a finer grade, these three particles are fundamental enough to discuss most aspects of chemistry up to University entrance level.

Chemical structures may be understood as arrangements of these basic particles. Indeed, as was suggested in the presentation above, most chemical structures can be understood as arrangements of nuclei and electrons, or even of *cores plus electrons*. Chemical substances may be defined in terms of such arrangements, and chemical reactions may be understood as processes resulting in *reconfigurations* of systems of nuclei (or cores) and electrons. After such rearrangements there are new configurations - thus explaining how chemical change produces new substances. The cores and electrons are conserved: but the overall pattern of cores and electrons is different. The stability of the configurations may be understood in terms of the electrical charges (and the restrictions of quantum mechanics), and the changes may largely be conceptualised in terms of electrical forces during interactions between different systems.

So far this analysis does *not involve the concept of an atom* at all, but atoms appear at a slightly larger 'grain size' (see point 12 above). Atoms are *one particular type* of structure which nuclei and electrons form: others are molecules, ions, metallic and giant covalent lattices. In this approach the atom is no more basic than molecules or ions - and, indeed, is *less* commonly involved in chemical processes than molecules or ions. The 'chemical atom' is one of a number of types of structure formed from the more fundamental units.

## Elements and compounds.

Up to this point I have referred to chemical substances without distinguishing between elements and compounds. This is, of course, an important *chemical* distinction. Both are classes of pure substances in that they have the types of arrangements of nuclei (or cores) and electrons discussed above: either as repeating pattern (if non-molecular), or as a vast number of discrete versions of the same pattern (if molecular). The distinction is in terms of the types of nuclei (or cores) present. An element has only one type of nucleus (or core) t.a.f.a (*i.e.* ignoring isotopes or energy states), but arranged as part of molecules, or metallic or giant covalent lattices. A compound has more than one type of nucleus (or core) in the molecule, or as part of the repeated pattern in a (ionic or giant covalent) lattice.

It should be noted that, when discussing the distinction between elements and compounds, *the notion of an atom is not central, nor even necessary*. Of course, I accept that chemists may commonly *talk* of elements as containing one type of atom, whereas compounds consist of two or more types of atoms. Yet, despite such descriptions, the chemist *knows* that methane consists of (cores and electrons arranged as) molecules and does *not* contain discrete atoms of carbon and hydrogen, and that the sodium chloride structure is a lattice of (cores and electrons arranged as) ions and that there are no neutral atoms present. So any reference to atoms in the definitions of elements and compounds is a habit of mind rather than being scientifically accurate. It could be suggested that this is a habit which acts as a convenience due to its shorthand value, but this paper will argue that there is an alternative interpretation which should be considered. This is that chemists do not consciously chose to talk of atoms in these contexts *because* they judge that this simplifies communication, but rather that archaic terminology is retained in the chemical community *in spite of* its potential to block effective communication. This is the theme that will be explored here.

Those chemistry learners who go on to become successful chemistry students, and, eventually, chemists themselves certainly learn to use the ‘atom’ shorthand without believing there are atoms in methane or sodium chloride. However, these are the elite, and I argue here that they come to develop appropriate structural chemical models *despite* an inappropriate focus on atoms in their schooling.

## Understanding the particle model of matter.

Before students can be expected to appreciate the distinctions between atoms, ions and molecules (typically at ages 14-16) they first need to have a basic grasp of the particle model of matter (typically introduced during ages 11-14). Any specific conception of the atom takes its meaning within this context.

Contemporary chemistry, indeed much of modern science, relies heavily on a particulate model of matter. According to consensus science, matter can be understood as comprised of discrete 'particles' which exist on a scale many orders of magnitude below that which we can directly observe.

These quanta of matter have some properties which are not analogous to the properties we recognise in particles of matter which we can see (grains of salt, specks of dust etc.), and so it could be argued that to describe them by the term 'particle' either (a) *extends* the normal usage of the term, or (b) uses the label *by analogy* with the usual meaning. This may seem a laboured point, but it is well recognised in science education that learners are strongly influenced by the everyday meanings of technical terms (Watts & Gilbert, 1983). There is evidence of the difficulty in this particular case from classroom observations (Wightman et al. 1986., p.196):

> teacher: "Helen, ... is there any difference between the particles which make up the sugar lump, the sugar particles, and the particles which make up solids, liquids and gases? Is it the same kind of thing, or can you think of any differences?"
>
> Helen (secondary pupil, age c.13 years): "Same kind."

Helen later explained that "when you say that atoms are particles they must be the same" as sugar 'particles' (*i.e.* grains) as one "can't have two different sorts of particles" (p.197). It could be suggested that another term might be preferred to emphasise the distinction - quanticle has been suggested (Taber, 2002b) - but expressions like molecular *particle* or sub-atomic *particle* are in common usage.

Research into learners' ideas about the particulate nature of matter has revealed a wide range of alternative conceptions (Nussbaum and Novick, 1982; Wightman et al., 1986; Renström, Andersson and Marton, 1990; Griffiths and Preston, 1992). Certainly at lower secondary level (i.e. 11-14 years of age) it is common for learners to completely fail to appreciate the scale being discussed, and to identify the 'particles' they are being taught about in science lessons with minute, yet still macroscopic, particles such as grains of sand (as in the case of Helen, above). It is also very well known that even when school pupils accept the existence of particles of a molecular nature they often take some time to fully appreciate the significance for the nature of matter (for example believing that the particles are embedded in the substance, or that air or some other substance exists between the particles). Further, even once this aspect of the scientific perspective is acquired, learners often fail to understand the way the 'molecular' model of matter is used in explanations. They are unable to explain the properties of substances at a molar scale in terms of the *distinct* properties of the particles from which is it conjectured to be comprised. Rather, they merely transfer the properties to be explained to the particles (Taber 2001c, 2002a). For example, butter may be said by students to melt because its molecules melt, or a metal rod said to expand because its atoms have expanded; and the malleability of copper is explained by its malleable atoms! (Ben-Zvi, Bat-Sheva & Silberstein, 1986).

This material will not be examined in detail here, where our focus is more specifically on the learner's notion of 'the atom'. However, this literature is certainly of interest, because it tells us a great deal about the way that a mode of thinking that the expert chemist takes for granted, can seem so alien to the novice.

The findings briefly reviewed above represent the stage in school science learning prior to that being critiqued in this paper. They are certainly relevant, however, as the argument to be presented here, that the model of atom presented in school science may be considered pathological rather than pedagogic, will be contingent upon a view of how conceptual development occurs, i.e. that conceptual understanding evolves through a process of building upon existing knowledge (the constructivist perspective). This will be considered after the presentation of findings about learners' ideas of atoms, and a consideration of the model of atom presented in school science.

## Learners' ideas about atoms.

In view of this literature about pupil difficulties in appreciating the particle model it is not surprising that some learners find learning about atomic structure to be quite difficult and confusing. I would like to distinguish here between two classes of scientifically incorrect ideas that have been elicited from pupils.

Firstly there are learners having such a weak grasp of particle ideas that they do not appreciate the basic system of entities presented in the curriculum. This can result in students suggesting relationships between concepts which are non-sensible (Taber, 1996a). Whilst such errors should not be discounted (as they are clearly significant indicators of an inadequate understanding), they are perhaps best explained as *confusing* the labels for concepts, or having *insufficient familiarity* with the molecular level to clearly differentiate between the different concepts.

Other research reports problems that are more significant for the present thesis, and should be considered as something more than mere errors. Pupils who *have* learnt the basic structure of the atom presented in the curriculum (i.e. negative electrons in shells around the positive nucleus) may present alternative conceptions of how the sub-atomic particles interact. For example, Schmidt (personal correspondence) reports students believing that the nucleus of an atom must contain an equal number of neutrons as proton, as the neutrons had the role of neutralising the protons. This could be an example of what Schmidt has elsewhere (1991) referred to as the label as a hidden persuader: in this case that the 'neutr' of neutron referred to a kind of neutralisation process rather than being of 'neutral charge'.

It might be thought that if learners can correctly identify the charge on the three main sub-atomic particles they would not make such an assumption: but Taber's work (1997a, 1998a) suggests that learners commonly fail to apply conventional electrostatic principles in the atom. It seems that learners do not automatically relate electrostatic principles from their physics classes to their chemistry learning: but rather tend to compartmentalise their knowledge. (This could also explain how learners are comfortable considering radioactive decay in physics classes despite seeing atoms as indivisible in chemistry.)

So, some students believe that the orbiting electrons *push* on the protons in the nucleus to hold the nucleus together, overcoming the tendency of the positive protons to repel. This suggestion both ignores the difference in proton-proton and proton-electron distance (which by the inverse square law tells us that the effect on a nuclear proton due to an orbital electron should be negligible compared with repulsion between protons) *and* suggests the negative electrons repel positive protons. The nature of nuclear interactions is not usually discussed in any depth in foundation (e.g. up to age 16) courses in chemistry, and is not required knowledge for the G.C.S.E. (school leaving) examination, but some (if by no means all) students clearly feel the need to explain nuclear stability. Schmidt's students' neutralising neutrons were actually much closer to the accepted explanation than Taber's students' pushing electrons.

Taber (1997a, 1998a) also reports a related common alternative conception (labelled 'conservation of force') of how the nucleus attracts electrons. It is assumed by many students that an atomic nucleus gives rise to *a certain amount of attractive force* depending upon its charge, which is then *shared equally* among the electrons present. Thus the increase in successive ionisation enthalpies is explained because each electron removed means a bigger *share* of the attraction for the remaining electrons! At the college level (16-18 years) students are taught that the removal of an electron should lead to a greater successive ionisation energy as (i) there is one less electron in the shell to repel, so that the electrons are attracted closer to the nucleus and so attracted more strongly; and (ii) as the next electron will need to be pulled away from a species with a greater positive charge. Yet students were found to commonly offer the alternative explanation that on each ionisation the remaining electrons received *a greater share* of the attraction from the nucleus: "*there is greater attraction by the nuclear charge on the remaining electrons, so the same nuclear charge is pulling on less number of electrons*", "the same positive charge *pulling on less electrons*, so, it's *more on each electron*" (Taber, 1997a, 304-5). It may be of relevance here that Harrison and Treagust (1996) report a pupil describing the atomic nucleus as the atom's 'control centre'.

The problems outlined above apply to learning about a simple nucleus + electron shells model of atoms. Another area of difficulty is experienced when more sophisticated models of the atom are introduced post-16 (e.g. Cervellati and Perugini, 1981; Mashhadi, 1994; Cros et al., 1986; Taber 1997a, 2002b, c; Harrison & Treagust, 2000). It would seem that learning about the structure of atoms is difficult for many students.

Even more significant for present purposes is the way learners conceptualise the role of the atom in chemical structures and reactions. For example it has been found (Taber 1996, 1997a) that students commencing college level chemistry (e.g. 16 years of age) often suggested that atoms were indivisible, and "can not be broken down", and that "an atom is the smallest thing in any matter". Yet these were not learners who were ignorant of the atomic structure in terms of protons, neutrons and electrons. *No contradiction* was apparently perceived in the atom being the "smallest particle that can be found, [yet it is] made up of protons, neutrons and electrons", nor in that "an atom is the simplest structure in chemistry [yet] it contains a nucleus with protons and neutrons, and electrons moving around shells". Although aware that the atom has structure, these students were still able to consider it as being *in some sense* an indivisible and ultimate particle.

For these students the atom was the basic unit of analysis in chemistry, and was *the* 'building block' of other structures. In other words, atoms are granted 'ontological priority' when conceptualising the world in terms of particle models. Seeing an atom as *the* basic unit means that molecules are seen as combinations of atoms (*e.g.* "a group of atoms bonded together"), and ions are considered to be altered atoms (*e.g.* "an atom which has lost or gained electrons"), rather than being viewed as entities as fundamental as atoms.

Clearly this presents an alternative way of viewing chemical structures to that presented in the previous section of the paper. Rather than seeing the basic quanta of matter in terms of nuclei and electrons, these students see *atoms as the basic units*, and everything else as *made up from* atoms that have been joined together *or altered* in some way. The ontological zoo of modern chemistry that was described above was at the level of 'sub-atomic particles', but pre-university learners are found to commonly operate with an 'atomic ontology' - a notion that the matter in the world is comprised of atoms (Taber 1997a, 1998b). It will be argued below that *although* chemists may sometimes seem to use similar ideas and language *there is a significant difference* in the way expert chemists and novices apply these ideas.

It is suggested here that this difference in perspective is not simply of academic interest. Rather, evidence suggests that holding such an 'atomic ontology' has consequences for learning about aspect of chemistry.

As was pointed out above, these students who believe that the atom is the basic quantum of matter are *not* ignorant of subatomic particles, and will readily describe how electrons are ‘shared’, ‘donated’ or ‘accepted’ in chemical processes. Yet in order to fit such knowledge with their atomic ontologies they consider that electrons *belong* to specific atoms. This is where we start to see the consequences of this way of conceptualising matter, as well as the anthropomorphic language commonly used to communicate it (Taber 1997a; Taber & Watts 1996).

In a covalent bond between two atoms the two ‘shared’ electrons may not be seen by learners as being equivalent - as they (still) belong to different atoms. (For these learners the distinct atoms still exist in the molecule.) Some students may actually believe this makes a difference to the magnitude of forces between the electrons and nuclei - as an atom is expected to attract ‘its own’ electron more strongly. On bond fission the electrons are believed to return to their own atoms. (This belief can then interfere with the learner accepting that bond fission may be heterolytic, as *only* a homolytic fission allows the atoms to get their own electrons back).

This is not the only way that an atomic ontology has consequences for the way students understand chemistry. It is commonly believed that ionic bonds only form between atoms where an electron has been transferred. As the anion has an electron ‘belonging’ to the cation there is considered to be some form of link between them. This is identified as being the ionic bond, and it leads to learners believing that there are two types of interactions in an ionic lattice: ionic bonds (between ion pairs where transfer has occurred) and ‘just forces’ between ions not having been involved in the electron transfers (Taber 1994, 1997a, 1997b). Some students go as far as to suggest that the transferred electrons will return to their 'owners' (*i.e.* the original atoms) before the ions can be involved in reactions (Taber 1997a, 2002a).

The influence of the atomic ontology is even more obvious when learners are asked to explain *why* chemical reactions occur. Because they perceive chemistry in terms of atoms, *students commonly make 'an assumption of initial atomicity'* when discussing chemical processes (Taber 1997a, 1998b). If students are asked to explain why sodium reacts with chlorine, or hydrogen with fluorine, they will very commonly present an argument that is based on the 'needs' of the *atoms* of sodium and chlorine, or hydrogen and fluorine, to obtain octets or full shells of electrons. This tendency to think in terms of atoms is so strong that even if the question is accompanied by formulae (such as $H_2$ and $F_2$) and diagrams showing the *molecular* structures of reactants, most students' answers are still couched in terms of why the separate atoms would 'want' to react (Taber 2000a, 2002a). One teacher who set a classroom probe asking *why hydrogen and fluorine react* to a group of 16-17 year olds observed (after seeing the students' responses) how it: "shows clearly how wedded they are to 'happy' atoms" (teacher feedback during a Royal Society of Chemistry project, see Taber 2002a).

This research into learners' thinking shows that for many students notions of *atoms as building blocks* and electrons as *belonging to atoms* were more than just metaphorical. Students commonly take the 'everything is made of atoms' notion as both fundamental and literally true in chemistry. They then think about chemical structures and chemical processes from this starting point. Because students make the assumption of initial atomicity when they think about chemical reactions, subsequent learning about the role of bond enthalpies and entropy in determining the feasibility of reactions may not be effective. As in the case of learning the curriculum explanations of patterns of ionisation energies (see above), teachers often find that students soon revert to explaining reactions in terms of the needs of discrete reactant atoms looking to fill their electron shells!

## The atom in the curriculum.

Given this evidence that many learners develop a way of thinking about the atomic nature of matter which is at odds with modern chemical thought, and which impedes effective learning of chemical principles, it is natural to ask how this comes about. It has been suggested that although some alternative conceptions derive largely from pre-school and out of school experience, others may be at least partly due to the way material is presented in class (Taber 2001a, submitted). Therefore it is appropriate to explore the extent to which learners' common misconceptions about these topics reflect the teaching they have received.

It is not possible to present a thorough discussion of this topic as more research is needed into the ways that teachers transform knowledge in the classroom. Such research would be complicated by the contingent nature of an individual's learning processes. Whenever students learn from a lesson they are interpreting their current experience through their cognitive apparatus and - in particular - their existing conceptual frameworks. This existing cognitive structure reflects prior learning based *not only* on formal teaching but also other aspects of the individual's prior experiences (Taber 2000e) . So any attempts to interpret classroom learning have to focus at least as much on the way teaching is interpreted by learners as on the *intentions* of the teachers.

One relevant report of classroom practice that is in the literature concerns a teacher introducing learners to the use of particle ideas (Wightman et al., 1986). Some of the pupils in the class of 13-14 year olds already knew the terms ‘ atoms’ and ‘molecules’. When one student referred to ‘molecules’ when reporting back on a group discussion, the teacher asked “can I write ‘atoms’ [on the board] instead of ‘molecules’ - cos it’s shorter?” (p.195). One of the pupils in the group was not satisfied with this, and suggested that atoms and molecules were “not always the same thing”, but the teacher decided “we’ll say that the common name is ‘atoms’, for the sake of argument”. Later in the sequence of lessons this teacher “conjured up an image of diffusion in solutions by referring to blue copper sulphate ‘atoms’, and colourless water ‘atoms’ wriggling slowly past each other at the junction of the two layers” (p.217); and referred to how in a liquid “the atoms [sic] are free to slide past each other”, and how in a gas “atoms [sic] are not bonded together” (Wightman et al., 1986, p.224.)

Teachers commonly follow schemes of work, which are themselves often informed and constrained by national or regional curricula and/or examination syllabuses. Such schemes and syllabuses provide evidence of the formal aspects of the curriculum, but each teacher will interpret these documents in the light of their own scientific subject knowledge, professional pedagogic knowledge, and their personal evaluation of the readiness of students to take on the new ideas (Taber 2000b).

It is clearly no surprise that students do not form scientific ideas which match cutting edge chemistry: scientists' science is distilled by committees into curriculum science which is interpreted through first the teachers' own conceptual frameworks and then through learners' existing ideas (Gilbert, Osborne & Fensham, 1982).

Yet it is possible to consider some evidence which may provide useful indications. Interviews with students about their ideas relating to atoms and bonding have found that they considered their ideas in these topics to be what they have been taught in formal science classes (Fleming, 1994). This in itself is not strong evidence, as clearly learners are unlikely to be aware when they misinterpret their teachers. However it is interesting that in one case study (Taber 1997a, 2000c, 2001b) a student strongly claimed that ideas that had been emphasised at school (up to age 16), and which he had duly learnt, were making it more difficult for him to make sense of the material he was meeting in a college course.

The chemistry sections of the National Curriculum for England (DfEE/QCA, 1999) contain a number of statements which can be considered to reflect an atomic ontology. For example, at lower secondary level ('key stage 3', *i.e.* 11-14 years of age), "pupils should be taught...that *the elements are shown in the periodic table and consist of atoms*, which can be represented by symbols" (p.32). Schmidt (1998) has pointed out how periodic tables often present a hybrid of properties of the elements, and of their atoms (cf. Scerri, 1997).

Although pupils should also be taught "how the particle theory of matter can be used to explain the properties of solids, liquids and gases, including changes of state, gas pressure and diffusion" (DfEE/QCA, 1999, p.32), there is no explicit use of the word molecule.

This may reflect a common practice to keep ideas simple at this stage and avoid confusing learners by expecting them to appreciate the differences between molecules, ions etc. (as in the classroom episode discussed above). However, the outcome of such a policy is often to use the term 'atom' generically to mean 'particle', when it is not always appropriate. Wightman's observations of secondary classes being introduced to particle ideas included details of a circus of simple 'experiments' which pupils were required to "explain in terms of atoms" (Wightman et al., 1986, pp.246-8). Among the phenomena to be explained *in terms of atoms* were diffusion of a dye, Brownian motion, the increase in volume of a coloured solution on warming, the different shapes of crystals and the difference in compressibility of air and water.

'Benchmarks' recommended in the United States by the American Association for the Advancement of Science, suggest that "by the end of the 8th grade, students should know that all matter is made up of atoms, .... Atoms may stick together in well-defined molecules or may be packed together in large arrays. Different arrangements of atoms into groups compose all substances" (AAAS, 1993, section 4D). This set of recommendations also refers to molecules, but clearly gives priority to the concept of the atom.

At the upper secondary level ('key stage 4', i.e ages 14-16) of the English curriculum there are a number of statements which, whilst quite vague, also lend themselves to interpretation in terms of the ‘atomic ontology’. Pupils at this age are to be taught “that new substances are formed when atoms combine” (DfEE/QCA, 1999, p.51). There are very few chemical reactions where the reactants are atomic. In order to illustrate this curriculum principle either the reactants must be (a) assumed to be in the form of discrete atoms, or (b) considered to be made up of atoms which are rearranged in the reaction. As we have seen above, learners do tend to see molecules as comprised of atoms, and to imagine *chemical reactions always start with atoms*.

These pupils should also be taught “that chemical bonding can be explained in terms of the transfer or sharing of electrons” (ibid.), and a similar requirement is found in the U.S. ‘benchmarks’: “by the end of the 12th grade, students should know that ... atoms form bonds to other atoms by transferring or sharing electrons” (AAAS, 1993, section 4D). We have seen that pupils often consider this ‘sharing’ of covalent bonding as being akin to a temporary social arrangement. More significantly, it is difficult to see how *bonding* can be explained in terms of transfer of electrons at this level. Learners commonly see the ionic bond as the transfer of electrons (rather than the attractions between positive and negative ions in a lattice), but this is not a helpful image. For example, if the pupils prepared sodium chloride by neutralisation, followed by evaporation of the solution (the most likely classroom preparation), they would obtain an ionic product. There has been no electron transfer in this reaction - certainly not between sodium and chlorine atoms (Taber, 2002a). Even if the pupils observed binary synthesis from the elements, the reactants would not be in the form of discrete atoms.

Another (mis)leading statement in the English curriculum is that pupils should be taught “how the reactions of elements depend on the arrangement of electrons in their atoms” (DfEE/QCA, 1999, p.51). Presumably this rather bland statement (“the reactions of elements”) is intended to refer to the stoichiometry of the reactions, rather than any other aspect. It is difficult to appreciate which other features of the reactions between iron and chlorine, or hydrogen and oxygen, school pupils are expected to deduce from atomic electronic arrangements. In terms of our current concern, it is clear that this statement could lead to an excessive emphasis on the electronic configuration *of atoms*, even though most elements are normally found as metals, or are molecular, and do not have the *atomic* electronic structures.

Common students’ explanations of reactions in terms of atoms ‘trying’ to obtain octets or full outer shells (Taber 1997a, 1998b) do not seem so surprising in such a context. Although the same U.K. curriculum does refer to how “giant ionic lattices are held together by the attraction between oppositely charged ions” (ibid.) this is not explicitly linked to ionic bonding. (This is reflected in the research findings showing that students often thought there was ionic bonding *and* electrostatic attraction acting in ionic structures: but the former was limited to those species with a history of being involved in an electron transfer). There is no attempt in the curriculum to relate covalent bonding to electrical forces: these bonds are just “formed when atoms share electrons” (ibid.). In this context it is no wonder that bonding is explained by students in anthropomorphic terms of what the atom ‘needs’, rather than through physical interactions.

If the evidence from the curriculum document is indirect, more telling evidence comes from school textbooks. Such books are often written by current or former teachers, and (in the U.K.) are often selected and procured by teachers. Such books have been found to contain text and diagrams which imply, or even state, that chemical reactions occur between individual atoms which need to obtain further electrons (Taber 1997a, 2002a). For example it is common for students who are asked to represent ionic bonding to draw an electron being transferred from a single sodium atom to a single chlorine atom. Similar diagrams were found in textbooks available in the U.K. Other diagrams showed covalent molecules being formed from separate atoms - for example methane being formed from a single carbon atom, and four hydrogen atoms (not two molecules!).

Another convention commonly used in texts books is ‘dot and cross’ diagrams. These figures distinguish electrons in molecules by using different symbols (*e.g.* • and ×). The different symbols indicate electrons that (are considered to have) originated in different atoms. Presumably this is considered to be a useful aid to electronic ‘book-keeping’, helping students check that the total number of electrons has been conserved during the formation of a molecule. In real chemical processes, of course, the ‘origin’ of specific electrons is often uncertain (if not indeterminate), and is usually irrelevant. Yet this mode of representation reinforces the notion that the bonding electrons in a molecule still ‘belong’ to a specific atom: indeed many students believe this is precisely what the different symbols are meant to imply. It is hardly surprising that each electron in a molecule is considered to be part of a specific atom when it is ‘coded’ in this way.

Definitions from text books also often reflect an atomic ontology. Some text book definitions of the atom available to learners are vague (the "smallest possible amount of an element", OSP, 1993); virtually meaningless ("the smallest particles that can be obtained by chemical means", Morris, 1991, p.264); or simply wrong ("the smallest particle of an element that still shows the chemical properties of the element", Gadd & Gurr, 1994, p.16).

Although I am selecting most of my examples from the U.K. context with which I am most familiar, the phenomenon is more widespread. One established American chemistry text defines the atom as "the smallest portion of an element that retains all of the properties of the element" (Sackheim & Lehman, 1994, p.27). I would suggest this rather obviously false claim is unlikely to be a typographical error, or an oversight, as I am quoting from the 7th Edition of the book.

Definitions of the molecule commonly present it as a group or assembly of atoms (*e.g.* OSP, 1993; Morris, 1991, p.265.; Gadd & Gurr, 1994, p.42). It would seem from the evidence available that learners' ideas about atoms may often largely reflect the way the atoms are presented in their education: as the fundamental units of matter from which all chemical structures are made, and which are the reacting entities in chemical processes.

## Distinguishing the use of the atomic ontology by the novice and the expert chemist.

From what has been presented so far it would seem that the model of matter at the level of atoms and molecules presented and learnt in school is significantly different from that presented earlier in this paper as the current scientific particle model of matter. However, it might be argued that although the formulation of the modern scientific model presented near the beginning of this paper is *technically* valid, it does not reflect the way that chemists actually think and talk. This was alluded to above: chemists do sometimes refer to everything being made of atoms, and talk and write as if atoms are the conserved entities in chemical reactions.

Consider, for example, the case of nucleophilic substitution. We may say, for example, that a chlorine *atom* substitutes for a bromine *atom* in a halogenoalkane. In practice the reactant species may be a chloride ion and the ‘leaving group’ a bromide ion. One more electron has actually been replaced than is suggested by describing the process in terms of substitution of atoms. However the expert chemist knows that this difference is not significant in this case: this ‘extra’ electron was located in a molecular orbital, and has been replaced by an effectively identical electron located in a similar (though not identical) molecular orbital. The shorthand talk of substituting atoms creates no complications *for expert chemists*.

Similarly the habit of conceptualising stable molecules as atoms overlapping their valence shells to have two (hydrogen) or eight (carbon, nitrogen, oxygen) electrons can be a useful approximation: particularly in organic chemistry where most structures of interest readily fit this pattern. This approach, based on the notion of the

Lewis model of the atom, provides a useful way of describing and communicating much important chemistry. So if chemists use these habits of mind to think about, and talk about, their subject, then it might be suggested that I am wrong to claim that pupils and students are using an inappropriate model.

Furthermore, the curriculum statements in English and the U.S. documents criticised above were prepared in consultation with representatives of the chemical profession. These statements about how *elements consist of atoms* and *all matter is made up of atoms* were apparently acceptable to the advisors of the English Curriculum and Qualifications Authority and the authors of the U.S. Project 2061.

Despite this, I suggest that there is a very significant difference between an expert chemist who is familiar with a series of atomic models (based on wave-mechanics, and orbital approximations etc.) of varying sophistication, and who in certain situations feels it is acceptable and appropriate to talk of atoms *in* molecules, and a novice struggling to make sense of molecular ideas who is *only* able to conceptualise a molecule as a group of overlapping atoms.

It is useful to think of the models of chemistry as a set of mental tools from which the chemist can select according to the needs of the job (e.g. Taber, 1995a). Coll's work shows that even when graduates have available sophisticated chemical concepts they will often use simple school-level models when these seem to work (Taber & Coll, in press). Coll further found that recent chemistry graduates had not developed full competence in working with multiple mental models.

This finding is consistent with work which explores the ‘stages’ at which different thinking skills are acquired. According to research based on the Piagetian model much of upper secondary school science (e.g. 14-16 years) is at too high a level of abstraction for many of the students who would not be classed as having fully attained the ‘formal operational stage’ (Shayer & Adey, 1981). Yet the level at which graduate chemists work, operating with multiple models, requires an even more mature conceptualisation that has been characterised as ‘a fifth stage’ (beyond the four main stages discussed by Piaget) or post-formal operations (Arlin, 1975; Kramer, 1983). Taber has produced evidence from a case study that suggests some (16-18 year old) students may be able to operate with ‘manifold conceptions’ seen as alternative stories from which to choose in particular contexts (2000c, see also Harrison & Treagust, 2000; Petri & Niedderer, 1998), but it seems likely that the multiple models of chemical theory creates difficulties for many students at college level (Finster, 1989).

To summarise, expert chemists may well sometimes operate with an atomic ontology when this seems appropriate, when they know (consciously, or tacitly) that this is *an approximation* which can be applied without difficulty (providing they are communicating with other expert chemists): however, for school-age learners the atomic ontology is their only available model, and leads to their later misunderstanding the nature of bond fission, ionic bonding, why reactions occur, etc.

It is not that upper secondary school pupils (e.g. 14-16 years olds) *sometimes select* to use the ‘everything is made from atoms’ approximation as an alternative to the modern molecular model presented at the start of this paper: rather they are only presented with a picture of the atom as the basic chemical entity which composes all structures (even though it clearly does not), and which is the reacting species in all chemical reactions (which it clearly is not). This asks to be explained.

## Teaching models and historical models.

One feasible explanation would be that this abstract area of science has been deliberately re-modelled to provide curriculum fare which learners are better able to make sense of. In other words, teachers and curriculum developers may have intentionally produced an alternative model suitable for learning, based on sound pedagogic reasoning. This would be reasonable in view of the evidence that some chemical concepts are too abstract for many upper secondary level (i.e. 14-16 year old) pupils (Shayer & Adey, 1981), and research suggesting that many pupils of this age do not appreciate the nature of science as a model/theory building enterprise (Driver et al., 1996, Grosslight et al., 1991), let alone have the maturity to work with multiple models (Finster, 1989).

The constructivist perspective on learning (e.g. Taber 2000e) has been very influential in science education, and this approach accepts the need to develop learners' ideas over extended periods. There is some evidence that it is more important that learners have some relevant ideas to develop, than that their early scientific ideas are technically accurate (Novak & Musonda, 1991). Clearly learners can go on to form acceptable scientific ideas after having demonstrated alternative conceptions in areas such as particles (e.g. Johnson, 1998a, b; Renström et al., 1990). It is also recognised that when teaching abstract and unfamiliar ideas, it is important for the teacher to find some way to ‘anchor’ the new knowledge among existing ideas using metaphors or analogies (e.g. Taber 2002a).

Yet it is also known that some ‘alternative’ conceptions may be very resistant to change (Chi et al., 1994; Garnett et al., 1995), and teachers may have to work very hard to persuade learners to change some ideas once they become fixed (Hewson & Hewson, 1984; Nersessian, 1992; Posner et al., 1982; Smith et al., 1993; Strike & Posner, 1985, 1992). The alternative conceptions about atoms and chemical change that many 16 year olds take into their study of chemistry at college level (e.g. 16-18 years) tend to be of this type (Taber 1998b, 1999).

It is important, therefore, that when the teacher offers introductory analogies to a topic, or simplifies complex ideas for learners, they have designed presentations that are a suitable foundation for further conceptual development, rather than limited ideas with the potential to become entrenched impediments to progression (Taber 2000d, submitted). It could be suggested that the model of the atom presented in the upper secondary school curriculum has been designed with these principles in mind: an introductory model suitable for development. If this is the case we would expect to find the justification within the educational literature.

Now there is indeed evidence within the research literature of how the atom is presented in the classroom. This literature does not, however, suggest that the concept of atom that we find in the curriculum has been engineered through careful educational design. Rather, it is suggested that the atom concept that is presented is a confused amalgam of historical models.

Gilbert and co-workers (Gilbert, 1998; Gilbert et al., 1998) present a typology of models with five main classes. Individuals form personal ‘mental’ models, which become available to others when they are ‘expressed’ (for example in scientific publications). In science some of these models become developed into ‘consensus’ models that are widely accepted as useful research (and thinking) tools by workers in the field. As the field develops new consensus models arise, and those that previously held this status become ‘historical’ models.

‘Teaching’ models or ‘curricular’ models are designed to be used for educational, rather than research, purposes and so will not fully reflect current consensus models. Rather, they will be suitably *simplified versions* of historical or current consensus models. However, Gilbert (1998) suggests, a valid teaching model must be designed so that it leads towards the current consensus model(s) used in the field. In other words, a teaching model may be designed to encourage learners’ thinking along an appropriate ‘conceptual trajectory’ (Driver et al., 1994, p.85) towards a more sophisticated level of scientific understanding.

Justi and Gilbert (2000) have described a sequence of historical models of the atom: ancient Greek; Dalton; Thomson (embedded mass); Rutherford (nuclear); Bohr (orbit) and quantum-mechanical. For Justi and Gilbert these represent distinct models which had currency at some time in the development of atomic theory. Each of the modern chemical models (*i.e.* from Dalton on) played a role in research - in designing experiments and interpreting data - without necessarily being viewed as an ultimate model of the structure of matter. For example, the Bohr model was recognised as having problematic aspects, being described a ‘a kind of mermaid’ (Niaz, 1998) due to its perceived lack of coherence. Yet, this model was still recognised as having heuristic value to the research community.

When Justi and Gilbert (2000) attempted to identify the curriculum models presented through text books they found that such books commonly presented composite pictures that did not reflect the key features of particular historical models, but rather confused hybrids. Gilbert has been quite critical of this practice,

> “What should not happen, but which often does, is that a ‘hybrid’ model composed of elements of several discrete models, is constructed and taught. Such an approach renders the topic ahistorical, so that it has no relation to the past, present, or future, of science *per se*...”
>
> (Gilbert, 1998, p.163).

If Gilbert’s comments seem hard, it should be borne in mind that research into learners’ understandings of the nature of science has found that learners’ appreciation of the roles that theories and models take in the scientific process is often very limited (Driver et al., 1996; Grosslight et al., 1991). Justi and Gilbert (2000) suggest that the conflation of distinct historical models in the curriculum undermines the potential to use a sequence of historical models to help learners understand about the role of models in science, and the nature of ‘progression’ in science.

It would certainly seem that the model of the atom that is presented in the curriculum is *not* an entity that has been carefully designed for pedagogic purposes. It will be suggested below that it is better characterised as a confused mishmash of features from distinct historical models.

## Bachelard’s notion of epistemological obstacles.

Although not all philosophers of science would accept the notion of ‘progress’ in science as unproblematic, the French philosopher Bachelard (1968: 17) described scientific progress as the “one form of progress which is beyond argument”. Bachelard had taught chemistry and physics in secondary schools, and was very aware that his pupils entered the class with pre-conceived ideas that, he believed, needed to be demolished before effective learning could occur (Souque, 1988; Goldhammer, 1984, p.xxiv). Today we would refer to these ideas as ‘alternative conceptions’ or ‘alternative frameworks’ (Taber 1999), but Bachelard used the term ‘epistemological obstacles’ for his learners’ alternative ideas.

Bachelard was aware that such obstacles could take a number of forms (Souque, 1988), some of which seemed to be largely due to intuitive responses to experience. Other forms of obstacle related to the way we learn through culture - the verbal labels and analogies and metaphors by which ideas are communicated.

Of particular relevance here is Bachelard’s notion that the practising scientist did not hold a unitary coherent version of a scientific concept such as ‘mass’, but rather held a multifaceted version which could be described through an *epistemological profile*. Bachelard believed that although the concepts of formal public science progressed over time, *in practice* individual scientists did not exclusively apply the most sophisticated version of the concept (something reflected in Coll’s recent work referred to above). Rather the concept in the mind of the individual included aspects of the various historical versions, something Bachelard described as "…this plurality of meanings attached to one and the same concept…" (Bachelard, 1968: 21).

Certainly this view has support from a number of areas. Thagard (1992) has suggested that before scientists who are strongly committed to one scientific theory can be persuaded to shift to a new approach they must develop a mental model of the new ideas - a lengthy process during which their existing conceptual frameworks for understanding the concept area remain intact.

Research into the learning of science also supports a view that our scientific conceptualisations may often be best understood as manifold conceptions (Taber 1995b, 2000c, 2001b) and Mortimer (1995) has applied Bachelard's notion of an epistemological profile to the conceptual development of students. However, as suggested above, school pupils and college students are not necessarily equipped to appreciate the nature of, or effectively operate with, multiple models. Indeed, where younger learners (e.g. 11-14 years) have been found to hold more than one concept of a concept such as energy it has been suggested that these different versions seem to be stored and applied in different domains - so the pupil uses one set of ideas in the classroom and another in the playground without apparently having metacognitive awareness or control over the selection (Claxton, 1993; Solomon, 1992).

For Bachelard the *epistemological profile* represents evidence of *epistemological obstacles*, that have acted historically, as the profile "bears the marks of the obstacles which a culture has had to surmount" (p.43). Bachelard perceived this in terms of a stage theory: all fields of science would pass through the same sequence of philosophical positions in their historical development - although at any one time some would be more advanced (or show greater ‘philosophical maturity’) than others. He thought that the earlier philosophical positions acted as obstacles to progress (p.37).

There may be a case for following through Bachelard’s specific ‘stage’ theory of scientific progress - perhaps asking to what extent the chemist’s atom shows less philosophical maturity than the physicist’s atom. (In 1940 Bachelard (1968: 44) characterised chemistry as being “the elected domain of realists, of materialists, of anti-metaphysicians”!) However, here I wish to draw on the more general thrust of Bachelard’s ideas.

From a Bachelardian perspective, the various models of matter that scientists have used will have each left their imprint in (scientific) culture, and - unless this is addressed - will act as epistemological obstacles,

> “the prehistory of science (even its mythology), to the extent that it persisted in the structure of the human mind, needed to be exorcised - the Aristotelian, the Euclidian, the Newtonian, even the criticist spirit of Kant, leave structural layers in the human mind akin to the geological strata of the earth, and we need knowledge about these layers, self-knowledge and self-correction, before we can proceed.”
>
> (Waterston, 1968, p.xi.)

## Discussion.

It is my contention in this paper that the apparent mismatch between the curricular atom and the modern chemical notion of the atom derives, at least in a large part, from epistemological obstacles of the type Bachelard described. The conception of the atom that learners acquire during school teaching is not a deliberate pedagogic invention designed to ease their learning about an abstract scientific notion. Rather, it is the outcome of fossilised thinking: ways of conceiving matter which were once fruitful for the progress of chemical science, and which may still be useful in some areas of chemical practice, but which act as barriers to learners trying to make sense of key areas of the subject. A number of the features of learners' thinking about atoms reflect aspects of historical models (e.g. Brock, 1982; Hudson, 1992).

It is not appropriate to refer to 'the' [single] ancient Greek model of the atom, but the version according to Democritus (and Leucippos) seems of particular relevance to this discussion. This ancient idea of the atom was (by definition) something indivisible, and for Democritus atoms were conserved during (what we would call) chemical change. New materials resulted from the rearrangement of atoms. Over twenty four centuries later, what *we now call atoms* can be 'split' and are not conserved as discrete entities in chemical processes - and yet learners still develop a conception of atoms which retain these features. The literal meaning of 'atom' has become a dead metaphor - i.e. the original meaning of the term has been lost as the modern theoretical entity called an atom has been constructed. Yet students develop a concept of the atom that - if not strictly indivisible - only 'lends' out its component parts (i.e. electrons) on a temporary basis. Molecules and ions are seen as transitory arrangements through which the atom may pass, before returning to its 'natural' state

(Watts & Taber, 1996) with its original set of electrons. For Democritus all substances were composed of atoms, and modern learners acquire the same belief.

Of course it might be appropriate to argue that the Democritus model is actually still quite valid, *as long as we use the term atom to refer to the nuclei and electrons* from which all materials are made, and which are conserved and rearranged in chemical processes. From this perspective we are not applying the term ‘atom’ at the most appropriate level of structure.

A similar point could be made about atoms in Dalton’s system. Lavoisier pragmatically defined elements in terms of being substances which had not (yet) been decomposed, and suggested that each element was composed of a distinct sort of atom. Dalton built on this, but his original table of atomic weights referred to ultimate particles rather than atoms. When he adopted the term atom, Dalton suggested that simple elements comprised of single atoms, and compounds of compound atoms (Hudson, 1992, p.81). The notion of the atom used here is not distinguished from molecules in the sense of modern usage.

Whereas Dalton’s system labelled the particles of gaseous elements, such as nitrogen, chlorine or hydrogen, as atoms, this did not mean they were universally accepted as *atomos* (indivisible). Avogadro believed the particles of these gases could split when involved in chemical reactions. He described the particles of these gases as ‘constituent molecules’ and thought they comprised of two ‘elementary molecules’ or ‘half molecules’ (i.e. ‘atoms’). Again we see that the terms atom and molecule had not found their modern usage.

The way in which the bestiary of atoms and molecules being suggested was moving away from the original notion of a simpler underlying pattern can be seen in Prout's hypothesis of 1816: that all these particles were comprised from a more fundamental prototype matter ('*prote hyle*'), which was identified as hydrogen. It later became apparent that it was not possible to explain all the particles as multiples of hydrogen - but the modern perspective does allow us to explain all substances as being fundamentally made up of a small number of basic types of particle: at the level of electrons, protons and neutrons.

Contemporary learners, in schools and colleges, cling on to a number of historically well established ideas. They believe that all matter is made of the same basic building blocks; that different substances reflect different arrangements of the basic units, and that these blocks are conserved but rearranged in chemical reactions. These ideas are ancient, and have been key notions in the development of the subject. It could be strongly suggested that these ideas are not incorrect: but that they are misapplied by selecting the atom as the basic elementary particle. This, however, is a mis-identification which is contingent upon the history of chemistry.

For the founders of modern chemistry the molecules of elements may well have seemed well described by the Greek term atom: but we now know that the atoms of ancient Greece would be better identified with the sub-atomic particles. Unfortunately the modern meaning of atom learnt by students today is an unfortunate combination of the properties of the molecules of elements, and those of sub-atomic particles, applied to an entity which has much less chemical significance - a neutral mono-nuclear configuration of sub-atomic particles which is only usually found in substances which are largely chemically inert. This model of the atom is a hybrid model (Justi & Gilbert, 2000) of the *worst* sort: it is confused from both historical and scientific criteria.

*Perhaps* this ‘atomic ontology’ is harmless for those pupils who chose not to study science further, for it will at least leave them with an ‘explanatory story’ of the particle nature of matter that will help them as citizens make some sense of media reports of technology (cf. Millar & Osborne, 1998). Perhaps, but more research would be needed to know if this is indeed the case.

Whatever the value of these ideas to the majority, they do not seem to serve the ‘elite’ very well. Evidence shows that when school-leavers (e.g. 16 years old) enrol as students for college courses to study chemistry further for university entrance, they have many difficulties understanding key aspects of the curriculum. So, for example, the assumption of initial atomicity leads to students commonly explaining reactions in terms of the needs of atoms even when these ideas are totally inapplicable (for example, when molecular hydrogen reacts with molecular chlorine). Similarly students hold a model of ionic bonding which is unable to explain the properties of, e.g., sodium chloride, due to their identification of ionic bonding with electron transfer between *atoms*. Eventually some of these students enter undergraduate programmes in chemistry where they learn more sophisticated chemical models. (Perhaps more students would aspire to this if they did not have to overcome the conceptual difficulties that result from the models they learnt in school.) Eventually (some time after graduation it has been suggested) the successful elite will become expert chemists who are able to select when to use the atomic ontology as a convenient approximation of modern chemical theory, one that is still useful in some contexts.

It is accepted in this paper that scientific ideas need to be simplified (Taber 2000d) and even humanised (Watts & Bentley, 1994) to help learners. It is accepted that the versions of scientific ideas that pupils will learn in school science are limited compared with the scientist's versions. However, curriculum models should be designed to be suitable 'intermediate conceptions' on potential 'conceptual trajectories' toward more scientifically sophisticated models (Driver 1989; Driver et al., 1994; Duit et al., 1998; Smith et al., 1993; Stavridou & Solomonidou, 1998).

The teacher described by Wightman, who had atoms of copper sulphate, justified his use of the word:

> "Using the word 'particle' would appear to confuse the situation - particle is not a specialist term. Most particles met in real life are certainly not atomic in size - particles of soot *etc.* Better perhaps to use <u>ATOM</u> which does suggest something a little special. They have all certainly heard of the word and are not scared to use it."
> Wightman et al. 1986, p.199.

It is probably educationally sound *not* to distinguish between atoms, molecules and ions at this point (e.g. 11-14 years), and a generic term is needed - be this quanticle or whatever. If the term 'atom' was only known to us in the sense of Democritus it might make a suitable choice, but this historical meaning does not match the modern chemical use, and so this teacher's choice of 'atom' to avoid two different meanings of 'particle' is counterproductive.

Talk of atoms as having needs and wants as a way of humanising science has been considered in some detail elsewhere (e.g. Taber, 1997a; Taber & Watts, 1996), and it has been suggested that it may be a useful tactic to help students form images of the unfamiliar molecular world. Such language can be a useful metaphor that provides learners with a way into understanding molecular level processes - an anchor that connects chemistry to the familiar social world. *However*, to be an effective 'conceptual bridge', this type of language must quickly be supplemented by more scientific descriptions so that it has a metaphorical function, and does not become a literal description for learners. Although more research would be welcome, there is evidence suggesting that for some college level (e.g. 16-18 years) students reactions do occur *literally* because of what atoms want. Such literal use provides these students with an apparently satisfactory explanatory scheme, and so can block the development of alternative ways of understanding.

In practice the research suggests that the model of the atom acquired during the upper secondary school years does not effectively act as an effective 'intermediate conception' (Driver, 1989), a bridge to a more appropriate conceptualisation, but rather as a barrier to progression (Taber, 2001a). This would be a disappointment if it reflected a carefully planned pedagogical route towards the level of understanding used in chemistry. It is suggested in this paper that there is no evidence that this is the case. Rather becoming a chemist involves breaking through the epistemological barriers of the curriculum atom, to gradually develop an appreciation of the scientific models of matter. Only then is the chemist able to see the atomic ontology as a useful simplification that can applied without difficulty in some contexts, rather than as 'the' scientific perspective.

The research into students' difficulties moving on from their 'atomic ontologies' has led to suggestions (in terms of emphasis, and topic sequence) for how teaching about structure in chemistry should be changed (Taber 2001c). Key recommendations include teachers focusing on physical principles, as students do not always make the expected connections by themselves (Taber 1998a); emphasising molecules and ions more, and atoms less; teaching bonds as being electrical in nature; emphasising the non-molecular nature of non-molecular lattices, and an order of teaching with first the structure of metals, then ionic crystals, then giant covalent structures, and finally simple molecules (Taber, submitted); and taking great care in the use of language.

However, it is clear that more research is needed. It would be useful to know more about the extent to which expert chemists are *consciously* aware of the limitations of the atomic ontology, rather than relying on their tacit knowledge (Polanyi, 1962) when selecting to talk of atoms in molecules, and atoms taking part in reactions. Are expert chemists carefully choosing a suitable simplification when they talk this way, or is their thinking automatically channelled by fossilised habits of mind from their own education? Another key question suggested by the thesis in this paper is the extent to which *teachers* of 14-16 chemistry think like expert chemists, i.e. are they aware of the limitations of the atomic ontology, considering it as a suitable simplification for educational purposes, or is their thinking more like the novice for whom this is the only perspective available? This paper also raises questions about the way some students compartmentalise their learning (e.g. physics and chemistry separately), and how they can be encouraged to look for more coherence across their scientific knowledge.

Until new approaches are explored in the classroom we will not know whether we are able to find a better approach to the key balance between providing sufficient simplification for understanding now and providing a suitable basis for later progression in scientific understanding (Taber, 2000d). What seems clear is that the current approach is not even designed with this purpose in mind.

## Coda.

This paper has explored a number of aspects of the atom concept: in science, in students' minds, in educational provision and in historical development. Clearly it has not been possible to treat any of these themes fully in a single article. However, I believe that the case made is a strong one: the way the idea of the atom is commonly taught and learnt is neither scientifically appropriate, nor justifiable as part of a planned pedagogic strategy, but is heavily influenced by epistemological obstacles of the type that Bachelard mooted.

I accept that other factors are *also* involved. There is the genuine educational issue of not confusing learners with too much detail when they are *first* introduced to molecular level particles (e.g. 11-14 years). It is good practice in teaching to find the optimum simplification that matches learners' readiness, but provide a sound foundation for further learning (Taber, 2000d). However, it is argued here that the current curriculum approach may be far from an optimum pedagogic simplification.

I also suspect that the idea of the curricular atom has an instinctive appeal (Watts & Taber, 1996). The notion of a fundamental building block of matter - the lego of nature according to one student (Harrison & Treagust, 2000) - seems to appeal to the psyche: the curriculum atom takes on this role, whereas a sub-atomic trinity does not seem to quite do the job. Learners therefor acquire a notion of the world made up of isolated discrete atoms (Taber, 1996b), which sometimes interact in chemical processes.

The most appropriate units for considering many chemical processes are cores and valence electrons, which seems a messy ontology, as the electrons appear as both stand-alone units, and constituents of the cores. Different types of structure (simple molecules; ionic, metallic and giant covalent structures) have different types of patterns of cores and valence electrons. There is a strong psychological urge to find a fundamental unity in this plurality (Scerri, 1999) and the fiction of everything being made from, and of, atoms is a comfortable fiction. Unfortunately, it is also an epistemological obstacle.

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