

Quality, Level, and Acceptability, of Explanation in Chemical Education

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Abstract

Chemistry seeks to provide causal explanations of phenomena that fall within its domain: to say why things happen and why they are as they are. The highest quality of causal explanation available in any field of chemistry can be defined as that currently used at the frontiers of enquiry in that field and will vary with time where that frontier is moving. An explanation of any given quality depends on the nature of the model that underpins it. This is reflected in the range of phenomena to which it can be applied and in the successful predictions to which it gives rise. Chemical education should ultimately lead, through a series of levels, to an understanding of those models currently producing the highest quality explanations. In the reality of the classroom, an acceptable explanation will be one that is taught in expectation that students will be able to understand, remember, and use it in relation to phenomena to which they can have access, often in a laboratory. However, students often learn explanations that are poorer in quality and at a more primitive level than is acceptable.

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On the notion of ‘explanation’ in chemistry

To most people:

‘...an explanation is simply what is accepted by the person who has given it, and by the person who has received it, as an explanation’

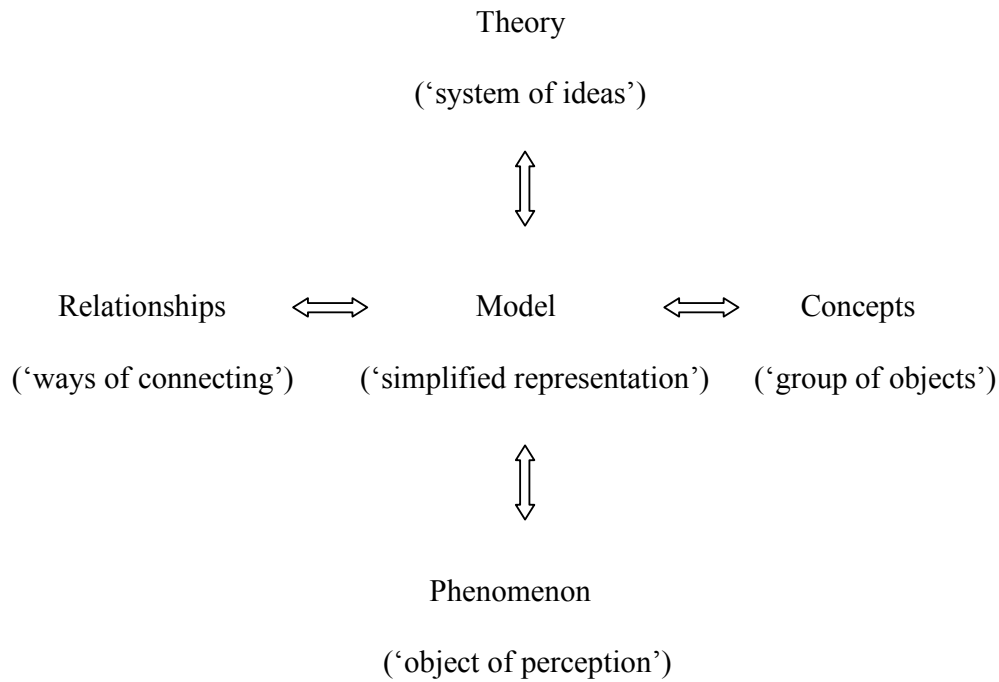
(Driver, Leach, Millar & Scott, 1996)

whilst, for philosophers of science:

‘An important aspect of explanation consists in relating the phenomenon to be explained ... to some accepted reality, that is to an empirical law. If this can be done we are on the way to producing a causal explanation as to why the phenomenon occurred and / or why it was as it was’

(Trusted, 1987)

In producing explanations, and in talking about them, the everyday person, philosophers of science, and scientists, make use of a series of words: ‘phenomenon’, ‘theory’, ‘model’, ‘concept’ and ‘relationship’. We suggest that the meanings of these words are connected in science as below (figure 1).

*Figure 1*

A 'theory' is inherently abstract and highly generalised e.g. the atomic theory of matter. A 'phenomenon', on the other hand, is inherently concrete and highly specific, being the outcome of observation. A 'model' sits epistemologically between the two. If a model is derived from a theory it is an attempt to make the theory more visualisable by applying it to a particular phenomenon. If a model is derived from a phenomenon it is an attempt to simplify and represent some specific aspect of the phenomenon so that theory can be more readily applied to it. A model can be thought of as consisting of a series of entities, of 'concepts', each a generalisation made across a series of objects (or across ideas treated as if they were objects) in specific 'relationships' to each other (temporal or spatial) (Gentner, 1989). For example, the atomic theory of matter applied to the phenomenon of a crystal of sodium chloride yields a visualisable model in which sodium ions and chloride ions are spatially arrayed. These categories are, at best, interactive: for example, it is hard to imagine an aspect of the world-as-experienced could have been given a boundary and a name (i.e. have become a phenomenon) without the guidance to perception provided by a model.

Explanations are based on models (Gilbert, Boulter, & Rutherford, 2000). A *causal* explanation of a phenomenon, the most valued type of explanation, not only states why a phenomenon behaves as it does, but also enables predictions to be made of its behaviour in different physical circumstances. The model that leads to causal explanations does so because it represents the concepts of which it is composed together with their relationships including those of cause and effect. A precursor to a causal explanation will have been an *interpretative* explanation based on a model in which the causal element was absent i.e. it only represented the concepts and their spatial and temporal relationships. The precursor to an interpretative explanation will have been a *descriptive* explanation based on a model that only represented the behaviour of the phenomenon. Of course, scientists always try to compact this sequence, leaping from measurement to causal explanation with the use of a single model in one mighty bound (and sometimes failing to make it e.g. Pauling and DNA).

In most fields of scientific enquiry, the *quality* of the explanations at the ‘cutting edge’ of research improves with time. Any distinct improvement in explanatory quality is marked by the introduction of a new (or much improved) model. Each successive model enables the *level* of explanation to be raised. Justi & Gilbert (1999a) used Lakatos’ (1974) idea of a ‘scientific research programme’ to identify the eight distinctive models used in the historical development of the study of chemical kinetics. Each model attempted to provide descriptive, interpretative, and causal explanations and more widely applicable and accurate predictions than its predecessor. Justi & Gilbert (2000a) made a similar analysis in the much more widely known case of ‘the atom’. Oversby, (2000) has made a sequential analysis in the case of models of acidity / basicity. Those models in any field that are superseded at the ‘cutting edge’ of research become ‘historical’ models (Gilbert et al., 2000) and are retained for commonplace purposes, in relation to those aspects of a phenomenon that they do adequately explain. In passing: old models – historical models - never die, they just pass into the school and university curriculum.

On the teaching of explanations in chemical education

The development of every major field in chemistry is marked by the production of increasingly sophisticated models and hence by progressively raised levels of explanation. How are we to decide what explanation to teach to any given group of students? The approach most commonly used is to enter the historical chain of models in a given field at a particular point and teach that model and its associated explanations. As students move to higher grades in the school and / or university, later models in the sequence are taught. For example, it is still common for school students to be introduced to the Thompson model of the atom in one year, to the Rutherford model the next, and to the Bohr model in the third. Progress is normally halted there, giving students the idea that Bohr's model, conceived in 1923, is the basis for 'state of the art' investigations. This does great violence to the history of science, for this 'progression' is rarely accompanied by any discussion of why an 'older' model was superseded by a 'newer' model. Worse still is the widespread practice of teaching 'hybrid' models (Justi & Gilbert, 1999b): these are made of parts of different models in an historical sequence, bolted together because they readily allow a particular set of explanations to be presented. This practice denies the possibility of a history of chemistry, for you cannot 'move on' from that which never existed.

If it is accepted that true explanations involve the use of a causal model, then the provision of such models will mark a transition by the students from macro-based thinking i.e. thinking about phenomena and their observable behaviour, to micro-based thinking i.e. thinking about atomic-level entities (concepts) and their relationships. What is needed at this juncture – this vitally important juncture, for failure will lead to chemistry being seen as unintelligible by students – is the use of *acceptable* models: acceptable in terms of being historically authentic and pedagogically useful. These are *curricular* models, simplifications of historical models that are *good enough* to support the learning of important explanations, yet have an intellectual integrity that will enable them to be extended and elaborated on in later years of chemical education.

Let us take the case of the National Curriculum for Science in England and Wales for 11-14 year olds as an example. Students have to be taught four major themes, of which one (Materials and their Properties) corresponds to ‘chemistry’. They have to be taught so that understanding moves through 8 ‘Levels of Attainment’. A crucially important transition occurs in Level 6, where ‘they recognise that matter is made up of particles, and describe differences between the arrangement and movement of particles in solids, liquids, and gases’ (DfEE, 1999).

There is evidence, from reports of formal school inspections, that many students do not understand the ‘particulate model of matter’, possibly because they had been taught a too sophisticated, or hybrid, model. An *acceptable* model has now been devised and trialled in schools (Gilbert, Newberry, & Grey, 2001).

We will not rehearse the good practice that has been developed over recent years for the teaching of such curricular models and for the development and use of *teaching models*, those designed to form bridges between students’ experience and the desired curricular model (e.g. Dagher, 1985; Glynn & Takahashi, 1998; Treagust, Harrison, Venville, & Dagher, 1996). More attention is needed to teaching students systematically that explanations are produced in response to questions: ‘How does this phenomenon behave?’, ‘Of what is it composed?’, ‘Why does it behave in the way that it does?’, ‘How will it behave if we change the experimental circumstances?’. This will entail a shift in the emphasis of classroom-language style from ‘didactic’, where the teacher produces an account of established knowledge, through ‘Socratic’, where the teacher does ask questions, to the ‘dialectic’, where knowledge is jointly constructed by teacher and students through questioning and the production (rather than the acquisition) of explanation (Gilbert & Boulter, 1998; Newton, Driver, & Osborne, 1999). This shift will lead students to develop the capacity to evaluate explanations: to find if they are *acceptable* to them.

On the learning of explanations in chemistry

If students are taught a scientifically acceptable explanation, then acceptable learning is shown by its successful use in solving ‘paradigmatic problems’ (Kuhn, 1970). Acceptable learning can be judged against three criteria (Taber & Watts, 2000):

Structure: does a student’s utterance (verbal or written) have the surface features of an explanation i.e. the use of appropriate conjunctions (e.g. ‘because’, ‘so’, ‘therefore’, ‘consequently’)?

Logical coherence: is a student’s utterance internally consistent i.e. is there an appropriate use of concepts and of the relationships between them in a model, with the correct use of cause and effect?

Scientific acceptability: does the utterance make use of the model, those concepts and of the relationships between them, which are set out in the curriculum?

The application of these criteria to students’ utterances shows that four broad types of learning can be identified. These are shown by the production of a:

Scientific Explanation: This is the case where the structure is correct, the logical coherence is correct, and the science is acceptable.

Alternative Explanation: This is the case where, whilst the structure and logic of the explanation are correct, the science is not acceptable.

Non-logical Explanation: This is the case where, whilst the structure of the explanation is correct, the argument put forward is logically inconsistent, and hence it is not possible to see whether it is based on acceptable science.

Pseudo – Explanation. This is the case where neither the structure nor the logical coherence is correct and the science is not acceptable.

While all teachers delight at receiving scientific explanations, the emphasis on improving the quality of learning necessitates a focus on the three types of *unacceptable explanations*. The boundaries between these three types are fuzzy: an individual student is often insecure in more than one aspect of explanation provision. We illustrate these categories with data drawn from an extended interview-based study into the learning of chemistry for the U.K. ‘Advanced Level’

examination by 16-18 year olds in a College of Further Education conducted by one of us (KT) (Taber, 1997).

Alternative Explanations

These are produced where, whilst the student knows how to structure a scientific explanation and makes use of logically consistent arguments built around a model, that model is not one that is acceptable to the chemical authority that set down the curriculum. This lack of acceptability arises through the use of *alternative conceptions*, the interpretation of concepts that differ from the accepted views (Gilbert & Watts, 1983).

Consider for example, student Annie's explanation for the stoichiometry of aluminium sulphate being $\text{Al}_4(\text{SO}_4)_2$ (Taber, 1995). Annie recognised that taking one of each ion would not balance, and found it difficult to suggest an appropriate combination. After some thought she suggested that to get a neutral compound "you'd have to use, say four aluminiums, and, two, sulphates". It is easy to dismiss this incorrect answer as simply due to a miscalculation, but Annie was able to explain why $(\text{Al}^{3+})_4 (\text{SO}_4^{2-})_2$ should be neutral. Annie held an alternative interpretation of the charge symbols + and - as deviations from an octet or full shell structure. Annie's conception of + was one electron over a full shell, and - indicated one electron short. In terms of these 'deviations' charges each Al^{3+} ion had three extra available electrons, and each SO_4^{2-} ion was lacking two electrons. Four aluminium ions provided 12 electrons, and the two sulphate ions accepted 4 of these to make up octet structures. This would seem to leave eight 'extra' electrons, but from Annie's alternative scheme this could be ignored.

"That'd make eight. It would make eight, so it would be neutral.

Anyway it would give you eight, eight plus. [Would that be neutral?]

A neutral charge ... because it would become nought.... if you had

eight plus it's like having eight minus, you don't really have that

because you have your shell with all your electrons in it, which could

be eight."

In other words, as deviation charges indicate a deviation from an octet, then eight electrons - an octet of electrons - counted as neutral. Annie's electron arithmetic only had to take count of the

remainder when counting in base 8. The explanation worked in terms of her deviation charges, but was not scientifically valid, as it was based upon an alternative conception of what was meant by ionic charge.

Non-Logical Explanations

These are produced where, whilst the student knows how to structure a scientific explanation, logically incoherent arguments are put forward, the result of which is that it is often impossible to see if the student knows and can use a scientifically acceptable model.

The most disconcerting case is where *circularity of argument* (tautology) is used. For example, Umar, was asked about the type of bonding in tetrachloromethane. He explained that the bonding was polar “because it’s between ionic and covalent, like the electrons might be pulled more strongly towards the chlorine than the carbon, ‘cause the chlorine’s more electronegative.” So according to Umar, the bond polarity was due to the electronegativity of chlorine, which he explained means “it’s got more tendency to attract an electron from another atom”. Umar was satisfied with this form of explanation, i.e. that chlorine attracts the electrons more than the carbon because “it’s got the greater tendency to attract an electron from another atom.” This argument was clearly of the form *agent X will cause event Y to happen because agent X has a tendency to cause event Y to happen*. From a scientific point of view we would say that a bond would be *classed as* polar because it was between ionic and covalent; and an atom was *characterised as* electronegative because it tended to attract electrons in bonds. For Umar, however, a bond was polar *because* it was between ionic and covalent; and an atom was electronegative *because* it tended to attract electrons in bonds. Umar seemed to feel that this labelling process had deeper explanatory power.

Another major sub-type is where the student changes her/his mind when questioned, showing a *lack of understanding of / commitment to the principles of interpreting a model*. In an interview Carol suggested that a diagram that showed a layer of ions in sodium chloride represented a

structure which would have ionic bonding. When asked how many ionic bond each chloride ion had formed, Annie replied,

“I’d say each bond has got one. ... Erm, oh no! Hang on. I think it could have seven. ...I don’t know why I said seven, but, erm, [pause] no, I reckon, it can have as many as it wants, as long as it’s got electrons to cover how many it does want. Because all the rest just carry on orbiting, I reckon.... Four. ‘Cause it’s in contact with four little circles sodium.”

It is *possible* to suggest a rationale for Carol’s suggestions. It is a common alternative conception that each ion in sodium chloride only forms one bond (Taber, 1994; Taber, 1997b; Taber, 1998). As chlorine has seven electrons, some students expect it to form seven bonds (Butts & Smith, 1987). However, in Carol’s case the interviewer was unable to explore her reasoning for each suggestion before she had moved on to another answer.

Pseudo – Explanations

These are those productions that are so far from scientific acceptability that the teacher might be forgiven for asking (internally!) ‘why did this student ever take chemistry as a subject?’, ‘why have I failed to teach him / her anything?’ etc! Rage and despair put to one side, three canonical forms of pseudo-explanation have been identified in the literature:

Anthropomorphic explanations

This involves the imbuing of non-human objects with human feelings and desires. An extreme form is *animism*, where inanimate objects are viewed as living beings. Signalled by the use of words such as ‘wants’ and ‘needs’, anthropomorphism is a standard form of metaphor, widely used by teachers. However, as Lempke (1990) points out, it is important that students see it as a linguistic device and not as something that has any part in scientific discourse. Alas, this distinction is not always made in practice, hence this sub-type of explanation. Examples, taken from the study quoted (Taber, 1997) are:

- two positive charges always ‘repel each other’ because ‘they are different charges and they don’t like each other’;
- a sodium ‘is lending chlorine’ ‘one of its electrons’;
- ‘fluorine’s being greedy trying to grab two electrons’;
- ‘when you heat it or boil it, the atoms of argon are free to move around if they want’.

(Taber & Watts, 1996)

Teleological explanation

Teleological explanations attribute effects to postulated purposes rather than to the operation of causes. These purposes often have to do with notions of ‘design’ or ‘utility’ (Friedler, Zohar, & Tamir, 1993; Jungwirth, 1979). For example, student Kabul suggested that a bond might form “so that both [atoms] can have ... paired orbitals”. His classmate Lovesh believed that chemical bonds form “to make a more stable species, at the end”. Students often seem satisfied that such purposes are reason enough for chemical processes to occur. Such explanations are often couched in the type of anthropomorphic language referred to above. Jagdish argued that “if [atoms] formed a bond they would both be at a lower energy level, and that’s what they all *want* ... to form a more stable species”. Jagdish explained that a stable species would not react, because “if it was already a stable compound, if it was already a stable species, what’s the point of it being attracted or repelled or whatever?”

Teleological arguments are sometimes closely related to a belief in a ‘natural’ state of affairs (Watts & Taber, 1996). When things match the (perceived) natural state, this is seen as explanation enough. When matters do *not* seem to match (the student’s intuition of) a natural state, then some cognitive conflict is experienced. One student could not accept that electrons from atoms of different elements could not be distinguished: “I reckon there must be [a] way.... it just don’t seem right’. Even a student who does accept all electrons are identical may still expect them to return to ‘their own’ atoms. After all: “it would seem a bit of an odd-ball, wouldn’t it, to have somebody else’s electron”. Another notion which seemed unnaturally odd to a student was the idea that in a

single pure substance (liquid hydrogen fluoride) there would be two different types of bonding (i.e. covalent [sic] and hydrogen bonding) between the same types of atomic centres (i.e. hydrogen and fluorine),

“but that don’t make sense, really, because... in the molecules there’s hydrogen and fluorine, and when the molecule joins another molecule there’s hydrogen and fluorine, and you can’t say one has got covalent, and one has got another type of bond. Because it just doesn’t make sense.”

This argument - that the same pairs of adjacent atomic centres should be bonded in an equivalent way - seems to make an intuitively reasonable (and reasoned) point. Unfortunately, this logical appeal to a symmetrical natural order falls short. The world is more complicated than this, and genuine scientific explanations can not rely on a gut-feeling for what might seem ‘fair’.

Discussion

Explanations in chemistry – in science in general - are based on models. The *quality* of an explanation depends on the *level* of the model used from an historical sequence of models. We suggest that simplified historical models - *curricular* models – be taught. These will be both *scientifically acceptable*, in that curriculum designers will be satisfied, and *educationally acceptable*, in that teachers will find that such models are *good enough* for their explanatory intentions. The teacher will thus have made the maximum effort to communicate the explanation to the students.

When students have to produce an explanation in response to a question from the teacher (or from an examination paper!), ‘good’ (successful!) students will produce a *scientifically acceptable* answer. However, things can go wrong. If the linguistic conventions for the structure of scientific explanation itself are not understood, pseudo-explanations will be produced. Students may not use the correct ontological categorisation for the components of an explanation – items from the perception of phenomena are confused with concepts – leading to the production of tautologies. Concepts may have been misunderstood, leading to alternative explanations. The relationships between concepts within a model, including those of cause-effect, may be misunderstood, leading to

non-explanations. A model of unsuitable level may be chosen as the basis for an explanation. World-view theories that are incommensurable with a given model may be, often tacitly, adopted.

These problems suggest that students should be explicitly taught what explanations are and how to construct acceptable explanations.

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