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LOST WITHOUT TRACE OR NOT BROUGHT TO MIND? - A CASE STUDY OF REMEMBERING AND FORGETTING OF COLLEGE SCIENCE

Received 25 August 2003; accepted 30 September 2003

ABSTRACT: There is a considerable literature from studies of memory that could inform research into learning in science. Yet this important area has not been a focus of inquiry in science education, perhaps because of the difficulty of carrying-out longitudinal studies. The present study reviews the main findings from memory studies and considers the implications for science learning (and associated research). A case study is presented of one learner's thinking about a key area of chemistry during, and then some time after, studying at college level. Previous published research from the case study is summarised, and then new data is presented to illustrate the ex-student's thinking. The data suggest that key areas of learning were readily brought to mind, but recall was both partial and distorted (reflecting the findings from memory research). The limitations of the case study, and the methodological difficulties of this type of research, are considered. It is suggested, however, that if the present findings were to be widely replicated, then there would be important consequences for curriculum planning and assessment as well as teaching. [*Chem. Educ. Res. Pract.*: 2003, 4, 249-277]

KEY-WORDS: *memory; recall; forgetting; consolidation; time-scale for learning; delayed post-course interview; chemical bonding*

INTRODUCTION

Learning and remembering

This paper considers the role of memory in learning science. In particular a case study is considered based on a delayed post-course interview. A former college level student, Tajinder, was interviewed in-depth about aspects of his college chemistry almost four years after completing the course. The central research question can be stated: 'What does Tajinder remember so long after his course?' The findings of that case study are related to our current understanding of memory processes.

The reasons for discussing a single, and perhaps singular, case are explored later in this paper, but in essence it is considered that complex phenomena (such as learning) can *only* be understood through in-depth studies of individual learners.

There are significant limitations to the inferences that can be drawn from a single case, but it is suggested that the present paper is important in raising key issues about learning that have received little explicit attention in science education research. Although the limitations of memory are well accepted in psychology, and there has been a great deal of research into learners' understanding of science topics (both before and after teaching), there has been little specific attention paid to what we mean by 'forgetting' of science learning. This is perhaps understandable in view of the complexity of semantic knowledge structures.

Much of what is known about memory derives from studies of autobiographical memories or of clinical learning of relatively simple test material (such as lists of words or simple stories).

The science teaching community often talks about ‘teaching’ and ‘learning’ science, and about ‘assessing learning’ and ‘what students can remember’ as if these notions are relatively unproblematic. Research into the psychology of memory suggests that ‘remembering’ and ‘forgetting’ are far from straightforward, and it is suggested here that these issues should be the focus of much greater attention in science education research.

One contribution of the present paper is to highlight the practical problems associated with these issues, and to demonstrate that questions such as ‘did Tajinder learn that...’ and ‘did Tajinder remember that...’ do not have simple answers when the ‘that’ refers to complex concepts that require understanding rather than trivial isolated facts. The paper concerns what Tajinder ‘remembered’ about aspects of previous study that (he reported that) he had not had reason to think about for some years. As will be discussed, Tajinder actually ‘remembered’ a great deal, although the ideas ‘recalled’ in the interview were neither complete nor unaltered.

Exploring learning in science

The evidence that learning has taken place is a change in behaviour. In teaching science we are often (though not exclusively) concerned with conceptual learning, i.e. developing a student’s knowledge and understanding. This will result in long-term changes in the student’s ‘cognitive structure’ (Petri & Niedderer, 1998) – i.e. *the facts, concepts, propositions, theories, and raw perceptual data that the learner has available any point in time, and the manner in which it is arranged* (Taber, 2000a after Ausubel & Robinson, 1971, and White, 1985). The ‘change in behaviour’ of interest will be demonstrated through the student’s answers to questions, and particularly through the responses to higher-order questions (i.e. a higher-order question might be ‘*why* can phosphorus display a higher valency than nitrogen in its compounds’, rather than ‘*what* are the formulae of the chlorides of nitrogen and phosphorus’).

The science education researcher, just like the science teacher, only has indirect evidence of the student’s cognitive structure, but techniques such as in-depth interviews are able to provide the data for researchers to develop models that represent aspects of students’ knowledge and understanding of science topics (Ault, Novak, & Gowin, 1984). Although it is important to remember that such models are (like all models) imperfect representations (Lakoff & Johnson, 1980), it is standard practice in science education research to develop and discuss descriptions of students’ alternative conceptions, conceptual frameworks, mental models etc.

These representations are often *only partial*, as they only reflect answers to the questions the interviewer thought to ask, and are *imperfect*, as the researcher inevitably has to interpret responses through her own conceptual frameworks. Often they are necessarily oversimplifications, as our cognitive structures are complex and often ‘messy’, and useful models need to be straightforward enough to be readily communicated, and to offer heuristic value (Pope & Denicolo, 1986).

Of particular relevance to the research discussed in the present paper is the way the researcher’s representations reflect a *temporal slice* of the student’s thinking. Data collected on a single occasion may not be fully representative of the student’s thinking about a topic, whereas a sequence of interviews allows the researcher to test for consistency and variations in response, and to reflect upon the ‘meaning’ of responses between interviews (something that can be very important in making sense of learners’ alternative conceptions - especially when they are tacitly held). However, as the students’ conceptual structure will be changing

over time (as learning occurs), and will likely be developed in response to the interviewing itself (Taber, 2002a), there will be some ‘temporal blurring’ in any model developed to reflect interviews spread over a period.

A useful analogy here is selecting a shutter speed when trying to photograph a moving object in low-light conditions - there is a trade-off between obtaining a brighter image and the amount of blurring of the image that might be acceptable. However, another telling analogy might be trying to characterise the position of an electron by shining light at it: the very act of measurement actually changes the state of that observed, and the more illumination that is used, the more the subject is shifted from its original position.

Despite these inherent problems, there has been a realisation within science education that research to explore student *learning* (rather than just cataloguing student conceptions) requires in-depth exploration of student thinking *over time* (Watts, 1988; Black, 1989). By definition, the learning experiences of a student who agrees to be a subject of such educational research cannot be considered to be typical, and might be ‘accelerated’ in some ways - for research interviews can often act as Socratic dialogues and provide a level of Vygotskian scaffolding that provides an ideal stimulation for conceptual growth (Taber, 2002a).

This is a serious limitation in that the case-study method is needed to provide the detailed understanding of how students learn about science that can inform developing pedagogy, yet the case-studies cannot be considered to report on representative students. However, this is not insurmountable. For one thing the notion of ‘generalisability’, as it would relate to positivistic studies does not apply to case-studies (Taber, 2000b; Eybe & Schmidt, 2001). The idiographic research tradition that leads to case-studies is quite different: instead these studies offer a rich description (Denzin, 2001) of the individual case which can offer insights that *may well illuminate* other cases that have not been subjected to research but can be considered in some way similar (Kvale, 1996). Within the social sciences (e.g. educational research) this is an accepted approach (Eybe & Schmidt, 2001).

Secondly, although in-depth studies of individual learners cannot be considered to report on typical or representative students, it is still possible to triangulate the findings of case studies with other approaches. Case studies provide the detail for researchers to build models of the way some learners are thinking. Where there are findings of potentially wider significance - such as the development of an alternative conception that interferes with intended learning - it is *then* possible to use survey techniques to explore just how common the substantially similar conceptions are among a representative sample of the population (Taber, 2000b). Surveys can never uncover the nuances and complexities of student thinking in the way case studies can, but can *complement* in-depth studies to help build up an overall picture of aspects of learning science.

Using case-studies to explore learning in science

The potency of the case study approach can be illustrated with a few examples from the literature (Taber, 1995; Petri & Niedderer, 1998; Harrison & Treagust, 2000).

One of the theoretical debates accompanying the vast research effort to explore students’ ideas in science under the umbrella of constructivism, or the ‘alternative conceptions movement’, concerns the status of the conceptions uncovered. Whilst some authors have described students’ ideas as tenacious and theory-like, with the potential to be major barriers to learning, others have suggested that they were less significant, sometimes being romanced-up (i.e. formed on the spot as a feasible response when the student did not have an ‘in-stock’ answer available), often having very limited foci of application, and being

readily discarded and forgotten.

This is clearly a very important debate when so much effort in science education has been concentrated on this area of research. If students' ideas can act as substantial 'learning impediments' then the research is highly significant, but otherwise a major research programme has been exploring phenomena that may be only of academic interest, having little practical relevance to teaching. Case study research can certainly illuminate theoretical questions such as these.

For example, Annie was interviewed in depth at three stages of a two-year college course (in the UK, age 16-18) to explore her developing understanding of chemical bonding. A semi-structured interview approach was used that allowed the interviewer to return to key points in different contexts and explore both his interpretations of Annie's comments and the consistency of her answers. In this way it was possible to characterise her thinking about aspects of chemical bonding near the start of her course, after the first year of study, and just before her final examinations. The published account of the case was able to highlight the way that some aspects of Annie's thinking were quite labile, and readily developed on her course, whilst other features were much more stable and more 'resistant' to teaching (Taber, 1995a)

Some criticisms of constructivist claims about the status and significance of students' ideas argue that students' responses are too inconsistent to be granted the status of evidence of stable and significant alternative conceptual frameworks (e.g. Claxton, 1993). This debate is not easy to settle. So Watts claimed that interviews with samples of students of different ages revealed a range of alternative frameworks for key topics such as energy and force (Watts, 1983a, b). However, critics (such as Kuiper, 1994) have argued that when extended sections of interview are considered, many students cannot be clearly assigned to one of Watt's categories.

There are at least three possible explanations for this difference in interpreting student comments. One possibility concerns the sensitivity that the researcher needs to build up to fully appreciate the language and thinking of an interviewee. Learners often 'demarcate' concepts differently to scientists, and use technical terms in everyday or idiosyncratic ways (e.g. Watts & Gilbert, 1983), and so interpreting their comments can be quite a subtle and complex process. Clearly, someone simply reading the research reports will not share in the iterative process of interpretation that the researcher has been through during data collection and analysis.

A second possibility is that the researcher's models of the learners' thinking (which are necessarily simplifications) have not taken into account the full complexity of the learner's thinking, and are *over*-simplifications that do not represent the learner's ideas well. However, critics may sometimes fail to appreciate that frameworks reported from research are often one stage further removed from the researcher's models of the thinking of individual learners. When the researcher tries to abstract common frameworks and conceptions from the data derived from large numbers of students there is inevitably a further stage of simplification, and re-representation. Alternative frameworks such as those reported by Watts are in effect 'metamodels', models of models of learners' ideas, and thus one step further from the thinking of any actual individual.

So criticisms that the comments of actual students cannot be readily fitted to the reported categories deriving from research can sometimes be explained by the critic misinterpreting the student's actual meanings (due to a different way of using language), or failing to allow for the attempt to model commonalities in the way different individual students think about aspects of science in their unique ways. However, there is also the further possibility, that sometimes students use 'multiple frameworks' (Pope & Denicolo,

1986).

The proposal that alternative conceptual frameworks represent stable and theory-like aspects of student thinking, yet individual students may shift between several inconsistent frameworks when thinking about a single concept area might sound like a dubious and desperate suggestion. At first sight such a notion would certainly seem to fail any criterion of being open to falsification: ‘when asked about energy, student X will use framework Y - unless she uses a different framework this time’! Yet careful in-depth research with individual students suggests just this: that learners may hold several alternative conceptions for a particular scientific conception, all of which are stable aspects of cognitive structure, and each of which is sometimes used when the student is asked about the topic area.

A little reflection shows that this is not actually such an unfamiliar notion - after all scientists do exactly the same thing (cf. Bachelard, 1940/1968)! Physicists will apply a relativistic framework to think about motion in some contexts, but use Newtonian mechanics on other occasions; and chemists may think of the same bond as covalent *or* polar depending upon the problem they are considering, and class the same substance as an acid, an oxidising agent *or* a dehydrating agent on different occasions. If scientists can use scientific concepts and models as components of a tool kit from which they select, then we should not be surprised if learners of science often do something similar.

Indeed, as learners are *by definition* people in the process of developing and refining conceptions, we should perhaps expect students to often hold a range of conceptions for a topic area matching the curriculum versions to varying extents (cf. Thagard, 1992).

When Petri and Niedderer (1998) investigated the changing conceptions of the atom of an 18 year old student in a German school, Carl, they found that there was progression from his initial planetary model towards an electron cloud model. However the authors described how “the final state of Carl’s cognitive system is an association of co-existing conceptions ... when several conceptions co-exist and are connected to form different layers of the cognitive system, with a metacognitive layer on top”. The presence of the metacognitive layer is significant as “Carl was able to reflect on differences, problems and advantages of each conception” (p.1083).

Harrison and Treagust (2000) describe a case study of developing understanding of atomic and molecular structure by an Australian student at a similar educational level. They found that Alex used several ways of representing covalent molecules and “appeared to believe that each model described a few of the many attributes of covalent molecules and that, collectively, these models adequately described a molecule”. The “set of multiple models” was considered “fruitful” as it could be used to solve problems, given explanations and make predictions. Alex saw the models as thinking-tools (p.375).

Taber (Taber & Watts, 1997; Taber, 2000a, 2001a) reports a similar situation with the study of Tajinder’s developing understanding of chemical bonding during his two year ‘A level’ course (i.e. for 16-18 year olds in the U.K.) in chemistry. However, rather than concerning multiple models, Tajinder’s manifold conceptions were described in terms of explanatory principles. At the start of his College course Tajinder had a well-established explanatory principle for understanding bonding, deriving from ideas he had acquired during school science. He developed two further explanatory principles during his course, but continued to use his original ideas as well. Tajinder was able to see his three different ways of explaining chemical bonding as alternative stories from which he could select. Tajinder’s case is explored in more detail below.

Remembering and forgetting

Despite there being a considerable body of work exploring aspects of learning in science, there seems to be little - if any - research primarily focusing on the 'forgetting' of science learning. However, the work of Gauld (1988, 1989) is of particular interest here. Gauld reports a study of classroom learning about electric circuits, where students' ideas were elicited *before* the classroom presentation, *soon* after learning, and then again after a *delay* of some months. Gauld's work derived from a study by Cosgrove and Osborne (1995), who had devised a teaching sequence designed to bring about conceptual change by providing critical experiments to challenge students existing mental models of circuits. Comparisons between students' ideas before and soon after the sequence of lessons showed significant shifts in thinking towards the more scientific model: but a year later many of the students seemed to have reverted to their prior thinking.

Gauld found a similar effect in the follow-up study, which this time included interviews with students 3-4 months after the sequence of lessons. Part of the teaching sequence involved students predicting the relative sizes of ammeter readings in circuits. So, for example, a mental model of current being 'used-up' around a circuit would lead to a prediction of decreasing readings. The demonstration that all the ammeters would show the same reading would provide a challenge to this model, and encourage students to adopt the scientific model where current is constant around the circuit.

What is of particular interest to the theme of the present paper is that - despite the efficacy of the evidence in changing students' minds *in the short term* - Gauld found that in the delayed interviews some students justified a model of current being used up in terms of their recollection that ammeter readings decreased around the circuit. In other words, although the primacy of the evidence seemed to bring about conceptual change immediately after teaching, in time the memory of the evidence became altered to fit the preferred mental model.

So here we see that not only are perceptions of classroom demonstrations and experiments often distorted by students' existing conceptual frameworks (Driver, 1983), something known in memory research as 'encoding distortion', but even when initial interpretation of experiments are accurate, they may later give rise to false memories. This finding is not surprising in the light of memory research where eyewitness testimony has been found to be notoriously unreliable.

A different feature of memory has been studied in work deriving from the information-processing tradition, in relation to problem-solving in science. So recent work by Tsapalis (1998) has explored the way that problem-difficulty in organic chemistry depends upon the number of different chunks of information that need to be activated by a learner in order to successfully solve problems. His results suggest that information that is cued and so recalled in the context of some problems may *not* be accessed by the same learner in other problem contexts that include the same cues but require more information to be recalled or considered. This was found even though the problems used were considered to be well within the nominal capacity of the student's working memory. Such research is very significant for the way students are assessed. The items used by Tsapalis were authentic chemistry questions of a type commonly incorporated in formal tests and examinations - responses to which are commonly taken as *prima facie* evidence of whether learning has taken place. However, the relationship between (i) student learning, (ii) examination questions, and (iii) students' responses, is in reality much more complex than this (Taber, in press).

Various aspects of memory have received attention in psychology, although it has been suggested that - despite the topic being the subject of much literature - our current

understanding is in many aspects rather provisional (Ramachandran & Blakeslee, 1998). Here I provide a, necessarily very brief, review of current thinking about those aspects of memory relevant to the present study (Guildford, 1972; Sacks, 1985; Luria, 1987; Parkin, 1987; Ellis & Hunt, 1989; Baddeley, 1990; Eysenck & Keane, 1990; Rose, 1992; Anderson, 1995a, b; Erdelyi, 1996; Greenfield, 1997; Kellogg, 1997; Carter, 1998; Catania, 1998; Dawson, 1998; Pear, 2001; Sousa, 2001).

It is not known for certain whether once something is committed to long-term memory the trace can sometimes 'fade' away, but it is widely believed among memory workers that complete extinction of such traces is unlikely. Failures to remember information that has been learnt are generally considered to be due to an inability *to access* the memories (i.e. to activate the trace), so that the memory is considered *available but inaccessible* rather than unavailable. Memories not brought to mind for many years have been known to be triggered by drugs, medical conditions such as migraine or epileptic events, or direct electrical stimulation of the cortex during surgery, sometimes much to the surprise of the individual experiencing the reminiscence.

Accessing memories (in the absence of chemical, surgical or traumatic intervention) requires suitable cues to activate the memory trace. Although some memories seem to be much more readily accessed than others, much recall of information is highly dependent upon the cues available. Such cues can include appropriate category labels, or other information stored at the same time (whether conceptually related or incidental). In view of this, forgetting should not be seen as absolute, but rather seems to be best considered as not recalling a memory *in a particular context* - at a particular time, with the subject in a particular mood or environment (perhaps matching that when learning took place), in response to a particular question etc.

Just as forgetting is not an 'all or nothing' phenomenon, so the formation of a memory should not be considered as an event, but rather as a process. Current thinking is that memories continue to be developed over a long time span. The process of 'consolidation' takes place over months and years (largely during sleep) and results in memories being further integrated with other information in cognitive structure. Indeed, there is a phenomenon known as hypermnesia whereby greater recall of information becomes possible after increasing periods since initial 'learning'.

As well as this subconscious process of forming connections (and therefore changing) memories, it is also believed that each time a memory is activated and called to mind (i.e. transferred from long-term store into working memory) it is both reinforced and altered. So memories can be strengthened by the conscious process of reviewing prior learning and relating this to new material, but even without this deliberately directed activity similar evolution of memories is taking place outside of conscious control.

One consequence of the way that consolidation is a long-term process is the phenomenon of interference. When new learning is similar enough to poorly consolidated prior learning it is possible for the two sets of information to become conflated, so that cues that might have activated the earlier memory may instead activate the newer information. Conversely, newer learning that is not reinforced may become indistinguishable from previously consolidated learning. This means that checking that students can clearly distinguish novel concepts from similar notions learnt previously *soon after the presentation* of new material is *not sufficient* to ensure that the ideas will remain distinct over a longer time span.

Just as we are not aware how our memories may have been altered since initial learning, we also usually fail to appreciate the degree to which *memory is a reconstructive process*. When the available cues are sufficient to activate only some of the relevant

information we tend to fill in the details ('confabulate') to give the memory an overall coherence, so that some of what we 'remember' is actually *inference* based on making sense of the information successfully accessed. As each act of recall is believed to act as rehearsal to strengthen the memory trace such confabulations can become consolidated into memory (so that on future occasions the 'false' memories are part of the information genuinely recalled).

In the light of such a view of memory it seems less surprising that some of Gauld's interviewees confidently reported false records of classroom demonstrations that were meant to act as critical experiments. Indeed, such a perspective on memory helps explain why it is so common for students who attended, and attended to, their science classes to produce unsatisfactory answers to assessment questions on topics they have studied. Even when course material is initially understood as intended - which is by no means always the case - this does not ensure it will be activated and recalled in an unadulterated form when cued by the assessment question.

Where students from a cognitive psychology class *were* tested for their memory of the class over an extended period it was estimated that they could recall about a third of the material after about ten years. However the 'forgetting' was not uniform: rather there was a quick decline over a period of about forty months, after which memory seemed to stabilise, so that material still accessible at this time was not later 'forgotten' (Kellogg, 1995).

The present paper considers a case of science learning where the student was interviewed 46 months after completing his course, at the stage when the findings from the psychology class suggest memory of the learnt material may have stabilised. The case is complicated by the nature of learning about science, which at college level often involves developing, or even learning to disregard, models learnt in school science.

Evidence from a case study: The research context

The present paper considers evidence from a case study of student learning. Tajinder was an A-level student at a Further Education College in the U.K. who agreed to be interviewed, and to provide other research data as part of the *Understanding Chemical Bonding* project. In this project students were interviewed at several points over the two-year A-level chemistry course to investigate any development of their thinking about bonding and related topics. (A-level is a university entrance level qualification, typically taken at 18 years of age.)

Interviews were semi-structured, mostly centred around a deck of line diagrams representing atoms, molecules and related structures (i.e., interview-about-instances, Gilbert, Watts & Osborne, 1985), with discussion initiated by asking the student if they knew what the diagram was meant to represent; (and then if the information had not been volunteered) whether they thought there was any bonding present; and if so (if the information had not been volunteered) what type of bonding. Responses usually provided sufficient information to provide suitable opportunities for follow up questions to explore details of the student's thinking. Interviews were supplemented by the other means of data collection, such as Kelly's construct repertory test, (Fransella & Bannister, 1977; Taber 2002b), and student-generated concept maps.

One aspect of the research was a concern that students should feel that their involvement was worthwhile, and that they themselves were benefiting from the experience of talking about their understanding of the science in the interview sessions. Simple feedback was collected, which indicated that the (mostly 16-19 year old) students did indeed recognise the opportunity to explore the extent and limitations of their understanding as valuable for

them (Taber, 2002a).

Tajinder was especially keen to be involved in the research (Taber & Student, 2003), and so the opportunity was taken to arrange a significant number of interviews over the two-year course so that nuances of Tajinder's developing understanding could be explored in some depth. Some of the interviews followed the standard format using the deck of foci diagrams, but others centred on specific areas that were identified from previous interviews, or even from areas where Tajinder suggested points that he thought he would like to explore. In all Tajinder was interviewed on 23 occasions for periods that were usually about an hour in length, but sometimes stretched to around two hours. Interviews were recorded on audiotape, providing a considerable data set for analysis.

Aspects of the case study have already been reported in some detail (Taber & Watts, 1997; Taber, 2000a, 2001a), and so the account given in the next two sections of this paper ('What ideas did Tajinder use to explain chemical bonding during his course?' and 'How did Tajinder's understanding of chemical bonding develop during his course?') will be restricted to give just sufficient detail for present purposes.

Almost four years after Tajinder successfully completed his A-level course, and went onto University study, he agreed to return for a follow-up interview. Although Tajinder had studied a science-related degree course, it was his view that his college chemistry had not been needed in the course, and he had not really had reason to think about chemical bonding since his chemistry examinations forty-six months earlier. This paper considers the extent to which he was able to call upon the knowledge and understanding that he had developed during his college course (and which had been documented in such detail) during the delayed post-course interview.

What ideas did Tajinder use to explain chemical bonding during his course?

During his course Tajinder commonly explained the chemical bond in terms of three distinct explanatory principles (EP). If Tajinder was asked why a bond was formed he was likely to respond in three different ways, which may be paraphrased (Taber, 2000a):

- so that atoms could obtain full shells;
- to give a lower energy level;
- because of the attractions between charged particles.

Tajinder's progression in understanding the bonding concept in chemistry may be understood in terms of *the shift in the extent to which each of these three principles were employed* (Taber 2001a). At the beginning of his course Tajinder used one principle in explaining chemical bonding - the Octet Rule EP. This label given to this principle reflects the way it is an invalid extension of the octet rule, a useful rule-of-thumb for predicting common ionic charges, and the formulae of many simple compounds.

The Octet Rule explanatory principle

- atoms are stable if they have octets/full outer shells (terms which tended to be used as if interchangeable), and unstable otherwise;
- an atom that is unstable will want to become stable;
- the unstable atom will form bonds such that it seems to have a full outer shell, and thinks it has the right number of electrons.

The anthropomorphic language used here (the atom ‘wants’ and ‘thinks’) reflects the way Tajinder discussed these ideas.

Later in his course Tajinder increasingly applied two other explanatory principles - the Minimum Energy EP and Coulombic Forces EP - as alternative frameworks for explaining bonding. Although a physicist might see these two principles as closely related (with forces acting to bring about states of lower potential energy), Tajinder saw them as *distinct* ways of explaining aspects of chemistry.

The Minimum Energy explanatory principle

- configurations of physical systems can be ascribed an energy level;
- lower energy is more stable than higher energy;
- physical systems will evolve towards lower energy configurations.

The Coulombic Forces explanatory principle

- there is always a force between two charged particles;
- similar charges repel, opposite charges attract;
- the magnitude of the force diminishes with increasing charge separation;
- forces acting on particles may be balanced at equilibrium.

These three explanatory principles may be considered in terms of their scientific status and their explanatory power (see Table 1). The notion of Coulombic forces has considerable explanatory power, and is an accepted scientific principle. The notion of Minimum energy as an explanatory principle is scientifically valid, but does not offer much explanatory power by itself (if a process occurs it must lead to a lower energy state). The Octet rule provides much opportunity for use in chemical explanations, but it is not a valid way of explaining why reactions occur and bonds form. Despite this, it is commonly used by chemistry students even at undergraduate and postgraduate levels (Coll & Taylor, 2002).

Over time Tajinder applied his Coulombic Forces EP to an increasing extent, but he nevertheless continued to apply his Octet Rule EP throughout his course. A key finding was that Tajinder’s explanations reflected the coexistence of stable manifold explanatory schemes in cognitive structure (Taber 2000b):

- each of the EP was applied over *an extended period* of many months, so that they each reflect some relatively stable aspect of cognitive structure;
- each of the EP was used in *a range of ‘chemical bonding’ contexts*, so that they were indeed acting as explanatory *principles* rather than isolated facts about particular examples;
- *more than one* of the EP was often applied to *the same specific examples* (sometimes in the same interview, see below), so these were indeed *alternative* EP that were employed.

TABLE 1: *Tajinder's explanatory principles.*

Explanatory Principle (EP)	Status	Explanatory power
Octet Rule EP	Alternative conceptual framework	high
Minimum Energy EP	Curriculum science	low
Coulombic Forces EP	Curriculum science	high

From the perspective of orthodox chemistry, the Octet Rule EP is deeply flawed and the Minimum Energy EP would not be considered to be independent of the Coulombic Forces EP; but to Tajinder himself, the three EP were viewed as alternative narratives that could be employed to make sense of chemistry, depending upon the context. This is demonstrated by the following extracts from one of the interview transcripts.

Tajinder offers three explanations of the bonds in molecular oxygen

In one interview during the second year of his course (at the end of January 1994) Tajinder explained why oxygen atoms would join together to form a molecule. He was able to offer three distinct explanations (see Table 1).

TABLE 2: *Tajinder's explanations of the bonding in an oxygen molecule.*

EP used	Tajinder's explanation for bonding in an oxygen molecule
Octet Rule EP	1. "If we have just one oxygen atom it's got six electrons in its outermost shell...and to become stable it wants an octet state, well it wants eight electrons in its outermost shell to become stable, as it were. And then another oxygen with the same arrangement comes along, or is present. And a way for it to bond together, for both the atoms to have full outer shells or eight electrons in this outer shell is to share two electrons...each oxygen atom starts off with six electrons in its outermost shell, and it wants to gain two electrons, by some method, to have a full outer shell, eight electrons in its outer shell to become most stable. And a way of doing this is by gaining or by sharing two electrons with another oxygen atom. The other oxygen atom is in the same situation so it can share an electron with the other atom, so it thinks it's got a full outer shell."
Minimum Energy EP	2. "Well an oxygen starts off...the electronic configuration is $1s^2 2s^2 2p_x^2 2p_y^1$ and $2p_z^1$, and then it's got two gaps that can be filled, with electrons...And to become more stable, or at a lower energy, it can gain two electrons, to move down in the energy state, therefore becoming more stable, and so, because there's a gap there, there's a tendency for covalent bonding to occur, as in the case of O_2 , where electrons can be shared, so therefore the atom can be at a lower state in energy terms, and therefore more stable, and that's why any species takes place in bondings in order to lower the energy state or become more stable."
Coulombic Forces EP	3. "two oxygen atoms, and overall their core charge, which is their nuclear charge minus shielding electrons, is plus six, because the core charge, nuclear charge is plus eight because its got eight protons in it, and there's two shielding electrons, which are minus two so overall is plus six, on each one, and the placement of electrons, so we can forget about the 1s shell because it's gone into the core charge, so we've got 2s orbital, we've got $2p_x$, $2p_y$...and $2p_z$. Now in the $2p_x$ orbital we've already got two electrons in there and the maximum an orbital can hold is two electrons, but in the $2p_y$, there's only one electron at the moment and the $2p_z$ there's one electron, and the orbitals are a sort of a guide roughly to...where we think electrons exist...where they spend most of their time due to attractions, repulsions between...other charges in the atom, or in the species, so there's a plus six charge, and there's six electrons in the outer-shell, but there's a gap in the $2p_z$ and the $2p_x$ orbitals, where there's an electron short, where an electron could be filled, and that plus six charge can attract electrons from another species to pull into there...there's an empty space to be filled in the $2p_x$ and $2p_y$ orbitals, and when another species comes near enough which is another oxygen atom...then the electrons are attracted to one another and they form a bond."

The first explanation was based around Tajinder's Octet Rule EP, as "to become stable it wants an octet state, well it wants eight electrons in its outermost shell", "it wants to gain two electrons...to have a full outer shell, eight electrons in its outer shell". Forming a double covalent bond, "to share two electrons", was a way "for both the atoms to have full outer shells or eight electrons in this outer shell", because, when sharing electrons, the atom "thinks it's got a full outer shell".

The second explanation is based around Tajinder's Minimum Energy EP, where the driving force is "to become more stable, or at a lower energy", i.e. "to move down in the energy state, therefore becoming more stable", and from this perspective the sharing of electrons allows the atom to "be at a lower state in energy terms, and therefore more stable". According to Tajinder all bond formation occurs "in order to lower the energy state".

Tajinder's final explanation was based on the third of his explanatory principles, the Coulombic Forces EP. The atoms had "core charge...[of] plus six", and their electrons were in orbitals, due to the "attractions, repulsions" between the charges in the atom, and the "plus six charge can attract electrons from another species to pull into there", so when two oxygen atoms come close enough "the electrons are attracted" and they form a bond.

Tajinder was aware that he was providing several distinct sorts of explanations, but he did not feel that any one was inherently better or more correct,

I: You've given me three different versions of why oxygen forms this bonding process....Which of those three do you think is correct?

[Pause c.10s for thought]

T: I don't think any single one is totally correct. I think you can take bits out of each of them to make a best answer. But I think if I was in an exam then I'd use the second one [Minimum Energy EP] bit more than the other two....Depends whatever situation I'm in.

(I: Interviewer [KST]; T: Tajinder.)

How did Tajinder's understanding of chemical bonding develop during his course?

The main features of Tajinder's *developing* understanding of chemical bonding may be summarised in terms of a *shift* from 'octet thinking' to 'electrostatic thinking' during Tajinder's course, but there was not a complete *conceptual revolution* (Thagard, 1992). Rather, Tajinder's conceptual development may be described in terms of the *evolution* of a conceptual profile (c.f. Bachelard, 1968/1940; Mortimer, 1995) in which electrostatic explanations were increasingly dominant.

Strike and Posner (1985, 1992) have considered the rationale behind conceptual change, and discussed the factors which influence the status of competing conceptions. Thagard (1992) uses the notion of 'explanatory coherence' to explain when a major shift of conceptual framework would occur. The changes in Tajinder's thinking were not abrupt, and have been described in some detail in terms of the 'shifting sands' of his conceptual ecology during the course (Taber, 2001a).

So, for example, when Tajinder had available a new concept of electron density he was able to re-conceptualise atoms' desires for full shells, as a desire to obtain a greater electron density around them. Although this was still an anthropomorphic notion, it was able to act as a suitable intermediate conception (Driver, 1989) that could be related to thinking about electrical forces - an atom with greater core charge pulling more electron density towards itself.

FINDINGS: A CASE STUDY OF REMEMBERING AND FORGETTING COLLEGE CHEMISTRY

What did Tajinder ‘remember’ about the topic of chemical bonding four years after completing his course?’

If Tajinder’s memory had not changed (i.e. in terms of the structure and accessibility of the chemistry he had learnt) since the end of his chemistry course then his answers in the delayed post-course interview would be similar to those given in his final interviews on the course almost four years earlier. A naive view of memory would suggest that this level of recall is unlikely, and that some of his previous learning would be forgotten over the many months of disuse. However, the research into memory processes reviewed above suggests that the situation may be more complicated, as consolidation of learning since completing the course, and the reconstructive nature of remembering could both act to distort Tajinder’s understanding of his chemistry at the delayed post-course interview.

The final interview with Tajinder during his A level course took place during May 1994, near the end of the second year of his course, a matter of days before his A level examinations (which he took during June 1994). Tajinder returned to the college to be interviewed again during April 1998, during the fourth year of his University studies. Tajinder was interviewed in private, and the session was recorded on cassette tape with his knowledge and permission. In this section key features of Tajinder’s comments in the interview will be reported. Sufficient detail will be provided to allow a comparison with his previously demonstrated level of knowledge.

The covalent bond

The interview commenced with Tajinder being asked about atoms, and he was able to discuss the arrangement of positive and negative charges present. When Tajinder was asked if it was possible to remove an electron from an atom he suggested that this could happen if there was “somewhere for it to go” such as “another atom”, and gave the example that “if two oxygen atoms come together, they form a molecule”:

- I: So what stops them falling apart and just becoming atoms again?
T: They come to a more stable energy level, is it, where they’re happier to be in that state, which is a lower energy. So therefore they’ve got no reason to go back to being where they were, if they drop down a level. ...
I: Do you know why [the oxygen molecule is at a lower energy level than separate atoms]?
T: Is it the fact that they form something called a covalent bond, which entails that the oxygen atom thinks that it has a full outer shell of electrons therefore it makes it less reactive.
I: Okay so if you start off with your two separate atoms, what has to happen for them to become a molecule?
T: There has to be another oxygen atom for it to join to, and they sort of come together, and where there’s six electrons in the outer shell, so then two of the electrons would form a covalent bond where they’d share...so sort of they would they’d come together so the outer shells of where the electrons are placed would sort of overlap one another therefore it would think it has eight electrons in its outer shells, whereas it doesn’t really...all atoms would like to have a full outer shell, and therefore be the most stable atom they could be. And therefore they try to do this by either bonding with something, or reacting with something, which is the same sort of thing...to have a full outer shell of electrons and therefore be at lowest energy.
I: And those two things are related together?
T: I think so. Not quite sure.

The ionic bond

When Tajinder was then asked whether there was another way an electron could be removed from an atom, he interpreted this as being asked about another form of bonding:

- I: Is there any other any other way you can take electrons from atoms apart from have somewhere for them to go?
- T: Do you mean another type of bond? There's ionic bonding as well, which is where the atom loses its electron completely, and then they form ionic bond.
- I: Okay, can you give me an example of this ionic bond then, give me an example of what might do this?
- T: Sodium and chlorine.
- I: So what happens in the case of sodium and chlorine?
- T: Well is it sodium's got just one outer electron, and chlorine's got seven outer electrons, therefore the aim is to have a full complete outer shell...therefore the sodium donates the electron to the chlorine and therefore the sodium has an overall positive charge, and the chlorine gaining an electron has an overall negative charge, and therefore the positive and negative charges can attract one another, and then you have what is known as sodium chloride, and this forms a molecule within itself.
- I: What exactly is the ionic bond in that, if you had to say that 'the ionic bond is'?
- T: Ionic bond is the bond which is formed due to the presence of a positive and a negative charge, where the positive charge has come about by the loss of an electron to a negative charged body.

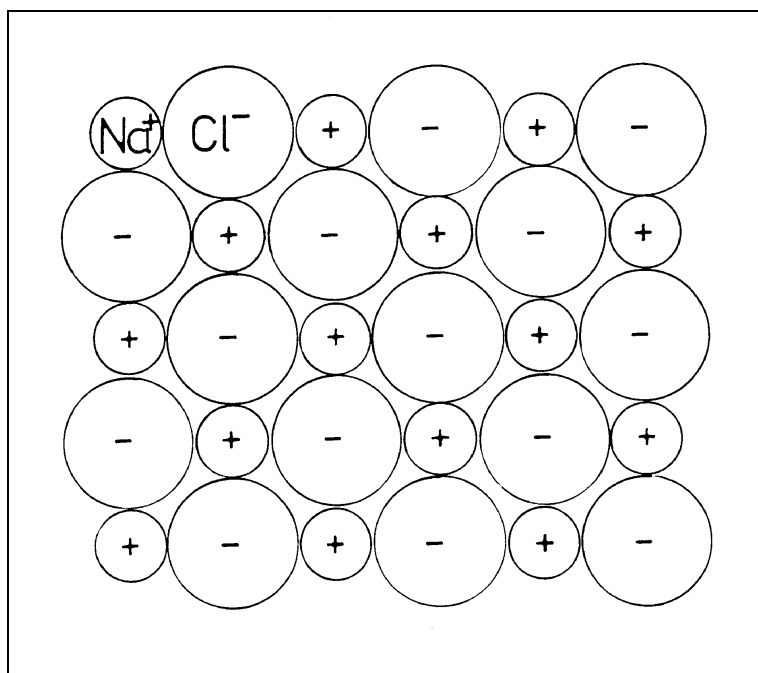


FIGURE 1: *Focal diagram of sodium chloride lattice.*

Later in the interview Tajinder was shown a focal diagram (Figure 1) meant to represent part of the ionic lattice in sodium chloride. He was asked about the bonding present. Tajinder was quick to identify the presence of ionic bonds, but when asked to locate them changes his mind: the diagram does not show ionic bonding but rather represents "sodium ions and chloride ions, which are attracted together due to their positive and negative charges". It is only after some thought that Tajinder recognises these attractions as

the bond: “the bonds are the fact that there’s interactions between positive and negative forces”:

- I: What do you think that’s meant to represent?
T: Sodium chloride structure.
I: Do you think there’s any bonds there?
T: Ionic bonds.
I: So where would there be ionic bonds in that diagram?
T: Well it’s not, no what it’s meant to represent is sodium ions and chloride ions, which are attracted together due to their positive and negative charges.
I: So any bonds there?
[pause for thought]
T: The bonds are the fact that there’s interactions between positive and negative.
I: Right, so are there any bonds there? I think you’re hedging a bit?
T: Yes there are, there are bonds there.
I: Right okay, and are they ionic bonds?
T: Yes, because ions are attracted to one another, yes.

The metallic bond

Next Tajinder was asked if there were any other types of bonding, and he suggested metallic:

- I: Are there any other types of bonding?
T: Er, metallic bonding, I think.
I: So what’s that then?
T: Metallic bonding’s like if you have a whole piece of metal it’s obviously just not one atom, it’s millions and millions of atoms, and what happens is, to form a lower energy level the atoms are able to come together and where the electrons on the outer shell are able to form a sea, sort of thing, where the electrons are able to move around the different nucleuses [sic] of the atoms.
I: So why is it that metals exist as these millions and millions of atoms with this sea, rather than just exist as separate atoms? Why do metallic bonds form?
T: It’s just that this is a lower energy level, I think.
I: Not sure why?
T: Is it the fact that if you have just a single atom, say of sodium, then it’s got one electron in its outer shell, if it forms, a body of sodium atoms there’s not just one single electron for the atom, there’s millions and millions of electrons swimming around, so therefore it sort of makes out that there’s a full outer shell, or it might be at lower energy level because of the amount of electrons which are moving about all over the place, so that might sort of stabilise it a bit more or make it seem like it’s at a lower energy level.

A definition for the chemical bond

After having discussed covalent and ionic bonding Tajinder was asked to give a general description of chemical bonding, and - consistent with his explanations to that point, he suggested that “it’s the movement of electrons to a another atom, or the sharing of electrons, to decrease the energy level of the whole molecule”.

After then discussing metallic bonding Tajinder refined his definition of chemical bonding to a “movement of electrons”, that would be tied to the lowering of energy, by giving atoms full outer shells,

“Why do bonds form? So the atom, or the two atoms or molecules which are bonding together are at a lower energy level, due to the movement of electrons. All atoms are trying, their aim, their goal, is to have stable configuration, which is to have a full outer shell of

electrons, however many electrons the shell can hold, so therefore by trying to do that they forms bonds.”

Tajinder was unable to think of any other types of bonding, apart from the covalent, ionic and metallic cases he had discussed.

Dichotomous classification of bonding

When discussing a molecule of hydrogen chloride Tajinder originally suggested this would have ionic bonding:

- I: So what kind of bond do you get in hydrogen chloride then?
 T: Ionic bond, uh no. An ionic bond? Yes, yes. It's an ionic bond.
 I: Yes, so is it H^+Cl^- ?
 T: Yes.
 I: So hydrogen's lost all the electrons then?
 T: Yes.

He later revised this to suggest the presence of partial charges (see below). He was *describing* polar bonding, and - although he did not label the bonding as polar - he related this to the difference in the charges on the nuclei. Later in the interview, Tajinder was shown several of the focal diagrams used in the original research (Figures 2-4), and asked about a number of other compounds that might have been expected to have polar bonds.

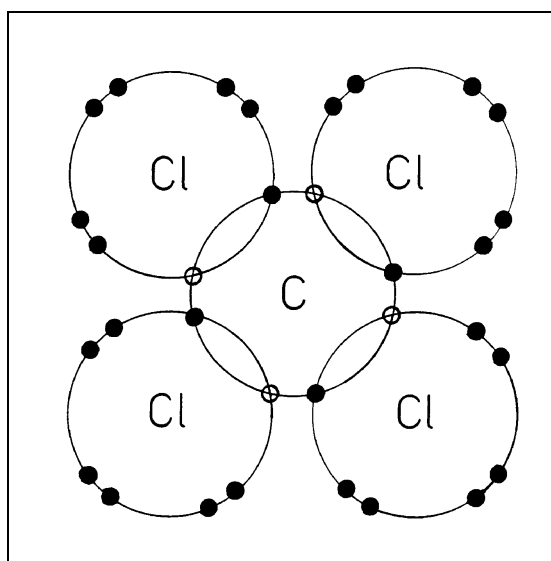


FIGURE 2: *Focal figure of a tetrachloromethane molecule.*

When Tajinder was asked about a figure representing a molecule of tetrachloromethane (Figure 2) he labelled the bonding as “covalent bonds” because of “the fact that they were sharing electrons, electrons were being shared”.

Even though the bonding electrons were described as being shared, they were still considered to ‘belong’ to specific atoms rather than to the molecule,

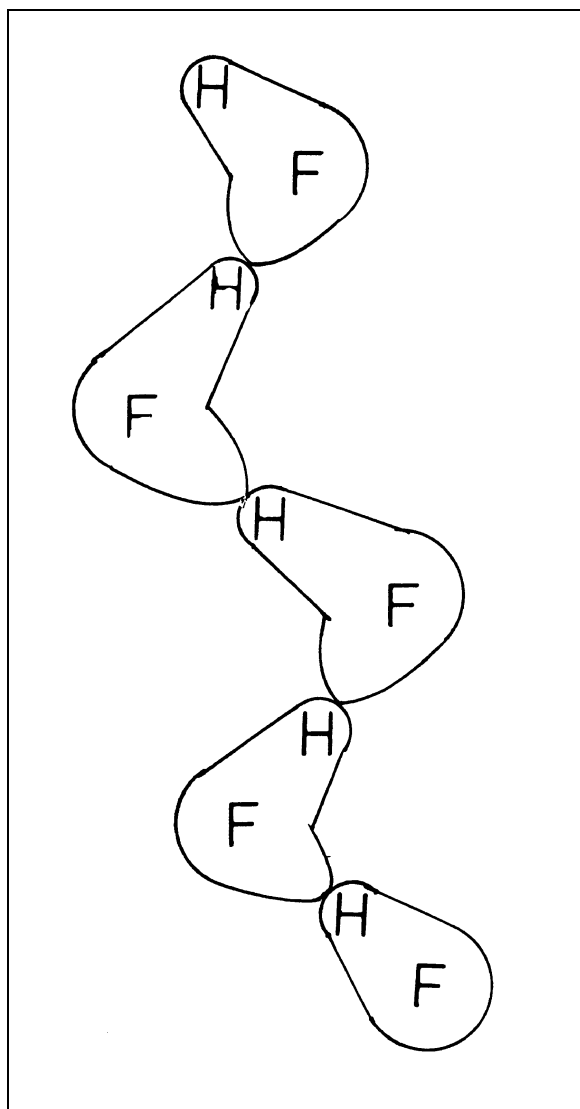


FIGURE 3: *Focal diagram of hydrogen fluoride molecules.*

“The lighter ones are the carbon electrons and the darker ones are the chlorine, electrons...there’s no difference, it’s just trying to distinguish which one belongs to which.”

Another focal diagram presented to Tajinder (Figure 3) showed an arrangement of hydrogen fluoride molecules (similar to the configuration that molecules take up in liquid hydrogen fluoride). The diagram was meant to imply both the polarity of the HF molecules, and the interactions between the molecules (i.e. hydrogen bonding).

Tajinder recognised that the hydrogen “has a δ +ve charge around it slightly compared to the fluoride...because the fluorine’s got a larger nucleus, so it’s got more attraction for the electrons”, but he nevertheless labelled the bonding (both the intra- and intermolecular interactions) as “covalent bonds”. So in this context Tajinder recognised the dipolar nature of the molecules, but mis-identified both the polar bonding and the hydrogen bonding as covalent.

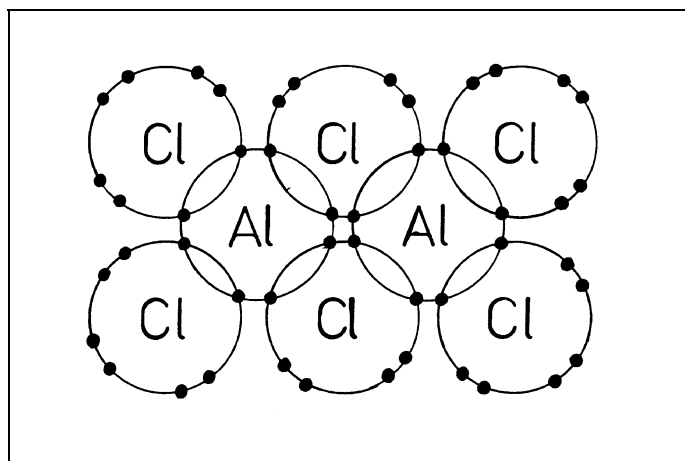


FIGURE 4: *Focal diagram of aluminium chloride dimer.*

Another of the focal diagrams (Figure 4) shown to Tajinder was meant to represent a dimer of aluminium chloride: a chemical species with polar bonds and dative bonding. Tajinder misinterpreted the diagram as showing part of a more extended lattice, but (again) thought that the only bonds present would be covalent,

“well if you form a molecule of it and then obviously because there’s more aluminium chloride molecules around, they can all join together, and just form covalent bonds in-between them all”.

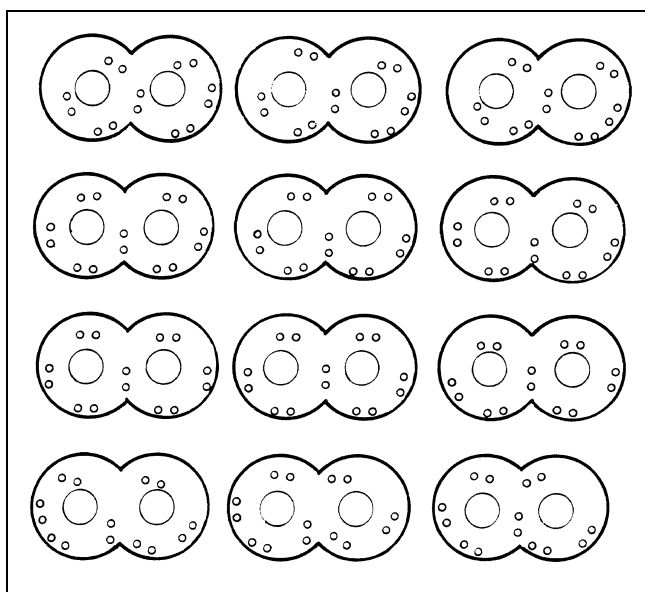


FIGURE 5: *Focal figure representing molecules in solid halogen.*

As a final example Tajinder was shown a focal diagram (Figure 5) meant to represent molecules in solid halogen, such as solid iodine. The detail in the diagram was intended to support an explanation for why lattices of neutral molecules should form (i.e. the transient dipoles of van der Waals’ forces). Tajinder seemed to focus on the level of a single molecule, which he identified as “two chlorine or fluorine atoms perhaps”. Tajinder identified the bonding as “covalent bonding”, although he also recognised the transient and fluctuating

nature of the charge distribution in the molecule,

“I think all it’s trying to show is, if this was like pictures taken of two atoms, then at any single moment the electrons wouldn’t be in the same place because they’re always moving around to different shells, so therefore one end is always slightly δ +ve, and one is slightly δ -ve, and therefore there’s always an interaction between a positive and negative because they’ll obviously attract, so then the overall structure’s always changing from one time to another, therefore it’s interaction between the charges.”

Tajinder explains the bonding in the molecule in electrical terms, but *not* as the attraction between the nuclei and bonding electrons, but rather the attraction between the partial charges at the two ends of the molecules. He did not comment on how the patterns of charge distribution in the molecule could influence other molecules.

Why reactions occur

Early in the interview Tajinder had talked about bond formation between *atoms*, a situation which does not reflect real chemical reactions (where the reactants are normally molecular, metallic or ionic). Tajinder was asked again why sodium and chlorine should react:

- I: You were talking about reactions...and you mentioned about the reason why sodium might react with chlorine...and the reason you said sodium would react with chlorine was because?
- T: All atoms strive to have a stable configuration, stable number of electrons in its outermost shell, and the easiest way for sodium to do that, is if it’s got chlorine in the vicinity to react with chlorine and to have form ions, and therefore the ions can attract one another and form a bond which forms the structure of sodium chloride.

Tajinder appeared to still be thinking in terms of discrete atoms, and so he was gently reminded that sodium exists as a metal, and that chlorine is molecular:

- I: So, if I had sodium metal, rather than sodium atoms, would that still react with chlorine?
- T: Yes.
- I: Why does it do that?
- T: Because it goes from sodium metal to a sodium chloride crystal, it’s at a lower energy again.
- I: And why is it a lower energy?
- T: Because of the fact it’s more stable. Because instead of having a sea of electrons, where it feels like it’s at a lower energy compared to an atom, it’s even lower energy because it does have a noble gas configuration. ...
- I: And what about the chlorine? The reason the chlorine reacts with sodium was because?
- T: Because it would be a lower energy level.
- I: And why is it at a lower energy when it forms sodium chloride?
- T: Because having just the chlorine atom, it’s got the configuration of 2.7, it’s got seven outer electrons, so by the fact that it gains another electron, makes it into a noble gas configuration...
- I: So if I now take my chlorine, not my chlorine atoms, but my chlorine gas, made of chlorine molecules. Will that still react with sodium?
- T: Yes.
- I: Why?
- [Pause for thought]
- T: The fact that in the final state atoms of both molecules would have a lower energy level, and the fact that they are able to break their covalent bonds, and break the metallic bonds, or to become free atoms, and to join one another, they have enough energy to do that, to go through that process, and at the end state they have a lower energy level.

Tajinder was asked about another example: the reaction between chlorine and hydrogen. Despite the question being carefully phrased in terms of the substances not separate atoms (“chlorine, as molecules...hydrogen, as molecules”), Tajinder still initially gave an explanation in terms of the electronic configurations of separate atoms,

- I: So, I'll ask you a different question instead then, I've still got my chlorine, as molecules, but I'm now going to mix it with some hydrogen, as molecules. Do you think hydrogen will react with chlorine?
- T: Yes.
- I: Yes? What do you get when hydrogen reacts with chlorine?
- T: Hydrogen chloride.
- I: Why does hydrogen react with chlorine?
- T: The fact that hydrogen has got one outer electron, and to form a stable noble gas configuration it would lose its electron.
- I: Yes?
- T: Yes.
- I: So, this is hydrogen gas we are talking about?
- T: Yes.
- I: Hydrogen molecules?
- T: Yes.

When it was drawn to Tajinder's attention that “I'm taking these H₂ molecules, and Cl₂ molecules”, he initially could not suggest a reason for the reactions. However, after some thought he suggested that,

“Is it something to with, because when there's two hydrogen atoms together, when there's hydrogen molecule, the nucleuses [sic] only have a certain share of the electrons as it were, in equal share, and so if the hydrogen atom reacts with a chlorine atom is it a different share of the electrons, and therefore something to do with that?”

This is a sophisticated argument based on the idea that the molecules in elements have covalent bonds, but that the bonding in many compounds is polar. When asked about the bonding in the product, Tajinder initially suggested it would be ionic (see above), but then changed his mind suggesting that the reaction had “something to do with δ^+ and δ^- and that”,

- T: Because hydrogen chloride is only ionic in aqueous solution, and it's not completely ionic when it's in normal gas, so it's sort of got δ^+ ve charge and δ^- ve. So by the fact that the hydrogen loses the electron to the chlorine, it's not fully gone, but then the hydrogen has an overall positive charge, and the chlorine has an overall negative charge which attract one another, and they sort of form together.
- I: Right, why do you think you get this overall positive and negative charge, why do you get this δ^+ and δ^- ?
- T: Due to the fact of the movement of the electron away from the hydrogen atom.
- I: Why does the electron move away from the hydrogen atom?
- T: Because it's got a bigger attraction towards the positive, larger positive chlorine nucleus...I just remembered one of your diagrams.

So in this portion of the interview Tajinder seems to have moved beyond discussing reactions in terms of obtaining full shells though electron sharing and transfer, and to be considering more subtle shifts in electron density.

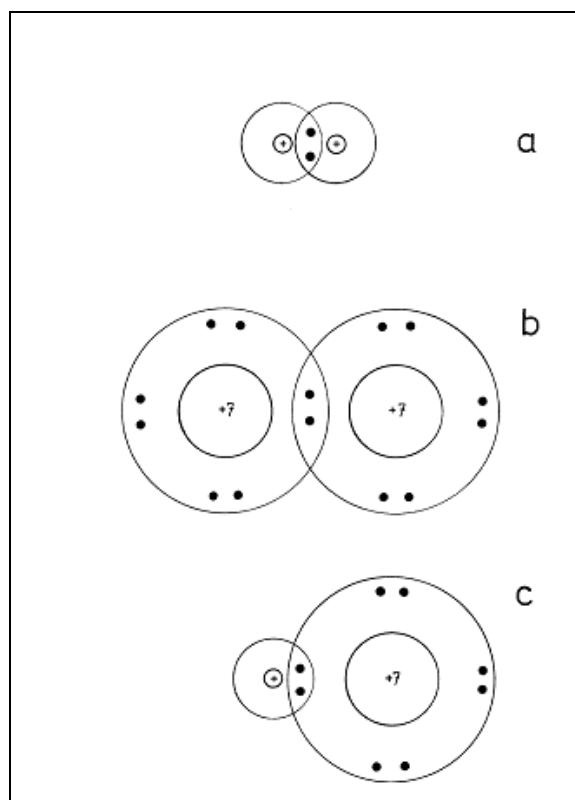


FIGURE 6: Focal diagram showing molecules of hydrogen, chlorine and hydrogen chloride.

As Tajinder seemed to be accessing electrostatic arguments in this context he was later given the opportunity to revisit his explanation of why hydrogen and chlorine should react. He was shown a focal diagram (Figure 6) of the molecules involved in the reaction between hydrogen and chlorine (in which reactant molecules, as well as product molecules, have noble gas electronic configurations), to see if he would now suggest the interaction between molecules was mediated by electrical forces. Tajinder took the opportunity to develop his explanation in terms of the unequal share of electrons in the product,

“Two hydrogen nuclei would have the same positive charge from each nucleus, therefore they’d have equal share of the electrons, obviously not at one moment, but overall it does. And same with the chlorine. So then if they come together, so if they whack into one another with a certain amount of energy, that energy’s able to break the covalent bonds between the two molecules, and to form a hydrogen chloride molecule where because the large chloride positive nucleus has a greater attraction than the positive of the hydrogen, it feels like it’s got a more share of the electrons, therefore it feels at a lower energy, and the same with the positive hydrogen nucleus, which feels it’s got a larger share of the electrons there.”

Recalling, forgetting and reconstructing memories - What Tajinder did, and did not, bring to mind four years after completing his course

It is clear from the evidence reported in this paper that Tajinder’s understanding of chemical bonding is a complex phenomenon. Yet this is surely *generally* true of learners’ ideas about science topics, and therefore it is valuable to explore how Tajinder’s presentation in the delayed post-course interview compared with his understanding of the topic revealed in interviews *during* the course.

The first point to make is that Tajinder was able to immediately and coherently discuss aspects of an abstract scientific topic, chemical bonding, that he reported he had not had reason to think about since completing his college chemistry course (forty six months earlier). Although Tajinder's explanations would not be described as model answers, they were impressive for an ex-student of the subject. Tajinder seemed to have sufficient information from his study of the subject stored in long-term memory, *and* readily accessible, to be able to enter into meaningful discussion of the scientific ideas.

Despite his creditable performance, it is noticeable that a number of relevant concepts and principles that Tajinder had previously demonstrated were *not brought to mind* at points where they might have been expected to have been cued by the questioning.

So when Tajinder was asked about the possibility of removing an electron from an atom his thoughts turned to first covalent bonding, and then ionic bonding. He did not consider the possibility of an atom being ionised except in the context of the electron being transferred to another atom. Yet ionisation energy had been a concept that Tajinder had studied in some depth, and he had spent considerable time in earlier interviews trying to explain patterns in ionisations energies.

Even more significant omissions were categories of chemical bonding beyond the classes of covalent, ionic and metallic bonds, because in these cases Tajinder discussed aspects of the bonding that might have been expected to cue his prior learning. So Tajinder, in effect, referred to the polarity of bonding without recognising polar bonding as a category. He even suggested that the separation of charge within a molecule (permanently in HCl and HF, or transiently in a halogen molecule) would be responsible for holding the single molecule together, whilst apparently being unaware of the role that such partial charges could play in holding together adjacent molecules by hydrogen bonding or van der Waals' forces.

This reflects Tajinder's level of knowledge *at the start* of his college course, when he was aware of only three categories of bonding: covalent, ionic and metallic. It appears that other types of bond he had learnt about during his college course and discussed in some detail in interviews had been 'forgotten', i.e. if traces of this knowledge were held in memory then those traces were not activated, and *the memories were not accessed*, during the interview.

As reported above, Tajinder's explanations of bonding during his course could be classified as fitting one of three explanatory principles. Two of these (the Octet Rule EP and the Minimum Energy EP) were much in evidence during the delayed post-course interview, and seemed to be brought to mind spontaneously when Tajinder was asked to explain about bonding.

However, the third type of explanation (the one having both high explanatory power *and* scientific validity), his Coulombic Forces EP, was much less in evidence. Tajinder was certainly very aware of the importance of the presence of charges in the chemical contexts discussed. He also recognised the role of the attracting charges in the case of the ionic bond - at least once electron transfer to form the ions was considered to occur, if not as a cause of the hypothetical electron transfer event itself. As the interview proceeded, and Tajinder was pushed to explain why there should be partial charges on atomic centres in molecules, he did recall Coulombic explanations given in class ("I just remembered one of your diagrams"), and so was able to explain the charge separation in molecules as being due to the greater pull on electrons of a more positive atomic nucleus.

Yet, despite this, Tajinder did *not* think of bond formation, or chemical reactions, being due to the electrical interactions between the interacting species. Even when he was discussing the presence of charges, and the influence of nuclear charges on electrons, questions about what bonds were and why they should form channelled his thinking away from electrostatic mechanisms to anthropomorphic notions of atoms trying to feel stable by

getting closer to full shells.

So Tajinder's explanations of bonding and chemical reactions tended to be based upon his Octet Rule EP and Minimum Energy EP. However, these - previously somewhat distinct - ideas seemed to have become more closely associated over the period since he completed his course. So, according to Tajinder, two oxygen atoms would form a bond because they would be *happier* to be in the lower energy state, which would occur when they *thought* they had full outer shells. By the time of the post-course interview the two distinct principles seem to have become integrated into a super-ordinate explanatory framework: all atoms like to have, and try to have, full outer shells and so be at the lowest energy.

At the start of his college chemistry Tajinder, like many students at that stage, had believed that chemical reactions occur to allow atoms to obtain full outer electron shells. This explanation seems tenable as the students often tend to conceptualise chemical reactions as occurring between discrete atoms (Taber, 2003a). One of the reasons why students like Tajinder are persuaded to adopt electrical explanations for chemical processes (in place of anthropomorphic explanations about octets and full shells) during college chemistry is that real chemical reactions seldom take place between discrete atoms, so reactant species usually 'satisfy' the octet rule as well as product species (see fig. 6). Then, once bonding is seen in electrostatic terms, it becomes easier for students to accept new categories of chemical bonding which could not be explained in terms of acquiring full shells terms (such as hydrogen bonding).

In the delayed post-course interview Tajinder reverted to making the 'assumption of initial atomicity' (Taber, 2003a), i.e. he described chemical reactions (between sodium and chlorine, between hydrogen and chlorine) as if the reacting species were discrete atoms: so the atoms of sodium, chlorine and hydrogen were said to be striving to obtain noble gas configurations.

However, when Tajinder was challenged on this point, he did not drop his allegiance to this type of explanation: rather he offered more sophisticated versions of the argument to meet the criticism. So the electronic arrangement in sodium metal (where the atoms were said to make out that they had full shells) 'felt like' a lower energy arrangement than being isolated atoms, *but* was not as low energy as in sodium ions where a noble gas configuration had really been obtained. In hydrogen chloride, with its asymmetric charge distribution, the atomic centres were able to 'feel like' they had obtained a greater share of the bonding electrons than in the elements.

So during this interview Tajinder had revealed a new perspective on bond formation as involving a movement of electrons that could allow an atom to "feel like it's got more share of the electrons, therefore it feels at a lower energy". Perhaps this notion *had the potential* to act as an intermediate conception, a 'conceptual stepping-stone' towards an explanation closer to the scientific model. During his course, Tajinder's notion of atoms trying to acquire more electron density seemed to have functioned in this way (Taber, 2001a), but within the limited timeframe of the post-course interview his elaboration only operated as a way of 'patching' his Octet Rule EP.

So overall it was found that almost four years after Tajinder finished his study of chemistry he was able to remember a good deal of the material he had learnt in school science and college chemistry. However, the ideas elicited during the delayed post-course interview better matched ideas near the beginning of his course: he seemed to have 'forgotten' about intermolecular bonding; and had reverted to relying heavily on anthropomorphic explanations about atoms 'trying' to obtain full shells, rather than considering how electrical forces could bring about chemical processes.

Yet to say that Tajinder recalled some of his chemistry, but forgot other elements, or

to suggest that his discussion of chemistry had regressed since the end of his formal study of the subject, misses a significant element. Such a summary would ignore the way that, in the post-course interview, Tajinder was able to present a fairly well integrated mental model of the bonding process that in some ways *went beyond* his previous thinking. Ideas that had formerly been considered as largely distinct explanatory principles, were now closely integrated in Tajinder's answers. He also presented a new way of defining bonding - as a movement of electrons that allowed atoms to feel they were closer to having full outer shells.

There is no way of knowing to what extent these novel features of Tajinder's explanations were the result of consolidation (i.e. the way that memory becomes reorganised and better integrated subconsciously over long time periods after learning initially takes place) or the reconstructive nature of recall whereby inferences are drawn to construct a coherent account from incomplete recall. What is clear is that Tajinder's 'knowledge' about these aspects of chemistry not only showed deficits compared to his previously demonstrated thinking, but also additional features that had not been elicited before.

DISCUSSION

The wider implications of the study

The literature on memory reviewed above suggests that over a period of months and years much of the material that has been learnt in a formal course of study (but not consciously reviewed since) ceases to be *readily* accessible in memory. Although traces may well be present in long-term memory, many of these would become increasingly difficult to activate through the available cues over time. It has been suggested that after a period of about 40 months or so such memory stabilises so that what is then readily recalled remains easily accessible indefinitely. Our understanding of how memory works also suggests that stored material continues to be consolidated - strengthening and altering the traces - over months and even years after being initially committed to memory, through subconscious processes that we neither control or even notice.

There seems to be little exploration of these ideas in the science education literature, although Gauld's (1988, 1989) reports of false memories being used as evidence to support alternative frameworks in the context of circuit theory demonstrate their relevance to the educational process. If a spiral curriculum (Bruner, 1960) revisits topics at different grade levels, but there is little reinforcement of the taught curriculum models in the meantime, it is likely that students will bring incomplete and distorted versions of the prior learning to the more senior classes.

The present paper presents a case study of remembering and forgetting - of what Tajinder brought to mind almost four years after he completed his college course - that is consistent with the memory literature: evidence of significant long term recall, but recall that was imperfect and included some distortions.

Previous accounts of Tajinder's case report how his ideas progressed during his chemistry course, so that he relied less on his Octet Rule explanatory principle. The new research in this case suggests that the gains Tajinder made, in terms of a more scientific mode of understanding, *during* his course seem to have been 'lost' over the subsequent the years when he had no reason to think about the topic.

The *specific* findings of the present study are of interest in their own right. Tajinder's Octet Rule EP reflects a very common alternative framework in chemistry that is considered to be a major potential obstacle to learning college-level chemistry (Taber, 1998). This 'octet' framework is a conceptual framework in the sense of Gilbert & Watts' (1983) use of

the term - a model representing *general features that were commonly found in the distinct ways of thinking of many individual learners* - in other words few students would match the framework precisely, but it will reflect some of the key aspects of thinking of many students. Near the start of his college course Tajinder demonstrated a number of features of this way of thinking, his Octet Rule EP being an obvious example. Students seem to find the Octet framework persuasive, and it has been found to be tenacious (Taber, 2002b) so that students commonly interpret chemistry through aspects of this conceptual framework even after they have been taught about more scientifically valid alternatives. Over his course Tajinder learnt to rely less on this way of thinking about chemistry (Taber, 2001a).

In the delayed post-test Tajinder's thinking could be considered to have 'regressed' in these terms as he showed a number of features of octet thinking: applying more restricted categories of bonding; defining covalent and ionic bonding in terms of electron sharing and transfer; considering bonding electrons in molecules to 'belong' to specific atoms; considering polar bonds to be covalent *or* ionic; ignoring bonding between molecules; and explaining reactions as if the reactant species were discrete atoms. In particular Tajinder's Octet Rule EP with its highly anthropomorphic explanations (of atoms thinking, aiming, liking, trying, striving and feeling) is very typical of the alternative framework (Taber, 1998).

Of the three explanatory principles for bonding that Tajinder had commonly used during his college course, his Coulombic Forces EP should have been the highest status (Thagard, 1992; Strike & Posner, 1985, 1992): it was coherent, applied both to examples that could and could not previously be explained, it had a wide range of application and was consistent with explanations used in the other parts of the course (about atomic structure, patterns in ionisation energy, shapes of molecules, etc.) Furthermore, at several points in the interview Tajinder discussed ideas that might have been expected to channel his thinking along these lines (de Bono, 1969). Yet Tajinder seemed to have 'regressed' to largely using his pre-college level ideas as a starting point for answering interview questions.

The octet framework could be described as insidious, as it provides students at the end of school science with a model of the molecular world that many find convincing. If a key aspect of progression in this aspect of college chemistry is students learning to move their thinking away from the alternative framework they bring from school science, then the present paper provides an unwelcome message.

Limitations of the present study

There are clearly limits to the significance that should be attached to any single research report. There are the inherent limitations to any case report, and particular weaknesses of the present study. It is not appropriate to generalise from this singular case to draw general conclusions about the extent to which students (in general) retain their science (in general). Tajinder cannot be considered as a typical student - if only because most students are not subject to intense research interest during their course, with whatever side effects that may have. In any case, the extensive literature on learners' ideas in science suggests that individual differences need to be taken into account in any consideration of 'how students learn science'. It seems reasonable to assume that Tajinder's level of recall is likely to be well above average: he achieved the top grade in his examination, and had spent many hours explaining his thinking in depth in quite intense interview sessions during his course (Taber & Student, 2003). However, qualitative research of this type is not intended to provide generalisable results in any 'statistical sense' - rather a case is offered to the reader as something that may be considered to offer insights into other similar cases (Eybe & Schmidt, 2001; Kvale, 1996).

There are methodological limitations of this particular study. This case report presents a motivated student who made substantial progress in understanding a chemical topic during his studies, but later seemed to regress significantly. A single interview provides a limited opportunity to explore Tajinder's thinking – the answers he thought to give in response to the questions asked, and in view of the particular diagrams he was asked to consider. (That the interviewer, form of questioning, and foci diagrams were all familiar to Tajinder from the earlier research does increase the strength of the comparisons.) Perhaps had Tajinder been available for a series of post-course interviews then he would have produced evidence of being able to recall more. Had the interview reported here been extended to several hours, to include more examples and to challenge Tajinder's responses, then perhaps his comments would have started to better match his thinking at the end of his chemistry course.

It is important to make these points even though they are purely hypothetical: there was only one post-course interview, involving a particular sequence of interviewer's questions and foci diagrams and of a certain duration. The key point here is that this is all we ever measure when we question students – how they respond to a certain stimulus in a particular context. As teachers, as examiners, as researchers: we collect responses to a specific set of questions and cues. We can never be *sure* what different questions (or question sequences) or cues would elicit. We can never be certain about what students 'know' – only what they tell us they recall in a particular context. As Tajinder's post-course interview proceeded he gave answers that indicated he was recalling more of his chemistry. He *appeared* to have forgotten other aspects of prior learning, but it is quite likely that under appropriate conditions cues could have been presented that would have activated other memories and 'brought them to mind'. This point is particularly salient in the context of assessment – examinations do not find out what students know, but what they can recall in response to a specific question providing particular cues (Taber, in press).

The value of further research

If the role of the teacher is to bring about learning then it is important we know what we think learning is, and how we expect to recognise it. It is too simplistic to think in terms of what the student 'knows', as knowledge that is stored in permanent memory and available in principle may sometimes only be activated by very specific (and even extreme) cues. The present study suggests that the science education community should take seriously, and focus more research attention on, the way memories are accessed, and how they may become inaccessible *or modified* when a topic is not regularly reviewed in class.

This case study also suggests that even when a student makes considerable progress in moving beyond a strongly held alternative conceptual framework *during* a teaching sequence, the memory traces left by the prior learning may ultimately be more persistent. This seems to have been the case in Gauld's study, and may also explain - for example - why so many students exhibit an impetus-like frameworks for explaining motion (Watts and Zylbersztajn, 1981; Gilbert & Zylbersztajn, 1985) even after learning about Newtonian dynamics (McCloskey, 1983).

If this effect (of prior alternative frameworks being easier to access than later learning, as time passes after teaching) is found to apply more widely, then it has clear consequences both for the importance of avoiding initially teaching over-simplified models that may appeal to students' thinking (Taber, 2002b, 2003b) and for the way that a spiral curriculum needs to be designed and executed. It is suggested that, at the least, research is needed from a wider range of science learning contexts to explore the extent of this phenomenon and its significance for curriculum planning and teaching.

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