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When the analogy breaks down. Modelling the atom on the solar system

Keith S. Taber

Abstract:

Analogy is one of the most potent tools in the teacher's repertoire, and has been recognised as a common feature of science teaching. It is also accepted, however, that teaching effectively using analogy requires careful planning. It is important to emphasise the limitations of the analogies used in explaining scientific ideas. The present paper also highlights another potential difficulty: when the analogue is not as familiar to learners as the teacher may assume.

Introduction

This paper considers some of the advantages and potential difficulties of *teaching with analogies*. A very common analogy - that the atom is like a tiny solar system - is considered as an example through which to raise some general points about the role of analogies in teaching.

Models, analogies and metaphors

Models are a key aspect of both doing and teaching science. There are different kinds of model, ranging from those that are simply scaled down replicas of larger originals, to those that are abstractions, such as sets of mathematical equations (Harrison & Treagust 2000). To be useful, models have to be simplified representations of something more complex (Gilbert 1998). Analogy is used in science teaching as a means of providing learners with a *model* of the phenomenon to be explained or understood. One common example of this practice is to model the structure of the atom on the solar system.

The difference between an analogy and a metaphor is whether the modelling nature of the comparison is made explicit. To suggest that in some ways an atom *is like* a tiny version of the solar system is to make an analogy. To say that the atom *is* a tiny solar system is to use metaphor (or to make a gross error of categorisation!)

Metaphor is commonly used in everyday life, and it is usually recognised that language is being used poetically. So, for example, the National Curriculum may be called a straight-jacket for teachers, and all science apart from physics has been described as stamp collecting. It has been argued that *all* of our concepts are derived directly or indirectly from metaphors with those primary concepts that can be directly physically experienced (Lakoff & Johnson 1980). It is not possible to delve into the full *depths* of this argument here, but there is a considerable *weight* of evidence to support this *point of view*.

The rhetorical force (sic) of metaphor may be blunted (sic) by the inclusion of the terms 'is like' or 'is similar to', but in teaching it is probably best if explicit analogies are used. A metaphor, after all, has 'hidden meaning', and clarity is usually at a premium in the classroom.

Making the unfamiliar familiar

Teaching could be characterised as *making the unfamiliar familiar*. Learning theory - supported by the wealth of evidence of children's alternative conceptions in science (e.g. Driver et al. 1994) - suggests that children are only capable of learning science accurately, and with understanding, if knowledge is built up incrementally (Taber 2000a). Pupils will recall and apply ideas that they have been able to *make sense of in terms of their existing knowledge*. Material that is too abstract *or too unfamiliar* will be learnt by rote (without the understanding that provides the ability to apply it in appropriate contexts) or not at all.

The purpose of any kind of model used in teaching is to *help make the unfamiliar familiar*. A scale model (e.g. of a steam engine) does this by providing a physical look-a-like with the constituent parts in the appropriate configuration. The learners can familiarise themselves with the physical model, and form a mental image of the actual system represented. An analogy makes the unfamiliar familiar by showing that the novel concept is in some ways *just like* something the learners already know about.

Corresponding and non-corresponding aspect of analogies

Any analogy is by definition a recognition of some *similarity* between two different systems. The human circulatory system may be seen to have similarities with a domestic central heating system. Both involve fluids passing through systems of pipes, with system components which act as pumps and valves. However there are clearly many differences between the two systems. This may seem obvious, but research suggests that learners may not have a very sophisticated appreciation of the way in which science uses models which are chosen for the relevance of *particular features* in *specific contexts* (Driver et al. 1996; Grosslight et al. 1991). In using any kind of teaching analogy, it is important for the teacher to focus on both those aspects of the analogue which map well onto the target system, *and those that do not*. Indeed, pupils can learn as much about the target by considering the differences as the similarities - as long as these are made explicit.

The tiny solar system

A very common analogy used in teaching science is that of the atom being *like* a tiny solar system. The justification of using this as a teaching analogy follows from the following assumptions:

(1) the concept of the atom is abstract, and its structure will be difficult for pupils to appreciate;
(2) the atom *is* in some ways like a tiny solar system;
(3) pupils are familiar with the solar system;
(4) by explicitly comparing the atom with a solar system the learner is provided with a useful starting point for learning about atomic structure.

The worth of the teaching analogy therefore depends upon the validity of these four propositions.

Which atom?

It certainly seems reasonable to suggest that the concept of the atom is abstract, and potentially problematic for learners. The atom is far too small to be seen directly, and its structure is certainly not intuitively obvious from experience (in the way one might develop an understanding of, say, the relationship between light sources and shadows). However, it is also a concept that is central to science, so it has a very important place in the curriculum. It is imperative for teachers to find ways to help pupils learn meaningfully about atoms.

Unfortunately, there is a very real question of 'which' atom pupils need to learn about. Clearly a full understanding of the modern notion of the atom based on quantum mechanics would *not* be appropriate at secondary level. Then again, the original, ancient, notion of indivisible solid polyhedra - whilst simpler to comprehend - has little value as a useful model in modern science. Usually, in secondary school, a type of hybrid model (Justi & Gilbert 2000) of Rutherford's nuclear atom with Bohr-type electron 'orbits' is favoured as providing the 'optimum level of simplification' (Taber 2000b). However, it is worth noting that those pupils who carry on their study of science after school will meet orbit*al*s and 'clouds' of electron density in place of electron orbits. It has been argued that initially teaching a model of the atom based on concentric electron orbits may be counter-productive (Fischler & Lichtfeldt 1992).

Positive mappings

If - despite such reservations - the atomic model that is to be taught comprises of a central nucleus surrounded by corpuscular electrons following near circular orbits, then the analogy with the solar system does produce some useful positive features.

Both the atom and solar system comprise of one central body/particle of a relatively large mass, 'encircled' by a number of much smaller bodies/particles. The orbiting bodies are attracted to the central body by a physical force in both cases. If a pupil can visualise the solar system, then it may act as a model for these aspects of the atom.

Differences

It may seem surprising for such a common teaching analogy, but it is much easier to find aspects of the analogy which do not correspond: where the two systems are different rather than similar. Clearly the size difference is extreme, but there are many other significant differences. The electrons in an atom are of identical type, where planets are of different sizes and appearances. Electrons are considered fundamental where planets are very much composite bodies. Changes in 'orbit' - and even entering and leaving the system - may happen abruptly for electrons, whereas planetary orbits change slowly. Each atom is identical to billions of others: where each solar system is distinct; planets attract each other (and may potentially collide!), whereas electrons repel each other. Solar systems evolve through a cycle of changes as the sun's composition changes: nuclei do not change in any comparable way. Planets often have moons (where electrons do not). The solar system is almost flat: atoms are not, and may approach spherical symmetry. The list could be continued.

This catalogue of differences does not necessarily undermine the value of the analogy. The solar system may still provide an *initial image* to act as a model of the atom: this can then be explored and developed in terms of the various points made above. Subject to some provisos, then, it seems reasonable to agree that the atom *is* in some ways like a tiny solar system, and that by explicitly comparing the atom with a solar system the learner *could be* provided with a *useful starting point* for learning abstract ideas about atomic structure.

Is the analogue more familiar?

Three of the four initial assumptions upon which this teaching analogy rests are seen then to be - at least partially - satisfied. Yet the solar system can only be used as a sensible model for making the atom more familiar if it is *actually more familiar* to pupils than the atom. Learners will have directly perceived at least some parts of the solar system, including the sun, the earth, some of the major planets and - less helpfully in this context - the moon. However, the learner's viewpoint is not one which makes the overall structure of the system obvious (as is clear from the cosmologies of most of human history). So, in practice, learners' familiarity with the solar system will rely on prior teaching.

At the same time, the atom has become an icon of the modern scientific age, and it might be questioned whether the image of the atom with orbiting electrons is any *less* familiar to pupils than that of the solar system.

Students' ideas about the solar system

It is well known that both primary and secondary pupils may have alternative conceptions about aspects of astronomy (Nussbaum 1985, Baxter 1995), and so it is not wise to assume that learners will have appropriate scientific knowledge about the solar system to form the basis of an effective teaching analogy. Indeed some tentative evidence from a study into students' understandings of chemical bonding suggests that caution is appropriate (Taber 1997). The students interviewed in that research were attending a Further Education College in England, and taking chemistry at A-level (GCE Advanced level, i.e. university entrance level).

Although bonding is a *chemical* topic, students' understanding of the interactions within and between atoms and molecules would be expected to derive from their ideas about electrostatics. One of the findings of the research was that the chemistry students *commonly misunderstood the forces acting in the atom* (Taber 1998, 1999). In particular, students made 'Newton-3 errors' - such as not recognising the existence of a paired 'reaction' force (e.g. the nucleus attracted an electron, but was not attracted by the electron), suggesting that the 'action' and 'reaction' forces had different magnitudes (e.g. a nucleus attracts an electron with a greater force than the electron attracts the nucleus), or pairing repulsions with attractions (e.g. that the protons in the nucleus are repelled by orbital electrons).

As part of the research some students were asked about non-chemical contexts to elicit their understanding of basic physics concepts (such as force and energy) that might be assumed to underpin their chemistry. Questions relating to falling apples and balls thrown in the air revealed evidence of students holding 'impetus' type conceptions of force and movement similar to those that have previously been widely reported (Gilbert & Zylbersztajn 1985; Watts & Zylbersztajn 1981).

A few of the students were asked about the forces acting in a solar system. Although the responses of a handful of learners can not be assumed to be representative of the wider population, it is certainly intriguing that the same types of 'Newton-3 errors' were revealed when the students talked about astronomy as were found when discussing the forces within an atom (i.e. the sun *not* being attracted by the planets; the earth attracting the moon *more* than the moon attracts the earth; the earth attracting the moon, but being *repelled* by it).

In terms of the question of which system - atomic or solar system - was more familiar, it is also of interest that it was proposed that the planets in a solar system would *repel* each other, and that one student tentatively suggested that inner planets might give rise to a form of 'shielding' effect: this latter idea provoked by "thinking about atoms". The knowledge of the solar system held by these particular learners would not have made a good model for understanding the atom, and there is even some suggestion that they were using their knowledge of atomic structure to suggest likely features of the solar system.

What value the tiny solar system?

This paper is *not* suggesting that teachers should no longer make use of the common teaching analogy between the atom and the solar system. Indeed discussing the similarities *and* differences between the two systems could be valuable at several stages in physics education. For example, explaining why the shielding effect found in atomic systems does *not* have a direct counterpart in the solar system would be a useful exercise for A level students. What the present discussion *does* suggest is that the value of any teaching analogy is based upon the relative familiarities of the target and analogue, the strength of the similarity between the two systems, *and* upon the aspects of the target which the teacher wishes to emphasise.

At a time when the atom of modern physics was an exciting new concept, and when the orbiting electrons type model was close to the cutting edge in science, there may have been a strong case for *introducing learners to atomic structure in terms of an analogy with the solar system*. Yet when science describes atoms in terms of quantum theory, and when images of atoms are common cultural icons, both the lack of novelty of the atom concept, and the limited similarity of the analogue to target, may reduce the value of this comparison. Where learners actually have very dubious understandings of the forces at work in the solar system, the case is weakened even further.

Conclusions: A checklist for teaching with analogies

Consideration of this example of a teaching analogy suggests the following check list for teachers when they introduce analogies:

1) Make sure that the analogy does map onto the key aspects of the target concept to be emphasised;
2) Explore both the positive and negative aspects of the analogy, and make sure that learners appreciate both;
3) Check that the analogue is actually *more familiar* than the target concept: otherwise time will need to be spent teaching about the analogue before it can be used.

As far as the last point is concerned, if analogy is intended to help *make the unfamiliar familiar*, it will only be effective where the analogue is itself *genuinely* familiar.

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