The Chemical Education Research Group Lecture 2000

Molar and molecular conceptions of research into learning chemistry: *towards a synthesis*

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CERG Lecture 2000

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Abstract.

The suggestion made in this paper is that research into alternative frameworks in chemistry, and research into learning using information processing ideas are in the same relation as discussing aspects of chemistry at the molar and molecular levels.

Whilst recognising the criticism that work into alternative frameworks has dominated science education research to the detriment of other approaches, it is argued that we should not look to *turn away* from the alternative conceptions research programme towards alternative approaches, but should seek to ensure it remains a progressive research programme. This may be done by regarding the large body of work cataloguing alternative conceptions as similar to descriptive chemistry (i.e., as the raw data of the subject), and to focus instead on developing the main theoretical findings.

Teaching chemistry is about changing learners' minds. One perspective on this is the psychological approach which considers such issues as how information is processed and stored in long-term memory. This might be considered as a molecular level of analysis, considering the mechanisms by which the brain of the learner makes sense of, and stores, perceptual data. Another, more molar, approach is to talk of cognitive structure, and to explore the learners' conceptions and conceptual frameworks. As with chemistry, an effective model of learning needs accurate descriptions of what is happening at both the molecular and molar levels.

By re-conceptualising research into learning chemistry as being analogous to research into chemistry, we may find a fertile approach by which to form a new synthesis which will take our research programme forward.

Molar and molecular conceptions of research into learning chemistry: towards a synthesis.

1. Introduction.

I am pleased to have been asked to give the Royal Society of Chemistry's Chemical Educational Research Group (CERG) lecture for 2000. The CERG lecture is a 'new tradition' (sic), and although I was not able to attend last year's meeting I was interested to read the papers in *University Chemistry Education* reporting last year's CERG lectures prepared by Alex Johnstone[1] and Onno de Jong[2].

I hope that the CERG lecture will continue, and, in time, become a genuine tradition; and, if so, perhaps the series of lectures can be more valuable if there is some sense of continuity and progression over time. Certainly I hope that my talk today will develop themes from last year's contributions.

Onno considered educational research that had been closely tied to psychological paradigms (behaviourism, cognitive psychology) and judged that such research had not been very helpful to teachers and lecturers as it had been *too general*. He welcomed a move to work that looked in detail how students learn about particular topics. He recognised that such 'domain specific' research had been strongly influenced by a perspective I will be discussing this afternoon - constructivism: an approach that has produced a great deal of data on learners' ideas in science[3].

A key argument in Alex's CERG lecture was that in-depth studies into learners' ideas in science have *not* been very productive in helping teachers teach more effectively. He suggests a more psychologically based approach is needed, drawing on ideas about information processing in the brain, and relating this to the structure of the subject.

Now these vignettes are clearly simplifications of Alex's and Onno's ideas: but I hope they are not complete *over*-simplifications. At first sight it seems they are offering opposite views (see table 1):

expert	*wants less of*	*and more of*
Onno de Jong	general psychological approaches	domain-specific studies

[1] Johnstone, Alex. H. (2000) Chemical education research: where from here, *University Chemistry Education*, 4 (1), pp.32-36.
[2] de Jong, Onno (2000) Crossing the borders: chemical education research and teaching practice, *University Chemistry Education*, 4 (1), pp.29-32.
[3] e.g., Pfundt & Duit 1991; Driver, Squires, Rushworth & Wood-Robinson 1994.

Alex Johnstone	studies into alternative frameworks in particular concept areas	work informed by a psychological model of how we process information

Table 1: caricature of expert views on chem. ed. research

I find this very intriguing - especially as I tend to agree with both of them to a large extent! But perhaps this is because I am one of those people who has been undertaking "studies into alternative frameworks in particular concept areas", but *believed* that I was doing so from a perspective "informed by a psychological model of how we process information". I believe that the way forward is to build a synthesis of research that builds upon both domain specific studies and general (but empirically based) models of learning. This is the argument I will try and develop in my lecture.

I have taken as my starting point a comment in Alex (Johnstone)'s 1999 CERG lecture. Alex laments the current state of chemistry in terms of public perception and in terms of the disappointing uptake of chemistry as an advanced subject for study. From the CERG perspective, we would - in particular - fret about the lack of graduates coming onto chemistry teaching, but this is all part of the same gloomy scenario.

One of Alex's main points (as I understand it) is that our approach to teaching chemistry sometimes goes wrong, because *we* (those who already know and understand) try and impart our subject to students by emphasising its logical structure and connections - which make sense to us, because we already understand! - rather than thinking about the psychology of learning[4].

I would certainly support Alex whole-heartedly in his attempt to

> "harmonise a logical approach to our subject with a psychological approach to the teaching of our subject so that young people will catch our enthusiasm and enjoy the intellectual stimulus which our subject can, and should, offer."
> Johnstone 2000a: 33.

Clearly, any attempt to teach a complex and sophisticated subject such as chemistry, without taking heed of the psychology of learning, is likely to be less than completely successful.

So, so far, I "harmonise" with Alex. The "But" is coming.

[4] e.g. Johnstone, Alex. H. (2000) Teaching of Chemistry - logical or psychological?, *Chemistry Education: Research and Practice in Europe*, 1(1), pp.9-15.

But, one specific criticism that Alex makes - and it is one that he has made on several occasions - is *that the journals that should be publishing research to take our understanding of teaching and learning forward are not receptive to this important area*. In particular, journals such as the *International Journal of Science Education* (IJSE) give too much space to an area of research that Alex seems to view unhelpful,

> "The International Journal of Science Education has devoted over a third of its space to work on 'Alternative Frameworks' and this has tended to encourage an approach which was negative and offered few solutions to the problems exposed."
> Johnstone 2000a: 33.

Although *IJSE* has an editor (Prof. John Gilbert) who has been associated with this area of research, similar points could be made about other journals. So Gilbert himself, reviewing the work of *Studies in Science Education* for that journal, reports

> "The field of 'the development of understanding by learners' is by far the most extensively addressed within *Studies* [*in Science Education*]."
> Gilbert 1995:180.

Now there are several related points here:

1) there is an identifiable research programme that Alex (Johnstone) refers to as 'Alternative Frameworks';
2) research from this programme has been widely published;
3) when journals (especially the prestigious ones) give a lot of space to work from a particular approach, they encourage more work in that area;
4) the research programme identified has been negative and offered few solutions.

Can you guess which of these points I wish to take issue with?

I can offer two clues:

1) I see my research area as being 'learning science', but I believe that Alex (Johnstone) would class me as an alternative frameworks person;
2) This year I am on secondment from Homerton College to the RSC (Royal Society of Chemistry) as Teacher Fellow: working on a project which was advertised as "focusing particularly on those areas that have proved to lead to misconceptions", i.e. where there are alternative frameworks.

I intend to argue that research into 'alternative frameworks' should be seen as an essential part of a *progressive research programme*[5] into chemistry (and science) learning. My expectation is that some of today's audience probably know little about this area of research, so along the way I hope to:

1) describe the 'alternative frameworks' research;
2) explain why some critics feel it is a degenerate programme;
3) explain why I believe those critics are wrong;
4) suggest how out how this research needs to be taken forward.

I also hope to present some interesting examples, suggest some ways to think about our [sic!] research programme, and publicise the RSC project that is funding my current secondment.

2. The constructivist research programme.

Alex refers to research into 'alternative frameworks'. This research is also known as 'the alternative conceptions movement' and 'constructivism' in science education. I prefer the 'constructivist' label. Before I explain why, let me say something about the 'alternative' tag.

Alternative conceptions?

The area which has given rise to this research programme was the study of students' failures to learn in science. (You will appreciate, this gives scope for a wide field of study!) The term 'misconceptions' is often used when our students seemed to have misunderstood what we have tried to teach them. The implication is that, for whatever reason, the communication channels broke down. Perhaps the teacher did not explain it very well, or mumbled, or the student was not concentrating, or has poor hearing, or could not read the board, or … Of course, all these things happen, and perhaps such faults are easily put right by a little remedial clarification.

[5] The term 'research programme' is one that was used by Imre Lakatos (1970). Later in this lecture I refer to Kuhn's notion of a disciplinary notion (or paradigm), but I believe that Lakatos' idea is more generally applicable, and less likely to be found objectionable by practising scientists. Research programmes that moving forward are referred to as 'progressive', compared to these that are stagnating, which are 'degenerate'.

Yet research shows that students are clever enough to 'misunderstand' scientific principles even before they have been taught them! Sometimes they have *preconceptions*. Indeed, research shows, often they have somehow devised their own understandings before they have been formally taught <u>any</u> science at all! So, young children seem to have their own '*intuitive* physics' before they even know there is such a thing as physics. (Interestingly, they also seem to have 'intuitive biology' and 'intuitive psychology', but probably not intuitive chemistry.[6]) The term 'misconception' does not seem appropriate here, and so an alternative (sic) term is preferred.

We can define an alternative conception as:

> *a conception (about some aspect of a science topic, say) which does not match the accepted scientific version.*

A key point is that research shows that these alternative conceptions must be treated with respect. It is not enough for the teacher to say

> "Oh, you have misconceived my teaching, this is what you are meant to think, now conceive it my way"

Sadly, such an approach does not usually work! Students' alternative conceptions are often tenacious in the face of attempts to 'correct' them[7]. Therefore it is not (always/usually) enough to identify that a student has got it wrong, to put it right.

[Of course, there is a whole spectrum of possibilities when a student has an alternative conception: sometimes (with some conceptions and some students) it is enough to raise the matter with them, but sometimes years of repeated tuition will not bring about the desired change of conceptualisation. This, in itself, shows that this topic needs close study.]

These are not just 'errors' that can be put right with a note in the margin of an assignment: these are alternative ways of looking at the world.

Now it would be possible to take a relativistic stance here: the student is as entitled to her alternative world view as the teacher is to hers. From this perspective, alternative conceptions must be treated with respect because there is no objective reality, and so your reality is no more valid than anyone else's. I appreciate this perspective, but do not adhere to it - if only for pragmatic reasons. Alternative world views do not usually go down well with examiners, and may be quite dangerous in laboratory sessions.

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[6] This is more than a throw-away line. One argument is that young children have wide ranging experiences relating to - for example - forces and motion, or plants and animals - but less direct experience of chemical processes. This is only partially convincing, especially if we take the basic distinctions of states of matter as part of chemistry. However, these is another source of argument - that might be termed evolutionary psychology - that believes that our near-human ancestors had more modular minds (e.g., Mithen 1998) - and that there was a module dealing with using tools etc., and one dealing with living things that were significant to survival, but not one relating to proto-chemistry as this was not enough of an issue. (I assume 'fire' comes under the tools module!)

[7] Although dated now, Driver's 1983 book is a very good introduction to the phenomenon.

No, the reason why alternative conceptions need to be take seriously is because

(a) they mean the student does not understand the chemistry; and
(b) they are often stable despite instruction.

That is, alternative conceptions are *significant for learning*, and therefore *significant for teaching*. That is why *it is important to study students' ideas about science*.

Alternative frameworks?

So if an alternative conception is a conception (about some aspect of a science topic, say) which does not match the accepted scientific version, then what is an alternative framework?

Well, I should come clean here, and admit that there is little agreed nomenclature in the field[8]. The people actually doing the research have used a wide range of terms: so one worker's *intuitive theory* is another's *alternative conception*. Some researchers use different terms to mean slightly different things, and some don't, and those that *do* often use different terms for the same phenomena, or the same term for slightly different phenomena.

So *in practice* 'alternative framework' may often be synonymous with 'alternative conception'.

However, I think a useful distinction *can* be made here. I think that the term '*alternative conception*' is best used at the level of a single idea or proposition, whereas the term '*alternative framework*' is best reserved for when a learner holds a complex of logically connected ideas. I think this is important because it will have repercussions when, as teachers, we are planning how to teach the holder of the alternative ideas. Alternative frameworks represented developed and established structures which will not be easy to eradicate or work around. I will come back to this point, later (see figure 28).

Anyway, the point about alternative conceptions and alternative frameworks *not just* being 'misconceptions' is that as they are not simple communication errors that can be readily put right, it is important to find out how to tackle them in the classroom. And this means we need to have some ideas about there origins. Not just

what does the student think?

but also

why does the student think that?

(And - to my mind - this means we need some help from psychology.)

[8] e.g. Abimbola 1988.

Personal Constructivism ...
...or a little 'stating the obvious' for beginners?

In fact, the constructivist movement in science education has drawn upon the ideas of a number of leading thinkers in psychology. This is not the place to detail either the psychology or the way it has been adopted into science education, but I would like to briefly outline how the ideas of the some psychologists have been very influential. (This is done *without* apologies to any real psychologists who may be offended if I take liberties in *construing* the psychology through the eyes of a science teacher[9].)

psychologist	**key contributions**
Jean Piaget	'genetic epistemology' learners construct their own internal models of the world, in interaction with their environment assimilation/accommodation/dis-equilibrium (c.f. pupil as scientist?) children think differently to adults! (clinical interview)
Lev Vygotsky	formal education seems to change ways of thinking (Luria) importance of social aspects of environment spontaneous and scientific concepts the 'zone of proximal development' (ZPD)
Jerome Bruner	scaffolding (in the ZPD) spiral curriculum dialogue allows constant transactional calibration
George Kelly	personal construct psychology - man (sic) as scientist repertory grid technique to construe the construct systems of others
David Ausubel	rote and meaningful learning cognitive structure

Table 2: Some influential psychologists

Jean Piaget: although his general stage theory of cognitive development is no longer thought to be the educational panacea that it seemed to be some decades ago, he has provided us with some important ideas.

[9] These psychologists teach us that we each construct our own set of meainings to make sense of the world: so they will have to excuse me if my explanations reflect my constructions as well as theirs!

For one thing Piaget was a constructivist: be believed that the individual learner has to construct their own model of the world internally (through a process that was due to normal development, but operated in interaction with the learner's environment). Piaget saw the learner as having a model of the world that was always, to some extent, tentative. The learner explored the world, and tried to assimilate aspects of it into her internal representation. When the world did not respond as expected this model would be thrown into disequilibrium, and this feeling of 'cognitive dissonance' acted as the motivation to accommodate the model to the world.

Does this sound a bit like science? A hypothesis is proposed and tested against nature, and revised accordingly. The late Prof. Ros Driver - who championed the notion of *pupil-as-scientist*[10] - was strongly influenced by the Piagetian school.

Piaget also found out something very obvious, by doing something very simple. He found out that young children do not think like adults. He did this by talking to them at length, and in detail. In this way both the 'clinical interview' and the notion of children's' alternative ideas about the world became well known. It is perhaps a sign of Piaget's significance that both the method and finding seem so obvious to us today.

Lev Vygotsky: was a contemporary of Piaget, but working in the [then new and revolutionary] Soviet Union. He was a polymath - a kind of Marxist-renaissance figure, if there can be such a person! He sent an expedition[11] under his colleague Luria - to the newly liberated Soviets in Asia, where it was discovered that those who had yet to benefit from the educational reforms of the new regime (i.e. being provided with formal education) seemed to have different way of thinking about things: not unlike Piaget's child subjects.

Piaget was a biologist by training, and seemed to see learning in terms of the individual organism (e.g. a chemistry undergraduate) developing in its environment. *Vygotsky* realised that those 'bits of environment' that were other people could have a special role in the learning process. These aspects of the environment include teachers and peers!

Vygotsky divided concepts into two coarse classes, depending on how they were acquired. He realised that some concepts are acquired by a kind of osmosis of experience. (For example, a youngster may acquire a concept that we would label as inertia.) These concepts are not formally defined, are not labelled, may not be well demarcated, and are often tacit. We operate with them, without always being aware of them.

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[10] op. cit.

[11] Vygotsky was too ill to travel so far himself, and sadly died very young. The Stalinist regime later did its best to send his ideas the same way.

However, other concepts are formally taught and learnt by definitions or through instructional paradigms. These ideas may be completely abstract, without any connection with our general experience. (For example, a bright youngster *could* be taught to recognise chess pieces and repeat their modes of moving without ever seeing or playing with a chess set.)

Vygotsky recognised useful learning took place when the experience that have been refluxed into the intuitive (spontaneous) concepts could be brought under conscious control, and when the abstract (scientific) concepts could be related to real life experience. That is, perhaps, that useful knowledge is based on real experience of the world, but organised in logical ways, and available to reflective thought.

However, one of Vygotsky's most useful insights is that learning takes place most effectively within something he 'helpfully' called the zone of proximal development (ZPD). This sounds like psycho-babble, so I have prepared a short object test item to see if you can appreciate what he meant:

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pre-test item on Vygotskian psychology:

As a teacher, you can most help your students to develop their understanding of the subject by

a) providing them with lots of rote exercises based on ideas they have already successfully learnt;

b) setting difficult exercises, that the students are not yet able to tackle;

c) providing graded exercises that stretch them beyond their current capabilities, but with support that can gradually be removed as they acquire competence.

d) none of the above - I am a *lecturer*, not a teacher.

Figure 1: a multiple-choice item!

As we found with Piaget's ideas, this educational psychology business seems to be a bit of a breeze.

Jerome Bruner: has popularised the writings of Vygotsky. This is important as a combination of an early death and the displeasure of Stalin's regime could easily have led to his ideas being overlooked. Thanks to the loyalty of his surviving co-workers such as Luria, and to détente, Vygotsky has now become very well known. (Sadly, as he is the new Piaget, his ideas will be seen as the new educational panacea, and will fail to match this, and will then be judged as having themselves failed. That is my prediction, in any case. If you are not familiar with the ideas of Piaget, think Freud and you get my gist.)

Bruner has popularised Vygotsky's ideas about the ZPD, through the more user friendly tag of 'scaffolding'. Like a building, our ongoing conceptual constructions need to be supported with strong scaffolding until they have enough structural integrity to support themselves, when the scaffolding can be carefully dismantled. Bruner has also been associated with the notion of a *spiral curriculum*: the idea that difficult ideas are revisited at levels of increasing sophistication at different times during schooling.

Bruner has done much more, and I would also like to mention that he has thought deeply about human conversations. Those of you who know a little about the philosophy of science will know about the Popper-Kuhn debate. Kuhn talked of scientists working in different paradigms (or disciplinary matrixes) being unable to effectively communicate because their ideas were incommensurate. (Unless you use the same words, to mean the same sort of things, how can you ever agree on who is right?) Popper did not agree with this[12], referring to the 'myth of the framework': after all, this could suggest that *we never understand each other*! Popper did not deny that scientists would use different frameworks, but thought that Kuhn's suggestion that this would prevent them communicating effectively was invalid. (As he was an ex-physics teacher, I am surprised that Popper was not more sympathetic to the problems of communicating meaning to people with different frameworks.)

In practice, we usually understand each other well enough to communicate fairly effectively, but we probably never understand each other fully. Bruner has discussed how through dialogue have continuous opportunities to test out our interpretation of what the other has said: *constant transactional calibration*. There is an important lesson here for teachers who want to be understood by their students.

George Kelly: was a therapist - someone who applied psychology in order to help people who were not coping well with their lives. His work was not based upon interpreting dreams, and was rather antithetical to notions of archetypes underlying our behaviour. (I seem to recall that Kelly was initially a scientist, before he turned to psychology - but then, so was Freud, so this may not be significant.)

[12] …but then perhaps he did not mean the same thing as Kuhn by the word 'incommensurate'!

Kelly focused on the way that each of us constructs our own model of the world, which is constantly tested against experience (c.f. Piaget[13]). Kelly referred to 'man-as-scientist'[14]. In order to interpret someone's behaviour, we need to try to see the world through their personal construct system. Of course, for this idea to be useful to help people in distress, it is important to note that personal constructs are not fixed, but can change: they are 'permeable'.

One of the useful points about Kelly's work was the way he conceptualised personal constructs as bipolar entities. (For example one construct for organising impressions about the world might be good-bad, and another might be masculine-feminine.) Although this may seem simplistic it provided the basis for exploring an individual's constructs through a simple clinical approach (the construct repertory test), which could be developed into a statistical technique (repertory grid technique) when needed. Now this may sound rather high powered, but:

- Kelly was aware that his ideas could be applied outside of their 'focus of convenience' (which he defined as human readjustment to stress) in areas such as education[15],
- the notion of personal constructs may be quite general - so another construct might be element-compound or soluble-insoluble, and
- the repertory construct test is actually very simple to use.

Indeed the construct repertory test is also know as the method of triads, and is a simple way of eliciting the ways students think about aspects of chemistry. Consider providing a student with three elements[16], and asking them to pick the odd one out - and then explain their decision. For example, if the elements were sulphur, copper and mercury, which would be the odd one out?

Clearly *sulphur* is not a metal.

But then, *mercury* is not solid at room temperature.

And *copper* is the only one used to make water pipes.

Mercury is not a component of copper sulphate.
And it is not found native.
And it is significantly toxic.
And the only one with a spacecraft sharing its name.

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[13] Note also the similarity with Bruner's ideas: each of us constructs our own model of [the world/what the other is saying] which is constantly tested [against experience/through dialogue].
[14] c.f. Driver's pupil-as-scientist.
[15] e.g. Taber, 1994.
[16] In the method triads three cards are presented, labelled with three 'elements'. For Kelly the 'elements' were often people in the life of the client receiving therapy. In chemistry the 'elements' could be elements, but they could be compounds - or atoms, molecules, classes of reaction, etc.! I have, elsewhere (e.g. Taber 1994) referred to 'triad elements' to avoid possible confusion.

This is a game that can run and run, and in part tests the extent to which a student is a divergent thinker[17]. But it also can show up discriminations that are *chemically wrong*, or it can highlight when the students *do not make* the expected 'obvious' chemical discriminations.

Kelly reminds us that if we want to understand why our students are making 'illogical' responses, we need to try to see the world through their eyes. Often the students answers make perfect sense through their own 'construct systems'.

Kelly's work also reminded us that we *could* learn to construe the world as others see it: indeed as a therapist, this was how he went about his work. As part of our internal representations of the world, *we can model the representations of others*. Of course, if our representations of something as simple as how bodies move under force are often 'wrong', we may not be very good at modelling something as complex as another's representation of the world[18]. Yet this process is not only of importance to scientists championing different world views (phlogiston vs. oxygen; heliocentricism vs. geocentricism; etc.), but also to historians of science trying to understand science that was once orthodox, but now seems ridiculous, and to educational researchers trying to understand the scientific ideas of pupils and students.

David Ausubel: the final psychologist on my list is Ausubel. He emphasised an important distinction between two types of learning: *rote* and *meaningful* learning.

Rote learning allows recall without needing understanding, and therefore with no possibility of application outside of the original context in which learning took place. Learning that involves true understanding, and can be applied, is called *meaningful* learning. I assume we would agree that as teachers we are concerned with bringing about meaningful learning.

Ausubel argued that learning can only be meaningful when the material to be learnt can be *related* to what is already known. A school pupil could be taught that carbon dioxide has double bonds, and might even remember this to answer question such as

- what type of bond does carbon dioxide have?
- give an example of something with double bonds

but unless the pupil knew what a double bond was, the learning is not very useful.

[17] c.f. Hudson 1966.

[18] Although if one accepts the modularity of mind argument (Mithen, ibid.), one module that was important in our evolutionary development was that 'intuitive psychology' module that enables us to read the minds of others - so perhaps we have a *head start* in psychology over chemistry?

Knowledge is only useful if it is structured: if one idea is related to another, which is connected to another, and so on. The way humans 'naturally' learn is such that this tends to happen, with new items on knowledge being connected to existing related ones. Our knowledge is not just a store of facts, but an extended network of concepts :a *cognitive structure*[19].

Knowledge is perhaps most useful when it is structured in a way that is compatible with the way other people have structured it. And in an education context this particularly so when those other people are teachers and examiners.

At this point I may seem to contradict what Kelly said, i.e. they we all have a unique way of organising our representations of the world. In fact, these ideas are not in conflict. We each have a *unique cognitive structure*, but there can *a lot of commonality*.

Constructivism in science education.

The constructivist movement in science education draws upon the work of these various psychologists, and leads to a general perspective, that might be summarised:

> Each learner is unique. Before starting school a child has already acquired a range of tacit conceptions about the world from their everyday experience. These early experiences channel the way their cognitive structures evolve. Children's natural 'informal' learning may lead to the adoption of ideas that are in conflict with scientific models. Later learning takes place by adding to, or modifying, what is already known. Some early ideas can block intended learning. As students have unique knowledge structures that do not match their teachers, they will often interpret teaching in a different way to that intended and expected, and will learn alternative versions of scientific ideas.

I have spent some time outlining the psychological background to the constructivist position, to demonstrate that this area of research is *not just about cataloguing quaint ideas*. It is from this theoretical perspective that I approach the study of children's ideas as research into the learning of science.

[19] More will be made of this notion, later in the lecture.

3. The external critique of constructivism - is work on 'Alternative Frameworks' negative?

Now to return for a moment to Alex Johnstone's comments that I referred to at the start. Alex accused the alternative frameworks' movement of having encouraged an approach that was 'negative' and which 'offered few solutions'.

Now I know what he means by that. Once journals started publishing work which described learners ideas in science the floodgates opened[20]. There is now an enormous literature describing aspects of learners thinking in most aspects of science at a range of levels - primary, secondary, college, university.

Much of this literature is concerned with 'what they got wrong'. It is negative in the sense that it highlights areas where pupils fail to learn the science in their curriculum. Now there are several possible interpretations of this, including:

1) generally pupils fail to learn the science they are 'taught';
2) it is more interesting to study, or to report, or at least to emphasise, areas where pupils do not learn what they were expected to;
3) perhaps journals are not generally keen to give space to publish papers along the lines of "a class were taught about redox, and were then tested, when it was revealed that they understood the concepts that had been taught. It was concluded that the hoped-for learning had taken place", unless the approach used was novel.

At first sight the latter suggestion might seem reminiscent of a news broadcast that reports that there have been no major earthquakes, jail breaks or plane crashes notified in the previous 24 hours. However, as the research literature seems to support option 1 (generally pupils fail to learn the science they are 'taught'), perhaps journals should publish more papers concluding that "the hoped-for learning had taken place", with an analysis of the factors contributing!

So Alex is right on the first point: alternative frameworks research has usually focused on the negative: on failures to learn.

This brings us to the point that this research has 'offered few solutions',

> "Research literature has been dominated by work on misconceptions, but little has yet appeared about how to reverse these or to avoid them altogether."
> Johnstone 2000b: 10

[20] For some workers, it must have seemed an easy way to find a niche and get published!

Is this true? Well, first please allow me to hedge my bets a little. I would like to consider two related questions:

1) has the constructivist literature offered any solutions?
2) does continued research into students' alternative frameworks promise the potential to offer solutions?

At the risk of removing any tension (?) that may be building I will immediately offer my own answers:

1) yes (the constructivist literature has offered some solutions), but…
2) yes (continued research into students' alternative frameworks has the potential to offer solutions), if…

Cataloguing 'alternative conceptions'?

Much of the literature on children's ideas in science could be seen as an effort to catalogue the kinds of ideas that pupils and students have about different scientific topics. This then leads to the question - to what purpose?

Well, firstly, let me say that there is nothing wrong with any research programme having a largely *descriptive* stage. Think of biology - a discipline that today is highly scientific. Biology is highly theoretical, whether studied at the level of molecules, genes, cells, evolution or ecology. Yet all of this required a long period of descriptive work, and taxonomic work, to provide the background data. Anatomy preceded physiology. Taxonomy preceded natural selection. Natural history preceded ecology.

For that matter, think of chemistry itself. The chemical revolution of Lavoisier et al. rested on detailed descriptive work. (Indeed, some chemistry texts from the twentieth century seem little more than descriptive catalogues.)

The descriptive *stage* is fine, if that is what it is: a stage through which the research programme has to pass.

At least ten years ago the atheoretical nature of much of the work was recognised, and calls were made to move the programme beyond the 'stamp collecting stage'[21]. At least one well placed critic believed that constructivism had peaked, and could henceforth decline[22]. (However, as Alex (Johnstone) has pointed out, the flow of publications has continued.)

I am sure there are niches that have not yet been explored. I have not made the analysis, but if anyone in the audience wishes to get out their conceptual 'butterfly net', and find a topic ripe for study, you need something like this:

	electricity	friction	photosynthesis	combustion	redox	digestion	…
KS1	✓	✓	✓	✓	✓	✓	✓
KS2	✓	✓	✓	✓	✓	✓	✓

[21] Watts 1988; Black 1989.
[22] Solomon 1994.

KS3	✓	✓	✓	✓	✓	✓	✓
KS4	✓	✓	✓	✓	✓	✓	✓
A level	✓	✓	✓	✓	✓	✓	✓
u/g	✓	✓	✓	✓	✓	✓	✓

Figure 2: niches for alternative frameworks research

If you do find that all the possible cells are already full, then simply introduce another dimension (e.g. cultural differences in different countries).

The point is, of course, what do we do with the data (apart from publishing it?) The whole purpose of the research programme is to inform teaching, and, unless it does that, it is a sterile exercise. This in turn has two aspects
knowing what to advise teachers, and
communicating the information to them.

Constructivist *teaching*?

The notion of constructivist teaching (as opposed to research) does not - in principle - rely on the vast literature cataloguing alternative conceptions and frameworks. Constructivist teaching uses the principles from psychology that I talked about above to inform practice. Put simply, the teacher should approach the teaching of any science topic to any class aware that:

1) to understand the new teaching, the students needs to understand certain basic prerequisite ideas;
2) many of the students are likely to hold alternative conceptions about this topic, and have distorted understanding of the prerequisite ideas;
3) because students' existing ideas are integrated into their conceptual networks, they may not easily change their thinking;
4) as new knowledge is built on the foundations of existing beliefs, teaching is likely to be mis-interpreted;
5) unless I take 1-4 into account my teaching is likely to be ineffective, and many in the class will not learn the key ideas adequately.

The constructivist teacher therefore:

1) starts from where the pupils are (not where she would like them to be); which means that
2) it is important to start a new topic with the elicitation of existing knowledge; and
3) lesson planning should reflect the elicited prior knowledge and understanding by
4) reiterating missing prerequisite knowledge, and
5) explicitly challenging alternative conceptions.

This latter point does not mean simple saying 'your ideas are wrong, think this instead', but using counter examples, data exercises, thought experiments etc. to show how *alternative conceptions are inconsistent or inadequate*, but *how the scientific model is much more fertile*.

The value of the literature to the constructivist teacher.

So how does the research literature help the teacher in this task?

Well, it certainly does a job of advocacy! Any science teacher who carefully reads a sample of the literature detailing alternative conceptions, or better perhaps, some of the secondary sources summarising findings, would find it difficult to deny that learners have alternative conceptions, or that these can act as significant impediments[23] to the intended learning.

Secondly, the literature provides some of the groundwork. Just as we do not (could not feasibly) expect students to come to understand modern scientific ideas by repeating all of the experiments etc. that led to current knowledge, there is no need for individual teachers to 're-discover' the alternative conceptions that have already been categorised.

I would like to be very careful about what I am saying here. Each learner is unique, and to teach a class effectively it is necessary to know the class, and the individual learners in the class, and to find out about their ideas. This information can not be obtained by reading someone else's research papers. However, although every student's cognitive structure is unique, they often have much in common. Of course they do - we are *genetically similar*, so our brains and sensory apparatus have similar structures, we share very similar chemical (e.g. nutritional) and physical environments, and usually *generally similar* social, cultural and linguistic environments.

To the extent that each learner has a *unique* genotype and environment, their conceptual structures are likely to be *different*: to the extent that we all share *similar* genetic codes and *similar* life experiences, our conceptual structures are likely to be *similar*.

The literature therefore provides a good *guide* to the types of alternative ideas that a learner at a certain stage of their education is *likely* to have about a certain topic. More than this, the literature claims that *there are 'common alternative frameworks' that are likely to be shared by many learners*. This means that the ideas of many learners are often *similar enough* that they can be summarised by a common description[24]. Of course, individual learners will differ in the extent to which they match the description, but this does not negate the common aspects. This means that if a teacher is teaching a certain class and level they can be forewarned about the *likelihood* of certain specific ideas being present in the group.

[23] Many learners' ideas may act as 'half-way houses' to understanding, and even if they do not it is often more helpful to think of a learners' current ideas as the conceptual resources available to the teacher in developing understanding, rather than as barriers. However, if the teacher ignores the learners' ideas and just proceeds with presenting the accepted science, then alternative conceptions *will* often behave as barriers to learning.

[24] An example of this, the octet framework, is discussed later on the lecture.

For example, if a class are receiving their first instruction about electrical circuits the teacher can be warned that it is highly likely that within the class:

- some pupils will think that only one wire is needed to take current from a cell to light a lamp;
- some of those that recognise the need for a second wire will think that this is because two different types of current have to flow through the different wires (perhaps negative charge through one, and positive charge through the other);
- because it seems something is used by the lamp, once the idea of current is introduced, some pupils will assume that it is current that is used up in the lamp.

If a teacher is introducing Newtonian dynamics to a class, she can be warned that it is highly probable that Newton's first law - the principle of inertia - will be highly counter-intuitive to a significant proportion of the class, who will expect that a continual force is needed to keep a body moving at a constant speed.

The research in the literature might suggest that in a class of 14 year olds something like 85% would show such a 'impetus-type' belief[25], and the teacher *might* find that in *her* class (e.g.) only 22 out of 29 pupils (76%) seemed to have such ideas. However, the literature suggests it is *unlikely* that none of her pupils would bring these ideas to class.

The literature warns teachers to be aware that alternative conceptions are 'out there', gives plenty of examples of the *type of thing* that learners could be thinking, and *in some cases* suggests particular ideas that are very likely to be met in teaching particular topics. The teacher must be sensitive to the ideas of her *particular* students, but the literature can provide a strong lead here, so that when the teacher seeks to elicit ideas at the start of a topic she is well prepared to *recognise* and *make sense of* those ideas[26].

Knowledge about likely common alternative conceptions also helps in *advanced* planning of effective lessons[27].

So is the constructivist programme 'negative'?

When Alex (Johnstone) characterised the alternative frameworks approach as 'negative' I guess he had two things in mind. Firstly, there is no denying that the entire bestiary of alternative conceptions can be seen as representing:

- learners' ideas which are '*wrong*';
- ideas which may be *barriers* to learning;
- examples of *failure*s of students to learn as required;

---

[25] Gilbert & Zylbersztajn 1985.

[26] Just as the student with a long-standing alternative framework may have difficulty seeing the topic the way that the teacher is trying to present it, the teacher may experience difficulty coming to see what the student is 'getting at' when talking from an alternative perspective. (The significance of the Kuhn-Popper debate is clear!)

[27] An example will be given below - see figure 26.

• examples of *failures* of teachers to teacher as desired.

From this perspective, it does not sound like a ‘positive’ research area.

However, field work in this programme may be compared to the ethnographer who is exploring an alien culture: it is often *very interesting* listening to children’s ideas and seeing how their minds work. This does not just mean spotting their mistakes, but recognising the *creativity* of their thinking, and the way that completely wrong science can sometimes be built into *ingenious* consistent structures. Providing a workable interpretation of learners’ comments can be a real challenge. The scientist in the researcher is constantly hypothesising about why a student make a certain comment, and then testing the hypothesis by asking critical (i.e. key) questions.

I don’t know if this description makes any sense to colleagues: but I would hope it is not so different from the way the bench chemist is challenged and frustrated, but then rewarded, by keeping at a problem until some breakthrough is made.

Yet to the outsider, it may perhaps seem like we are laughing at learner’s mistakes.

I remember reading some Piagetian research where the questioning went something like this:

Interviewer:	Where do you live?
Child:	Geneva.
Interviewer:	Where is Geneva?
Child:	It is in Switzerland.
Interviewer:	Do you live in Switzerland?
Child:	No, I live in Geneva.

I wonder how you (the audience) react to that?

I can imagine one might just feel that this child had not yet mastered adult logic. But I thought this was fascinating, that a child could not see the logical contradiction in the responses.

When Vygotsky sent Luria to talk to the adult (but not formally educated) population of soviet Asia, he found similar types of patterns: these adults did not share what we would consider normal conventions of logic and dialogue.

For example, if the premise was put that

• *in the far North, where there was snow, the bears were white*

and then it was suggested that

• *a traveller had been in the far North, where there is snow, and had seen bears*

and the peasants were then asked

• *what colour are the bears in the North?*

they would decline to speculate! As one subject reasonably replied:

"I don't know what colour the bears there are, I never saw them.[28]*"*

The peasants were not being stupid, or awkward, but they had not been initiated into the 'language-game' of the syllogism.

I find a similar fascination in the case studies of mental deficit that result from various neurological conditions. For example, I find Oliver Sacks' reports on his patients' peculiarities and limitations very engaging, but the fascination is not some voyeuristic trip, for the interest is as much in how these brain damaged patients often find their own accommodations to life.

When I read Piaget's conversations with children (and these were often his own children), or Luria's reports of soviet peasants' style of thought before communism educated them; or Sacks' case reports of his patients learning to function with various mental deficits I feel that I am learning a little more about how human beings *can* think and function. I sometimes find the same sense of awe in reading samples of classroom dialogue, either teacher-pupil or between student peers. This material gives insights into the 'phase-space' of possible human conceptual and cognitive performance that we all occupy. And as a teacher, I feel such insights are very valuable.

interpreter	*trying to interpret the ideas of*	*which are different because of*
any human	any other human	different experiences
translator	non-native speaker	different language
child psychologist	child	different stage of development
neurologist	brain-damaged patients	neurological deficit
ethnographer	a different people	different culture
science historian	past scientists	different 'paradigm'
science teacher	student	alternative frameworks

Table 3: science teachers as interpreters

[28] Luria 1976: 111.

So, from my perspective *within* the field, although the literature might largely report on deficits, I do not find those reports as largely negative. (However, I doubt that I will convert anybody to the constructivist cause with my own subjective responses to these various studies into human reasoning and thinking, so I had better move on.)

The second aspect of 'negative' that I referred to above, is that alluded to when Alex refers to the alternative conceptions work offering 'few solutions to the problems exposed'.

> "As researchers we have solved almost none of the reported problems in chemistry teaching: the mole, bonding misconceptions, misunderstandings about the nature of matter, equilibrium, free energy and many more."
> Johnstone 2000b: 10

Now I would like to suggest that there are two responses to this. Some research does offer genuine advice to the teacher. We need more of that, and I will have more to say on this later. However, much of the research can be characterised as catalogues of failures of intended learning, and I would like to first consider this material.

I referred above to the Kuhn-Popper debate about incommensurability in science. Kuhn suggested that when two scientists (e.g. a phlogiston adherent, and an oxygen champion) debate the relative merits of their ideas, they can not simply look to objective experimental evidence to see who is right: they do not agree on a framework for making such a decision: definitions, procedures, the meaning of data, the relevance of data etc. Popper suggested that if Kuhn was right, then none of us would ever understand anybody else who had a different perspective. Kuhn later clarified his ideas, and claimed to be suggesting that communication 'across paradigms' could at best only be *partial*. I think this is a realistic position. His point was that it may seem to be stupid to believe in phlogiston, or that the sun goes round the earth, *now*, but these were relatively coherent, well supported positions to take at the time they were in vogue. If we can not see this, it is because we are approaching the topic from a vastly different standpoint.

Now I think this is relevant to how much of the constructivist literature may be seen. I think we can all agree that the literature contain a large amount of material detailing alternative conceptions: learners' ideas in science that are 'wrong'.

For someone who is *not* working within the constructivist programme, the literature may seem largely irrelevant. Indeed, it may seen as just a reminder of the difficulty of teaching effectively, and a wasted opportunity for useful research. It could even be seen as a *de-motivating* factor: after all, no matter how well you teach, the literature suggests they probably won't learn it right: as all these alternative conceptions will get in the way.

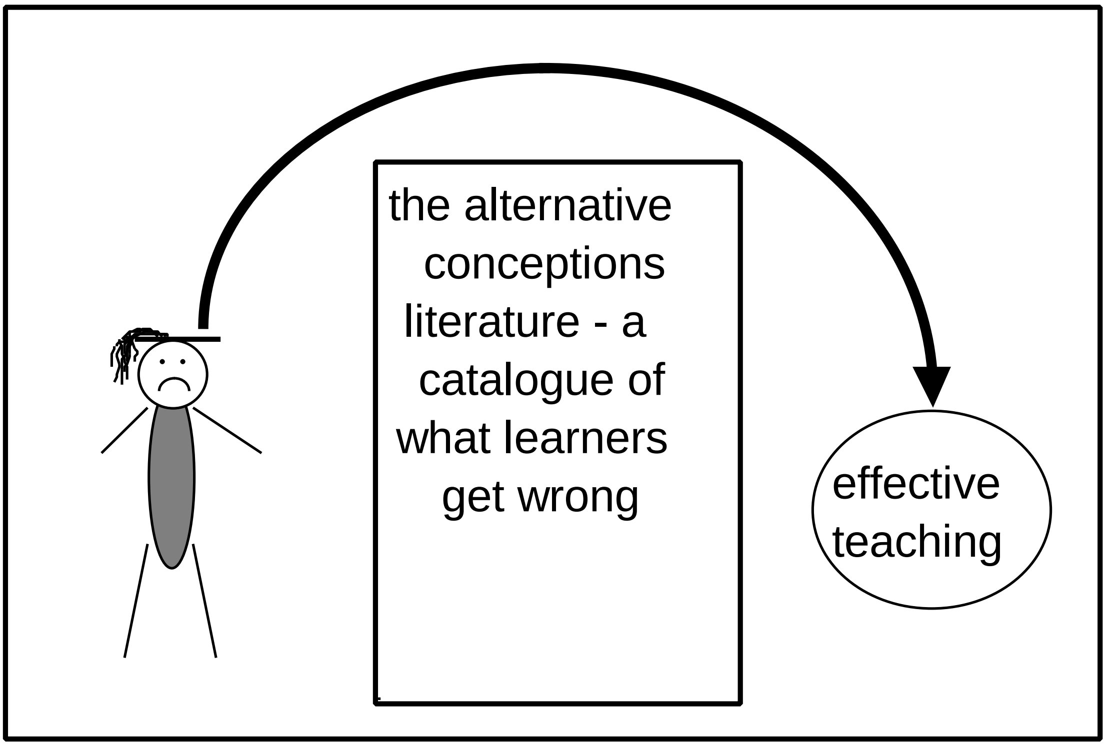


Figure 3: constructivism as revealing obstacles

Yet, to the constructivist, learners' ideas are the starting points from which effective teaching can follow. Our learners will have alternative conceptions, so we should start from that point in our teaching:

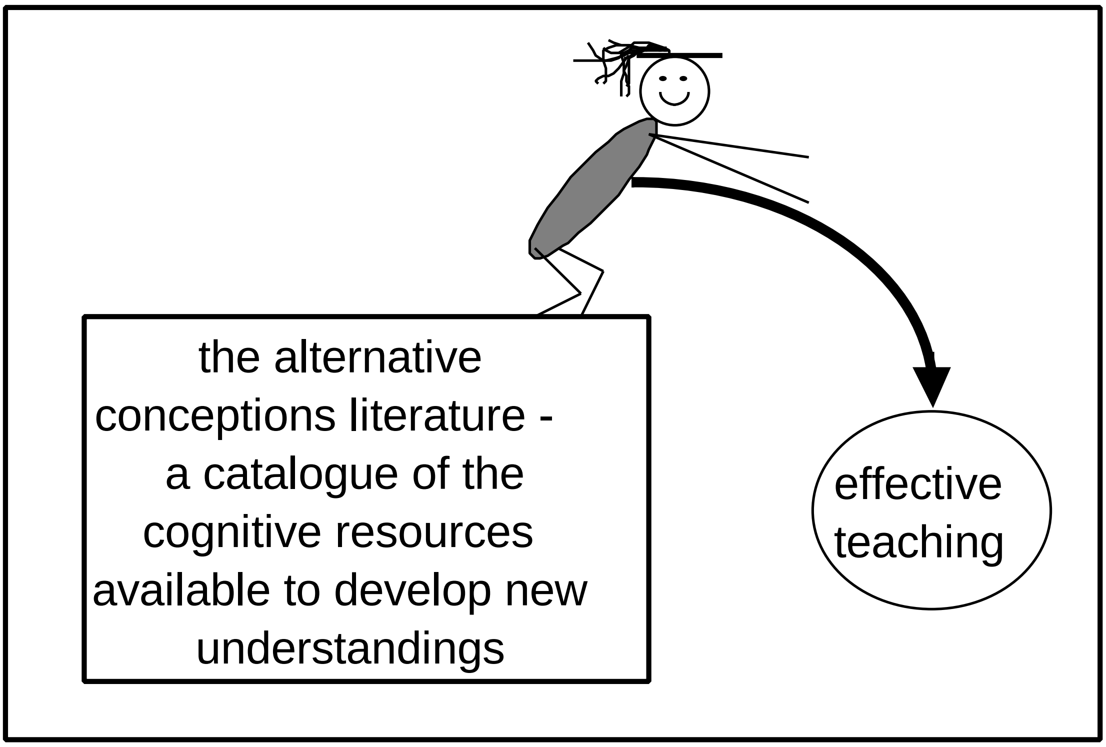


Figure 4: constructivism as presenting opportunities

The literature does not *create* failures to learn, but given that failures to learn are common, it is good to *know* as much about them as possible. Rather than being seen as negative information, the literature is seen as *positive information about a negative situation*!

Those within the constructivist camp highly value the work detailing learners' ideas in science, because they are *working within a general psychological framework* which provides significance to those results. Perhaps some of those who criticise the 'alternative frameworks' literature are doing so from a different perspective, outside that 'paradigm' or 'disciplinary matrix'. *They* see alternative frameworks as little more that another name for misconceptions - for having got it wrong! - whereas, from within the field,

> "Productive or unproductive is a more appropriate criterion than right or wrong, and final assessments of particular conceptions will depend on the contexts in which we evaluate their usefulness."
> Smith et al. 1993: 147

Of course, a lot of work may be published about learners' ideas that is not informed by a strongly constuctivist position, but those who present their results ground within a theoretical framework *should not be held responsible* for those who do not, or for the decision of journal editors who accept their papers. (So whilst Alex (Johnstone) is right that *IJSE* continues to publish much materials from within this research field, I do not think he point to papers in *that journal* in the last few years that simply describe learners' alternative conceptions without also trying to contextualise this in theoretical terms.)

4. The internal critique: is constructivism in science education a degenerate research programme?

So Alex's criticism that the 'alternative frameworks' work is negative, does not hold up from *within* the constructivist perspective, as *from this point of view* the data is an essential resource for planning constructivist teaching, because the learners' conceptions are the raw material for developing understanding. Criticisms that much of the literature offers little practical advice can be countered by the argument that each teacher has to re-construct scientific knowledge with their own individual learners, and that teaching is an interactive process, and each teaching episode will be a unique event that cannot be specified by fiat, but must evolve within its own context. The literature can provide a theoretical framework, and can provide some of the data (although - remember - every learner is unique), but the teacher has to take responsibility for the teaching.

Of course, this partly true, and partly 'cop-out'.

To the extent that this is partially true, there is one strand of the constructivist literature which is less concerned with learners' ideas, than with teachers' metaphors for teaching. In particular, this literature has looked at how teachers can take up constructivism as a core referent for their teaching.

Teaching *is* an *interactive process*, and each learner is an individual, and each class is unique. Teaching *is* a *craft*, where highly skilled practitioners are needed who can be *sensitive* to their students, and are *flexible* enough to *respond* to classroom situations as they arise.

That certainly does not mean that preparation and planning are not relevant. It is not *just* 'chance' that favours a prepared mind, *so does* success in teaching. For the teacher to be an effective classroom practitioner she needs to be an expert: in knowing the subject matter, in knowing the students, and in knowing about how the subject is learnt. We can represent this in a triangle:

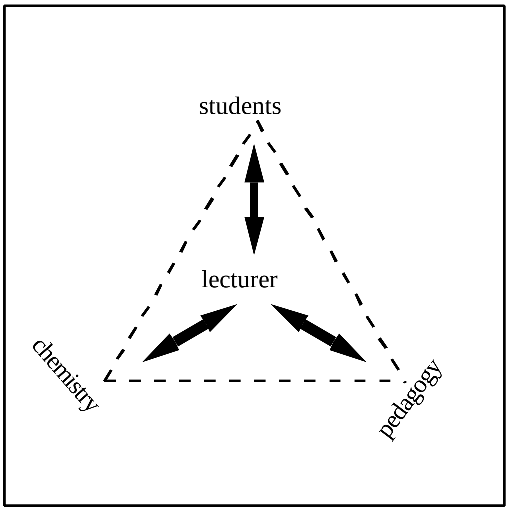


Figure 5: the chemistry teaching triangle

In developing a presentation of a chemical concept (whether to a class or an individual) the lecturer uses her knowledge of the subject matter, of the accepted body of knowledge about teaching the subject matter, and of the particular students themselves. During this teaching process the subject matter is reworked into a form that is considered appropriate for the level of course and depth of treatment required; the teacher uses her self-knowledge to select teaching methods that build on her own professional strengths, and perhaps develops the pedagogy of the subject (if only at a personal level). And, of course, the learners themselves should *change* as a result of the interaction!

Now, clearly, some knowledge in all three areas is available in advance. The most 'problematic' area is the students themselves, but even here there is always likely to be some information about them which can help advanced planning. If the students are not yet known personally to the lecturer then she may find the alternative frameworks literature helpful!

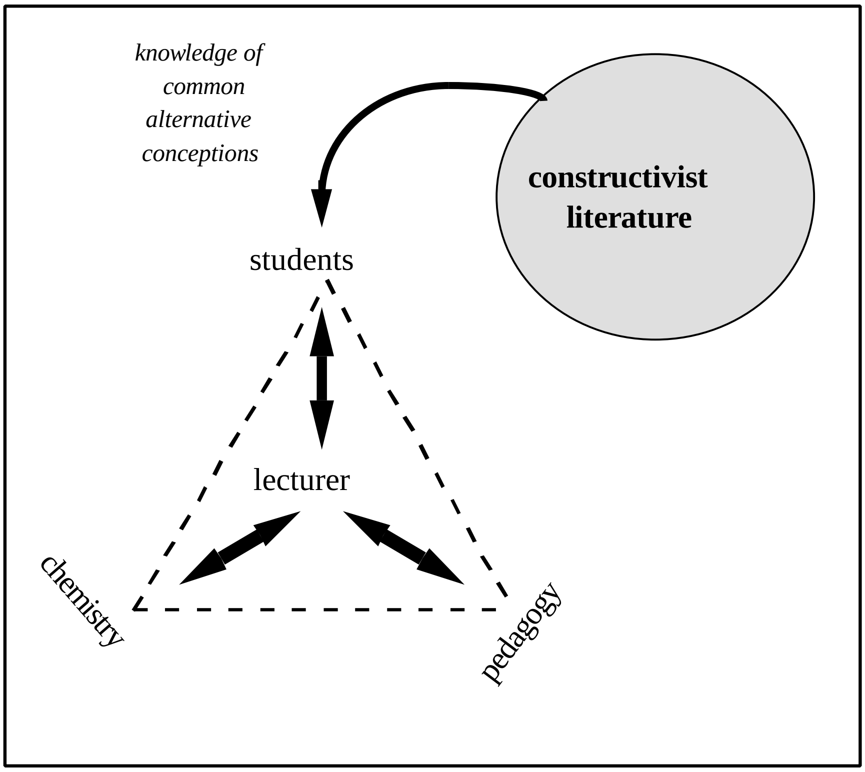


Figure 6: knowledge of alternative frameworks informs teaching

However, if I thought that was all the constructivist programme could offer, then I might well join Alex (Johnstone) in complaining about the amount of journal space it occupies. Clearly a point would be reached where useful information about learners' alternative conceptions would be readily available, and only esoteric and peripheral studies could be undertaken. Perhaps there would be a place for these reports in lesser, more obscure, journals, but space in IJSE etc. could be freed up for something more profound.

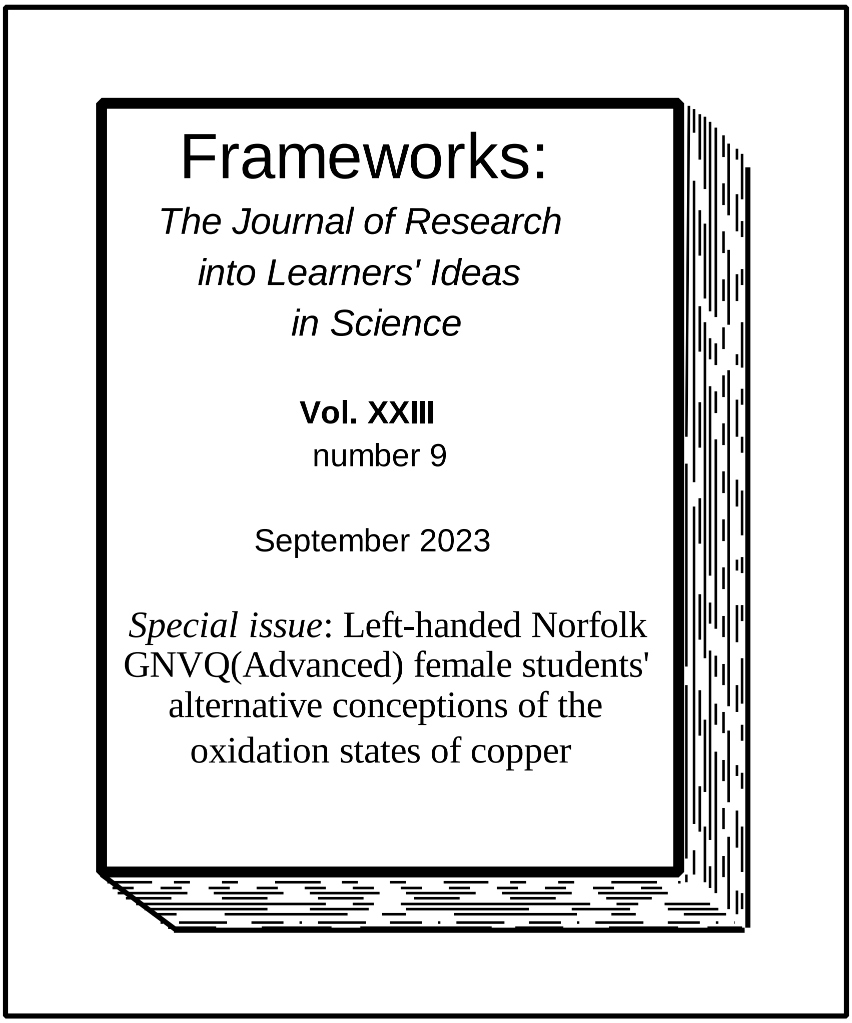


Figure 7: The future of alternative conceptions research?

If the constructivist programme is to be a progressive research programme it needs to offer something more.

Now, for those of you who have read something about wider aspects of constructivism, I would like to made it clear that I do *not* mean ‘radical constructivism’. This is the notion, a philosophical position, that all we know is our own personal realities, the models of the world that we have personally created: and therefore each of realities is equally entitled to be considered a valid model of the world. All realities are equal!

I think this is related to the 'strong' programme in sociology of science which builds on Kuhn's thesis (i.e. that because scientists are trained within a disciplinary matrix, they can not help but be biased[29] against being fully objective when judging their existing theories against new alternatives), and takes this view to the extreme: that science is a social phenomenon with as much objectivity as a world view as any other (I suppose Darwinism and Einsteinism are seen as on par with hedonism, Catholicism, cubism, Freudism, Marxism, Thatcherism, and - as John Lennon put it - ismism.) From this point of view chemistry is *just* a social construction:

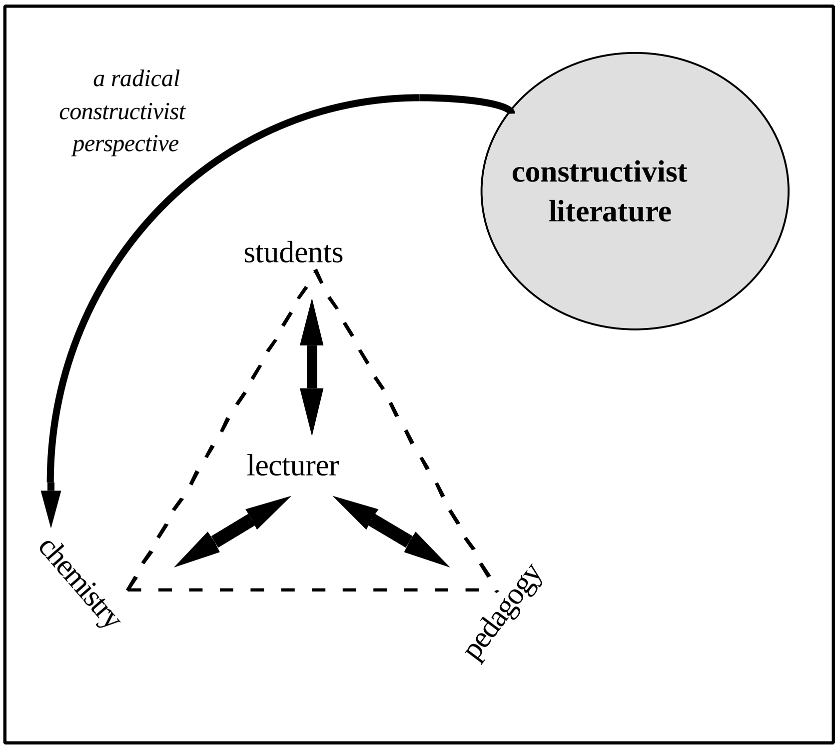


Figure 8: relativist perspective on chemistry

I do not hold such a perspective.

[29] Biased in a literal sense, but not in a deliberate or deliberately obstructive sense.

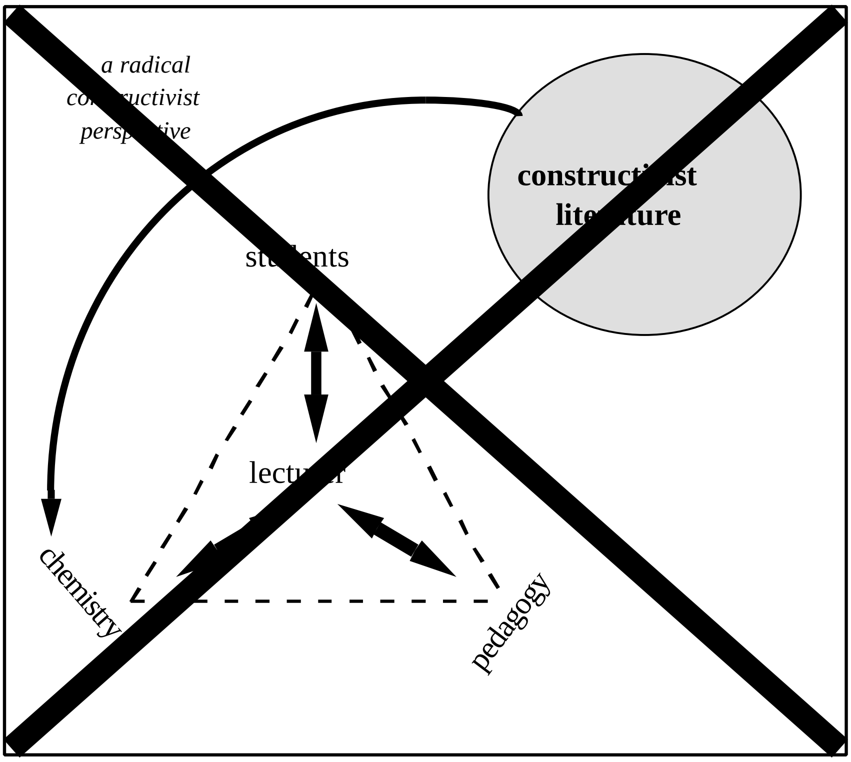


Figure 9: radical constructivism does not help classroom teachers

Of course there is a *social* aspect to science. Of course *one might argue* that everybody is entitled to their viewpoint. But one aim of science education is to teach orthodox, accepted science; and another is help students learn about the processes of discourse, and of examination of empirical evidence, through which science develops a consensus. Teachers and lecturers certainly want their students to use their imagination, and to demonstrate ingenuity and originality; but they also want them to be are able to provide acceptable answers in examinations (and to stay safe in labs!)

Those investigating learners' ideas in science do not grant them equal epistemological status with orthodox science. The significance of alternative conceptions is not that they are equally valid, but in how they may influence to learning of accepted science.

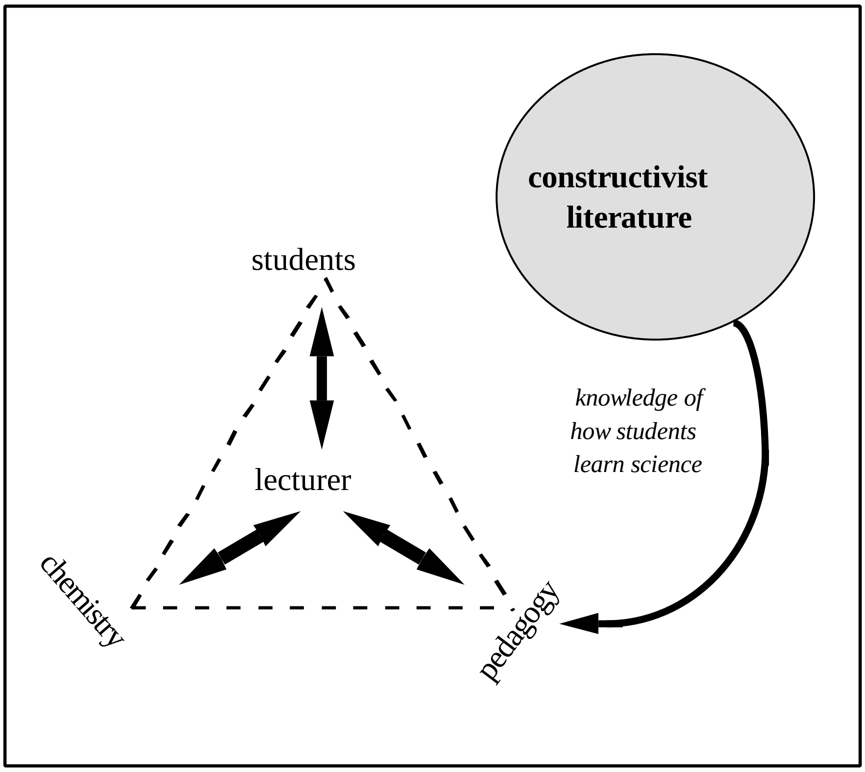


Figure 10: research must inform subject pedagogy

Where the constructivist programme *has* to offer more is in supplementing the knowledge about *how to learn science*, and *how to teach* it.

Now, there is nothing new in this statement. Over a decade ago it was pointed out that much of the early research into learners' ideas in science was akin to 'fishing expeditions' or 'butterfly collecting' and a more systematic approach was needed[30]. In the absence of a progressive research programme, constructivism would stagnate. Joan Solomon recognised this when she wrote that researchers needed to "try and avert a long period of stalemate while overused theory slides into decline"[31].

[30] Watts 1988; Black 1989.
[31] 1994: 17.

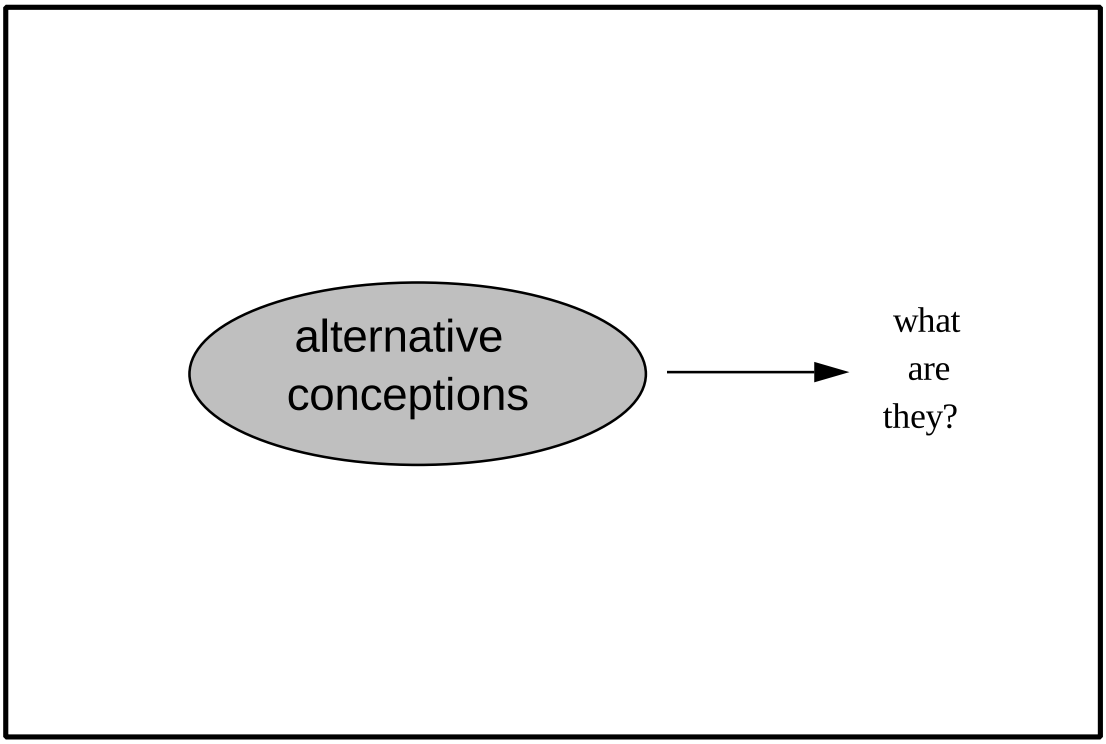


Figure 11: cataloguing alternative conceptions

Smith and colleagues argued that "It is time to move beyond the identification of misconceptions' in 1993:

> "We now need research that focuses on the evolution of expert understandings in specific conceptual domains and builds on and explains the existing empirical record of students' conceptions. Especially needed are detailed descriptions of the evolution of knowledge systems over much longer durations than has been typical of recent detailed studies."
> Smith et al. 1993: 154

Whilst those looking at the alternative frameworks work from outside might be conceptualising the findings in terms of cataloguing misconceptions (figure 11), those working within the field were often looking beyond this: looking at how ideas developed over time, and how learning had to be seen in context, rather than as isolated events (figure 12). Many of these issues were highlighted almost twenty years ago[32].

[32] Gilbert & Watts 1983

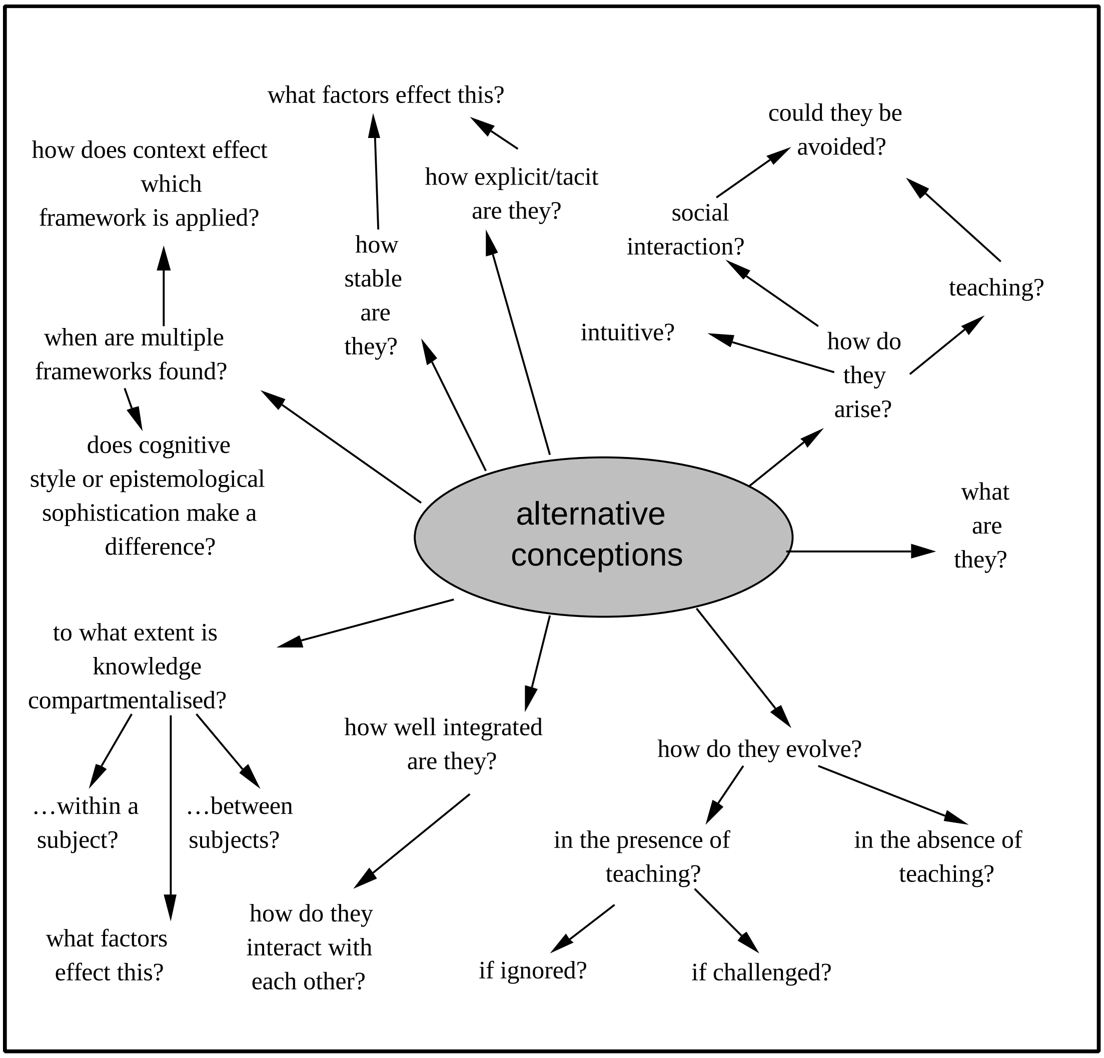


Figure 12: some constructivist research questions

A most important context in which to understand a learner's response to being taught about a topic is the way the new information relates to the existing 'cognitive structure'. The constructivist researchers have been moving beyond butterfly collecting, and have switched from being naturalists to being *conceptual ecologists*:

The difference between these two approaches to alternative conceptions is summarised in table 4[33]. The first column represents a naive view of teaching where the expectation is that learning should *not* be a problematic business if students are able and motivated.

The second column represents a view that considers the existence of alternative conceptions as significant, but considers that the appropriate response is simply to challenge and so replace them.

[33] Immediate source: Kinchin 2000. (Derived from Smith et al. 1993.)

The final column moves beyond this to accept that the complexity of the learning process. Alternative conceptions do not exist in isolation: but within a conceptual ecology. From this perspective, alternative conceptions are still significant, but the teachers most appropriate response to them varies. So, for example, rather than always try and present orthodox science as a better *alternative* to the learners ideas, it sometimes makes more sense to think of trying to *develop* the existing notions towards the desired knowledge structure.

OBJECTIVIST VIEW	**MISCONCEPTIONS VIEW**	**[ECO]SYSTEMS VIEW**
Pupils come to class *knowing little* about the topic.	Misconceptions exist – pupils come to class with preconceptions that *differ* from scientific conceptions.	Novices answer conceptual questions incorrectly, but there is a great deal of *continuity* from novice to expert thinking.
Pupils may have some *wrong facts* gleaned from informal sources such as TV, friends and family.	Misconceptions originate in *prior learning* – classroom instruction or interactions with physical or social world.	Misconceptions result from the *extension of productive prior knowledge*.
Any *wrong facts should disappear* when the pupils learn the right facts - if presented in a clear and authoritative manner.	Misconceptions can be *stable, widespread and resistant to change.*	Misconceptions are not always resistant to change; *strength is a property of conceptual [eco]systems* , not of individual misconceptions
Pupils *should recognise their wrong facts* as such when they are taught the correct facts	*Misconceptions interfere* with learning expert concepts.	Pupils' *prior conceptions provide the only starting point* for instruction.
Emphasis should not be placed on the wrong facts, except to *briefly point out* that they are wrong.	Teaching must help pupils to *replace* their misconceptions	Teaching should help the student *to appropriately extend* their prior knowledge.
Teaching should focus on *explaining the correct ideas* in as clear a fashion as possible	Teaching should help pupils *confront* their misconceptions.	Teaching should help pupils fruitfully engage in the *gradual process of systemic conceptual change* or reorganisation.
Research should focus on how to most *clearly explain* ideas.	Research should focus on *uncovering* misconceptions so that they can be confronted.	Research should focus on the *evolution of pupils' ideas* from root conceptions.

Table 4: three perspectives on alternative conceptions

It would seem there is a lot more work to be done to understand how to effectively teach science in the face of learners' alternative ideas!

5. Applying constructivist ideas to help teachers.

In this section of the lecture I wish to turn away from the general arguments about the research programme, and consider some specific examples. I wish to look at two aspects of my own work. The first is the findings from *my* research into students understandings[34], which I wish to use to illustrate that - in my view - this type of research can offer *real* suggestions to teachers and curriculum planners. Then I wish to consider the project for which the RSC Teacher Fellowship was awarded, which will produce materials for schools and colleges.

An alternative conceptual framework from chemistry education.
The research I wish to refer to was focused on *the developing understanding of the concept of chemical bonding by A level students*. It used in-depth case studies of a small number of individual learners, but supported by a wider data collection from a greater number of informants[35].

I should emphasise two reservations before I describe this common alternative framework.

1. Firstly I should point out that the alternative conceptual framework described is a generalisation of the analyst's interpretations of the responses of data from a range of students. Most of the students interviewed demonstrated thinking about bonding and related topics which is strongly reflected in the framework I describe: however most did not show *all* aspects that I list below, and some drew on this form of explanation more heavily than others.

2. My second point is related: as I will discuss below, during their course, most students could best be described as being *in transition* between this way of thinking, and applying more orthodox scientific forms of explanation. Some started further along that pathway that others, some travelled faster than others, and some had progressed further by the end of their A level course.

Nevertheless, for most of my informants, 'octet' thinking was very common at the start of the A level course, and by no means extinguished by the end.

The key findings of the research included:

- A level chemistry students were not familiar with basic electrostatic principles e.g. common 'conservation of force' conception.

- A level chemistry students commonly operated with a key explanatory principle based upon the 'octet rule'.

[34] Taber 1997.
[35] Taber 2000.

- development of the bonding concept appropriate to an A level course involved a transition from *seeing chemical bonds in terms of satisfying atoms' needs for particular numbers of electrons* to *seeing chemical bonds in terms of electrostatic interactions between positively charged atomic cores and negatively charged electrons*

- Quantum/orbital ideas were often not well understood, but seemed to be less of a barrier to successful understanding than the presence of 'octet thinking'

The lack of appreciation of conventional electrical notions was particularly evident in the presence of a common alternative framework which was labelled 'conservation of force'[36], and which was the belief that - *a charged body gives rise to a certain amount of force (depending upon its charge), which is available to be shared amongst oppositely charged bodies.* A wide range of students' comments (many from discussions about patterns in ionisation energies) were interpreted as demonstrating this view:

> "in the [helium] ion, the two protons are only attracting one electron, but in [the helium atom] they've got two electrons to attract, so therefore like sort of *their attraction is like spread out over two instead of one*".
>
> "[when a sodium atom is ionised, the electrons would] be attracted more, because the same positive charge *pulling on less electrons*, so, it's *more on each electron* [as] … that nuclear charge used in pulling that outer electron … is like *distributed across the other remaining electrons*"
>
> "as we start removing the electrons, you know the *net nuclear charge acting on the remaining electrons* will increase".
>
> "the force divides".
>
> "it's force will be distributed amongst less [electrons]"
>
> "the core charge … has to *spread its attractive forces* equally to each electron"
>
> "When an electron is removed the effective core charge is *shared* out between one less electron"
>
> "the remaining electrons receive the lost electron[']s *share* of the attraction to the centre"

Some of the A level students interviewed studied physics as well as chemistry, but as one explained to me:

[36] Taber 1998.

> "I can't think about physics in chemistry, I have to think about chemical things in chemistry."

In the absence of a good appreciation of electrical principles (or, at least, an inability to apply them in a chemical context!), much of the molecular level thinking of these students followed an alternative conceptual framework*: the octet framework*. This can be summarised below:

The octet rule framework:

- An atomic ontology: atoms as the units of matter - the building block metaphor. The assumption of initial atomicity. Ownership of electrons.

- The octet rule as the basis of an explanatory principle. For explaining bonds. Rationale for chemical reactions.

- The use of anthropomorphic language to discuss atomic phenomena.

- Significance assigned to electronic history. Ionic bonding seen as electron transfer. References to ionic molecules.

- Electrovalency as the determinant of the number of ionic bonds formed.

- Dichotomous classification of bonding.

- The 'just forces' conjecture: distinguishing between bonds, and 'just forces'.

The notion of *an atomic ontology* means that the pupils viewed atoms as the units of matter - the building block metaphor. Now this may sound like a principle that all chemists use! But I feel there is a significant difference between the expert chemist (who uses the idea of atoms as building blocks a useful metaphor[37]) and students who seemed to take the idea too literally:

> "atom is a particle which is the building block of *everything*"

> "Everything, every matter is made up of the smallest part called an atom it is the smallest thing in any mater [sic.]"

Clearly, this definition leaves no scope for nucleons or electrons! Consider these *self-contradictory* definitions of an atom:

> "smallest particle that can be found. Made up of protons, neutrons and electrons"

[37] I suspect that many chemists might feel they were using the idea literally: but I believe that due to the extensive experience, hey are tacitly aware of the limitations of the notion.

"an atom is the simplest structure in chemistry. It contains a nucleus with protons and neutrons, and electrons moving around shells"

This 'atomic ontology' encourages the '*assumption of initial atomicit*y'. When asked about chemical systems at the molecular level, pupils tend to think in terms of discrete atoms:

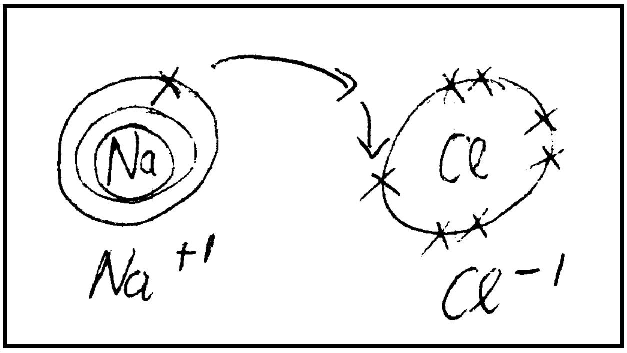


Figure 13 : discrete sodium and chlorine atoms

"The reaction [between oxygen and hydrogen] occurs because hydrogen *needs* 1 electron to complete its shell of electrons and oxygen *needs* 2 electrons in order to complete its outer shell, therefore they *share* the electrons in a covalent bond, so that they both have the required number of electrons in their outer shells."

"Sodiums' [sic] electronic configuration is 2,8,1 and Chlorines' is 2,8,7 so both elements have unstable outer shells. Sodium loses an electron to Chlorine making them both stable and making sodium chloride."

"Sodium atom has one electron more while chlorine atom *needs* one electron to complete an inert electronic configuration. Hence both atoms react with each other"

"Sodium has to get rid of an electron to achieve a full outer shell status and Chlorine has to *try* to gain an electron to complete its outer shell. Therefore Na and Cl combine in an ionic bond where Na gives Cl an electron to complete both shells and both atoms stay together in an ionic bond because they both [sic] have opposite charges."

Ownership of electrons. Pupils who think of atoms in this way may tend to consider electrons to be owned by particular atoms:

"the sodium atom is *lending* chlorine one of its electrons"

"the sodium will still want *its* electrons back"

Perhaps this would not matter if it did not have consequences for the students' expectations about chemical processes. So when considering bond fission of the carbon-chlorine bond in tetrachloromethane, there is a tendency to expect homolytic fission, as:

> "the chlorine would leave with *its own* valence electron, and the carbon, atom would keep its, *its own* valence electron"

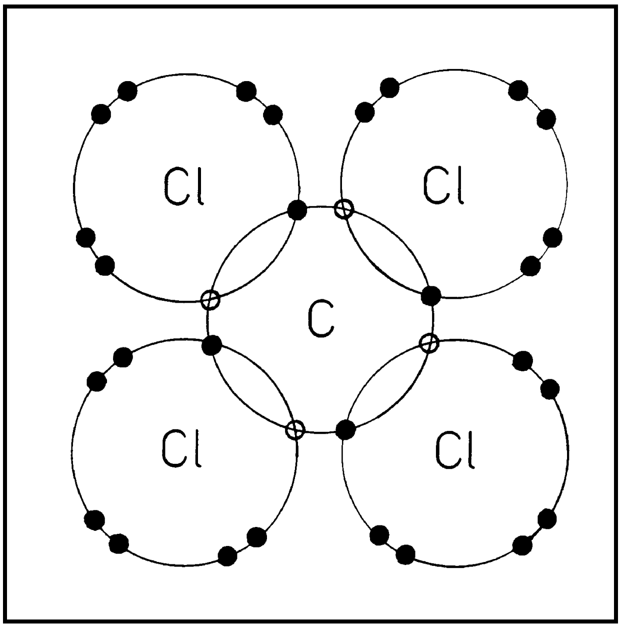


Figure 1: focal figure presented to students

This may even extend to the point of believing in *selective* electrical interactions:

> "the protons in the chlorine nucleus, they're attracted to that [poking diagram, see figure 14] particular one, in its own outershell, its *not attracted* to that carbon's electron"

Covalent bonding as sharing of electrons. It was found that covalent bonding was very often described in terms of atoms *sharing* electrons. Whilst this is a common metaphor used by professional chemists, it was (again) used differently by some students. For these learners, 'sharing' was not a shorthand way of describing the way the electrons are positioned between the nuclei, or a way of referring to molecular orbitals, or some other physically valid view of the system. Rather 'sharing' was taken much more literally, and was seen as, *of itself*, explaining the bond, rather than merely an image for it:

> I: Could you explain to me what holds the two atoms together?
> P: The covalent bond.
> I: Right, so how does that hold the two atoms together?
> P: 'cause it's *sharin*g the electrons.
> (P - A level student)

> "because they're *sharing*, it's kinda like a link, yeah like a stable link that, you know, this one is *sharing* electron with that one, and that one is *sharing*, it's like a force that's holding them together"

So the 'act' of sharing an electron gives rise to the force that held the atoms together (rather than vice versa):

> "when two or more atoms join their electrons are shared (covalent) or given (ionic) this *makes a force* between the atoms"

> I: Now, what holds the [hydrogen] molecule together?
> U: The two electrons, *shared*.
> I: And how does that hold them together?
> U: 'cause they're *sharing* the same shell and electron.
> I: And why does that hold them together?
> U: Makes them more, together like, makes them more like joined together like one.
> (U - A level student)

The alternative conceptual framework is called *the octet framework* because it uses the octet rule as the basis of an explanatory principle. The basis of 'octet thinking' is

> the ***full shells explanatory principle***:
>
> **that atoms form bonds in order to achieve stable electronic configurations** (variously referred to as octets, full outer shells or noble gas configurations/structures[1]).

A great many examples of this sort of argument being made by students were collected during the research. A few examples are given:

---

[1] These terms are not always equivalent - but were found to be commonly used as if they were.

> "bonding is when 2 atoms chemically combine to become a molecule of sorts. The 2 types of bonding are IONIC (donating electrons) and COVALENT (sharing electrons). It is done in order to try *to achieve a stable structure i.e. 8 electrons in the outer shell* of the atom"

> "in all cases what an atom is trying to do is to become stable, and so obtain a *full outer shell*"

So when considering covalent bonds:

> "the sharing of electrons between two species, in order to gain fully full outer shell"

> "the electrons are shared *to* create a *full outer shell*"

> "A covalent bond is one in which two atoms join together by the *sharing* of electrons. Each of the atoms *achieves noble gas configuration* in the process of covalent bonding."

> "Covalent bonding is the sharing of electrons by 2 or more atoms to achieve the result of a *full valent shell*."

And similarly, when explaining the ionic bond:

> "[ionic bonding] involves, one of the atoms donating all of the electrons, to the other atom which is sort of deficient in electrons, so making it up to the number it needs, to like have a *full stable outer shell* which is *what all sort of compounds are aiming for*"

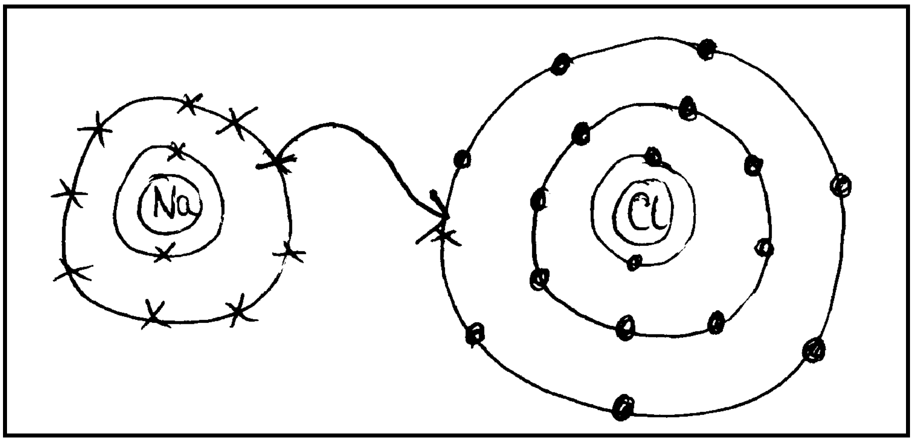


Figure 2: student representation of the ionic bond

> "When two elements form ionic bonds, … like sodium, and chlorine …. sodium, sort of, to gain a *full outer shell* wants to lose an electron, and chlorine wants to gain an electron to become a *full outer shell*. So that way they can both be stable, together, sodium and chlorine"

Sometimes 'octet' arguments were also used in explaining the metallic bond.

> "by electrons moving around, they're, they're getting, *a full outer shell*, but then they're sort of losing it, but then like the next one along will be receiving *a full outer shell*"

> "because in [a] lithium atom there's one outer electron, so it's not stable, it can gain a *noble gas configuration* if it loses an electron, and … it's like doing that by constantly losing an electron, well not losing but giving it away, passing it around, sort of thing"

> "in the lattice each ion … loses an electron to form a positive ion, so *to get a noble gas configuration*."

> "metallic - formed by the one, two or three valent shell electrons being donated to lattice *so a noble gas configuration is achieved*. The electrons hold the atoms together."

Sometimes the same sort of explanation could be applied to dative bonds. So, for example, aluminium chloride dimerises as

> "in order to attain a stable state you must have *eight* electrons"

> "in order to attain a stable state you must have *eight electrons*, so one of the chlorine atoms seems to donate two electrons, and form a dative bond."

> "they have to have [an] *octet*, you know, *eight electrons*, so the other two electrons are just donated by chlorine"

> "to obtain the *octet* state, because *octet* state is usually stable"

> "to obtain a *full outer shell* it would need two more electrons, and it gets them from the chlorine"

Rationale for chemical reactions. The full shells explanatory principle was also used to explain why reactions would, or would not, occur. The inertness of noble gases is explained that way:

> "noble gases, they don't react because they've got complete outer electron shell, so … it doesn't need to donate or accept"

The 'full shell' argument was also used to explain why these atoms should be difficult to ionise:

> "Neon has *eight* electrons in its shell and therefore contains a *full shell* making it very difficult to remove electrons."

> "… it has achieved it's *octet* i.e. its second shell is *full with eight electrons* and cannot take any more so to remove 1 of these will disrupt the configuration as all charges are balanced out and ∴ it is very difficult."

Other elements (which are often conceptualised as discrete atoms) are seen to react in order to obtain such electronic structures. So hydrogen:

> "has got one electron in its outermost shell, and *it cannot exist on its own*, so it will combine with another hydrogen, to form hydrogen molecule"

As one student summarised:

> "in all cases what an atom is trying to do is to become stable, and so obtain a *full outer shell*."

If this sort of thinking does not seem so problematic consider the following three chemical species:

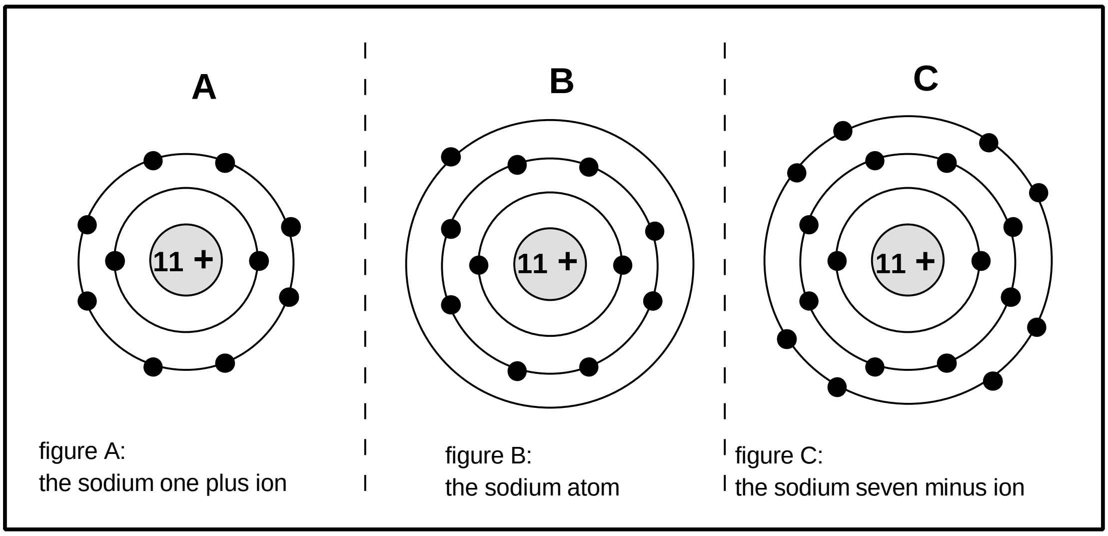


Figure 3: three chemical species

It was found that the majority of students in two A level classes thought that the sodium *anion* would be more stable than the neutral atom! They argued that:

> "B is less stable than C because … the outer shell of C is *full* with *eight* electrons but B only has i electron in its outer shell and is less stable."

> "B is not as stable as C because it needs another 7 electrons to *fill* the outer shell"

This is a worrying finding, leaving aside the 'technical' error of considering the third electron shell to be 'full' once it had an octet! Clearly, students commonly see the octet as having some mystical significance!

> "If an atom has been filled up or [is] all ready full up (of 8 outer electrons) it becomes stable and therefore it is unreactive. *The atom will stay that way forever* and not react or loose or gain any electrons."

(All that is lacking at the end of this comment is an 'Amen'!)

The use of anthropomorphic language to discuss atomic phenomena. Now one feature of some of the quotations given above is that the students talk of atoms as if they are sentient beings which are able to act deliberately to bring about desired ends. Anthropomorphism has a strong tradition in science, and it may sometimes be seen as poetic, metaphoric language used for educational or rhetorical purposes[2], or it may sometimes be considered as just sloppy!

However, in my research it became clear that a lot of the anthropomorphic language seemed to stand in the place of any alternative form of explanation. In the absence of having a physical mechanism to explain chemical phenomena a social mechanism was implied! The most common examples were where atoms were regularly said to *want* or *need* the right number of electrons:

> "This reaction occurs due to the covalent bonding which takes place. Hydrogen *needs* an extra electron to *copy* He [helium] and have a stable condition. Oxygen *needs* two electrons, and so two hydrogens and one oxygen bond together covalently so that each hydrogen *shares* an electron with oxygen so that their outer shells are all stable."

> "[sodium]*wants* to lose an electron, and chlorine *wants* to gain an electron to become a full outer shell"

However, there were many variations on the theme:

[2] Taber & Watts 1996.

> "oxygen has 6 outer electrons so it *requires* another two electrons to fill the outer shell. Hydrogen has i spare electron so 2 hydrogen electron is *required* to fill oxygens outer shell [by] combining to make a full shell."

> "[atoms] *like* to achieve a stable noble gas configuration"

> "[atoms] *prefer* to have eight electrons"

> "[a hydrogen atom was] *very eager* to get the 1 electron to complete its outer shell"

> "the aluminium *thinks* that it's stable because it's got eight outer electrons, but really it hasn't, but it *thinks* that it has"

> "all elements *try* to gain noble gas configurations to become stable"

Significance assigned to electronic history: the history conjecture. Perhaps related to the tendency to see all chemical structures as derived from atoms, and to use anthropomorphic explanations, students often felt that *history* was important in chemical systems. In particular, electrons were seen as belonging to particular atoms. So, for example, in considering bond fission in tetrachloromethane (figure 14),

> "the chlorine would go back to being an atom, so it would acquire one of those electrons that *it gave in the first place* to form the bond, so … it would probably take … *the one from the chlorine*."

> "[the carbon] electron would return to its *own* nucleus, and the chlorine electron would be returned to its *own* atom"

> "the chlorine electron would stay with the chlorine atom, the carbon electron would stay with the carbon", because of "which electron *belongs* to which"

Students seemed to feel this was the natural order of things: as the following justification suggests,

> "it would seem a bit of an odd-ball, wouldn't it, to have somebody else's electron"

Ionic bonding seen as electron transfer. Where covalent bonding was commonly seen simply as 'electron sharing', ionic bonding was most commonly seen as 'electron transfer'. That is, when asked about *ionic bonding* students would commonly focus instead on *ion formation*:

> "ionic bonding *is* the *transfer of electrons* from one atom to another, and … the aim again is to try and get, erm, complete outer shell" outer shell"

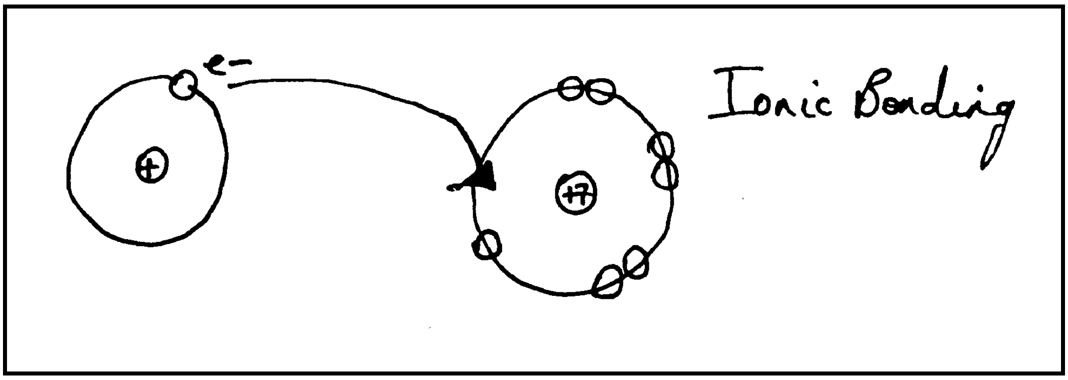


Figure 4: ionic bonding or electron transfer?

In *some cases*, despite this confusion of two separate phenomena the nature of ionic bonding was appreciated. However, for other students an ionic bond could *only* exist where there had been a discrete electron transfer event between the atoms forming the ions. So one student reported that counter ions in solution would not attract, as

> "attraction is only possible when a bond is formed"

Indeed for some students the bond formed ion-pairs that were akin to ionic molecules:

> "[Sodium chloride dissolves in water] because the water breaks up the large salt crystall [sic] into tiny *molecules of NaCl*, I don't think that any atomic changes go on in this process."

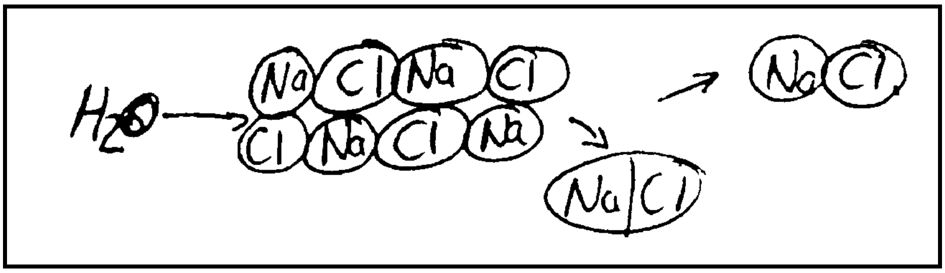


Figure 5: Ion pairs as pseudo-molecules

Electrovalency as the determinant of the number of ionic bonds formed: the valency conjecture. When the ionic bond is conceptualised in terms of electron transfer, the number of electrons that can be transferred during ion formation is seen as determining the number of counter ions that an ion could bond with. So an atom could form as many ionic bonds,

> "as it wants, *as long as it's got electrons to cover* how many it does want"

In the most common example, NaCl, which is seen as the archetype for ionic bonding,

> "one chlorine is only bonded to one sodium, because a sodium atom can only lose one electron, so, therefore … it can only gain one bond"

Dichotomous classification of bonding. For pupils commencing A level courses there was often a view that "bonds can be either covalent or ionic". This dichotomous classification was based on either whether electrons were shared or transferred, or whether the elements involved were metals or not.

covalent	ionic
electrons are shared	electrons are transferred
between non-metal atoms	from metal to non-metal atoms

Table 1: a bonding dichotomy

Classification of polar bonds. This dichotomous approach meant that polar bonds were often seen as being either ionic or covalent - and this was even the case when the student was not sure which!

> "well, ionic I suppose. Well, no, covalent I think"

So when the (very electronegative) non-metal chlorine was in a compound with (the much less electronegative) non-metal phosphorus the bond was likely to be seen as covalent:

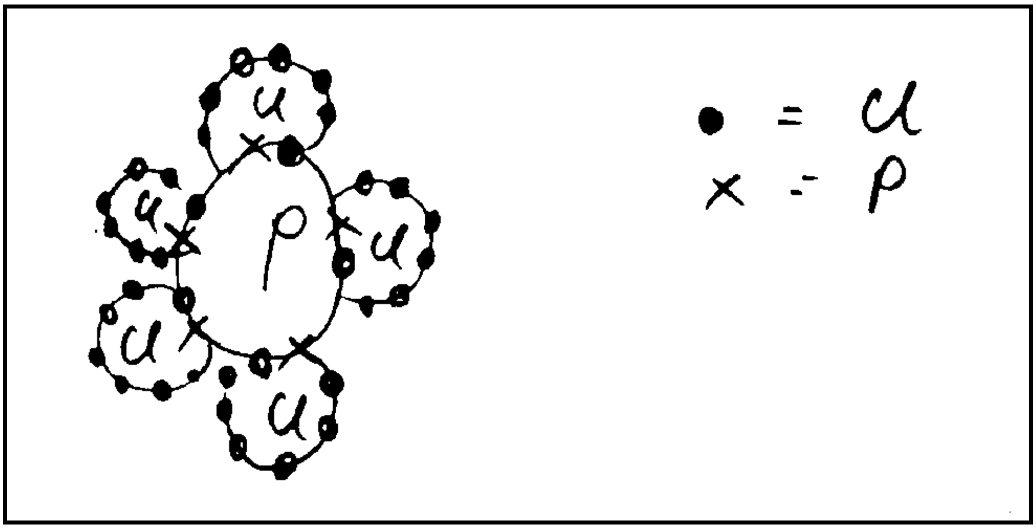


Figure 6: "Phosphorus (V) chloride is [sic, has] covalent bonding, in which one electron is supplied by each atom."

So students would, for instance, refer to bonds that were "*trying* to be ionic", or were "ionic but *trying* to be covalent"

Classification of dative bonds. Dative bonds are commonly formed between 'weakly' metallic elements such as boron and aluminium which are 'electron deficient' in their compounds, and more electronegative elements with lone pairs of electrons (such as fluorine and chlorine). Yet from within the octet framework dative bonds are seen as:

> "When an atom donates both electrons to a *covalent* bond"

Classification of metallic bonds. Even at the start of their course many A level students *appreciated* that metallic bonding did not fit the covalent/ionic dichotomy: although for some this was little more than an odd anomaly!

> "it's made of, like, the metal sodium, and it's just like bonded like between itself, *it's not ionic, and it's not covalent either, it's like, it's hard to explain this*. It's just like that metal's bonding there, I mean you don't have something like chlorine mixed with it, and, do you get me? {laughs}"

Students' representations of the metallic bond were often vague:

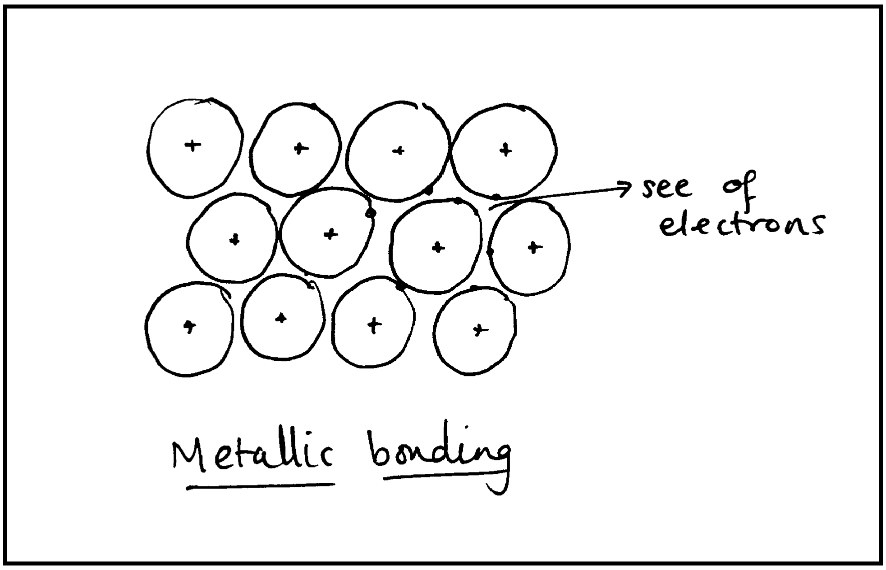


Figure 7: A metal with devout electrons?

And sometimes they showed scant respect for electrical neutrality:

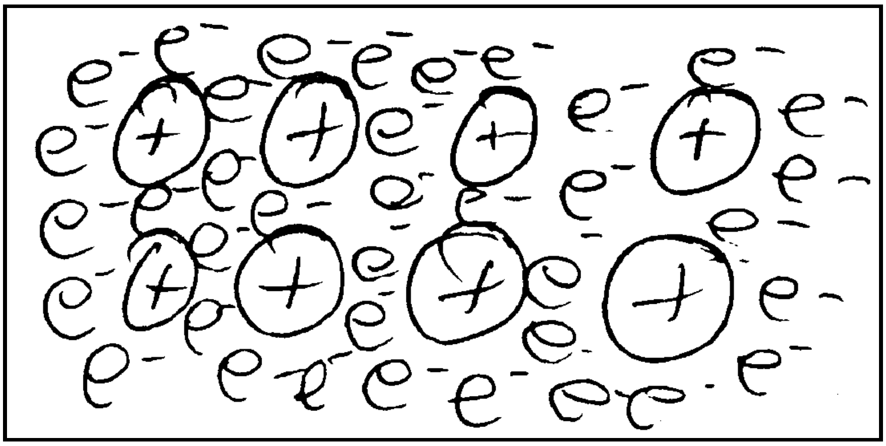


Figure 8: metal awash with electrons?

> "Copper. This has mettalic [sic] bonding. In Mettalic bonding the atoms are held together in a "sea" of electrons which acts like a glue."

Classifications of intermolecular bonds. Other types of bond presented even more of a puzzle from within an 'octet perspective', unless they could be explained away. So, for at least a few students 'hydrogen bonding' was simply where hydrogen was bonding to something:

> "because, if you think about it, you know, 'hydrogen bonding', that's like, you know, 'what is *hydrogen bonding* to?' It's kind of that sense"

> "Hydrogen bond is when a hydrogen shares the same electrons with another element"

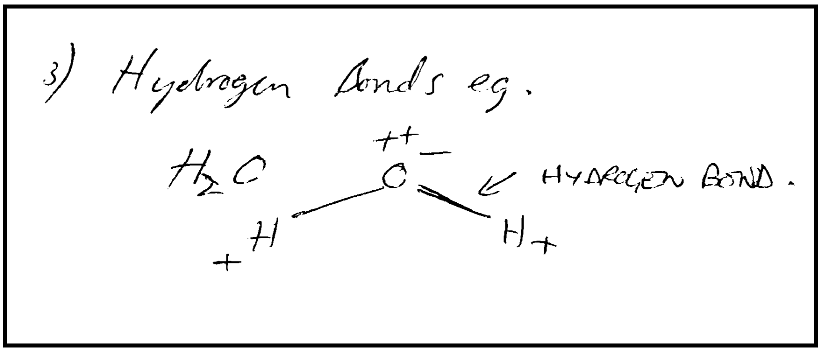


Figure 9: A hydrogen bond?

The ‘just forces’ conjecture: distinguishing between bonds, and ‘just forces’.

One common way of avoiding explaining bonds that did not fit the dichotomous pattern (and so could not readily be explained as atoms trying to complete their shells), was to define them as something other than actual bonds: usually as just forces. This was a possible explanatory device as bonds were not seen as forces (but rather as the sharing or transfer of electrons). This approach could be used with various types of interaction that were not considered either ionic or covalent:

• **Metallic bonds as just forces.**

> “Ionic and covalent bonds, are formed with other atoms or groups of different atoms, where atoms lose or gain electrons, or share them, whereas *metallic bonding is not the sharing or loss or gain of electrons*. It is *just a lose association* with metal ions, and electrons they have lost, where this helps to hold the solid metal lattice together.”

• **Hydrogen bonds as just forces.**

> “*not actually a bond*, but it’s a force”.

• **Solvent-solute bonds as just forces.**

> “the hydration energy is the energy given out when an ion is surrounded by water molecules” … “because it’s *like* a bond being formed and so it’s an exothermic process” … “it’s *just an attraction* really”

• **Van der Waals bonds as just forces.**

> “it’s actually a type of force, it’s not actually a chemical bonding”
> “it’s *not bonding*. But there’s sort of van der Waals’ forces”
> “neither ionic, or covalent, you know. *Just an attraction and repulsion* between atoms.”

Sometimes, the students did not seem to be entirely convincing with this form of argument:

> “This is also a type of bonding, but it’s not, it’s actually a type of force, *it’s not actually a chemical bonding*. What are we doing, chemical bondings, ain’t we? …Yeah, this I think could be counted as chemical bonding, but … one molecule is not actually chemically linked to another molecule, it’s *just a type of force*, that’s held in, holding them together.”

Ionic bonds as just forces.

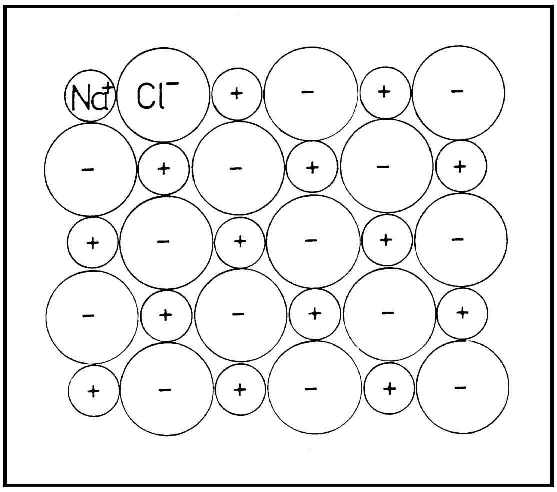


Figure 10: an ionic lattice - not bonded?

For some students there no bonds[3] in the ionic structure:

> "they don't actually overlap or anything" …"it would probably get held together by *just forces*"

Most students thought there were *some* ionic bonds in the structure, but the 'valency conjecture' limited the number of ionic bonds that any ion could form. (In figure 23 each ion would be construed to have one ionic bond, with one of its neighbours[4].)

So in ionic lattices, the students had to explain why ions seemed to be attracted to a larger number of neighbours. As students generally did *not equate bonds with forces* this was not usually a problem. For example, one student explained that an ion is *most strongly attracted* to "the *one* it forms a bond with", because "that's where it's transferred the electrons".

So, as long as the bonds were not identified with the electrical attractions, it was possible to believe that

> "[ions would] *not bond*, but go together 'cause they're opposite charges".

The evolution of learners' thinking.

The research I have been discussing did not set out to find out if students had any alternative conceptions about bonding. Rather, it aimed to explore students *developing understanding* about chemical bonding.

[3] Indeed some students seemed to distinguish between bonds and bonding - so the presence of ionic bonding may not imply to all students that there were ionic bonds!
[4] And some of the students I talked to could actually point out *where* there would be bonds in the diagram!

It was found that most students relied on the octet framework quite extensively near the start of their A level studies. Electrostatic principles *were* often *also* used, although not usually widely, and sometimes not accurately. It was felt that by the end of the course it was desirable for students to explain aspects of chemical bonding in terms of electrical and quantum ideas (such as orbitals and spin). In practice, even a successful student was unlikely to make a complete transition during a two year course (see figure 24)[5].

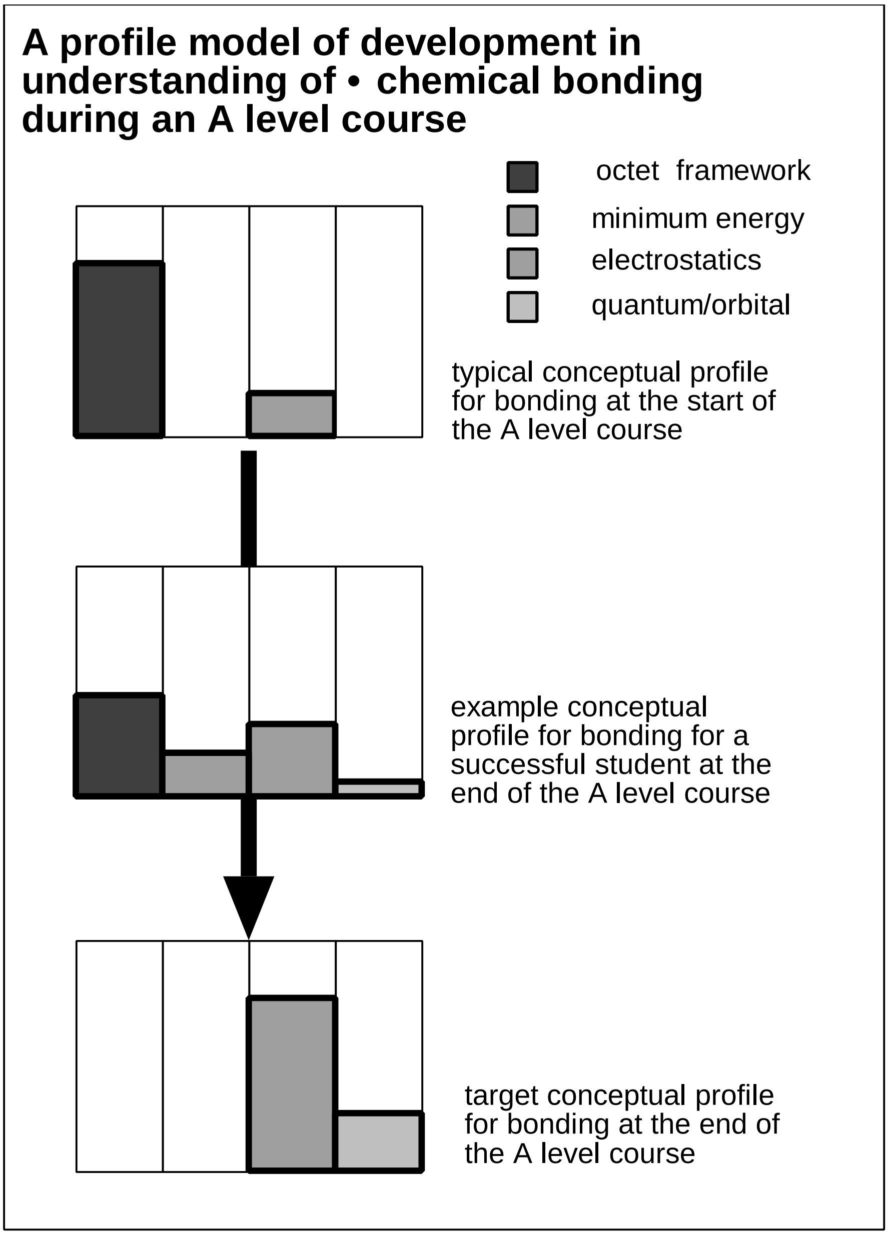


Figure 11: Evolution of a student's conceptual profile.

[5] The 'conceptual profile' for this student showed that sometimes the notion of minimising energy was used as an explanatory principle that was seen as *independent* of electrical ideas: Taber & Watts 1997; Taber 2000b.

The origin of the alternative framework.

The research also considered the question of the *origins* of the octet framework. Some alternative frameworks that have been reported are believed to derive from early childhood experience (e.g. the ‘impetus framework’ for force and motion), but this was hardly likely - at least in any direct sense - for ideas about how atoms interact! A typology of ‘learning impediments’ was developed, where a ‘learning impediment’ was considered to be some aspect of the way the learner’s conceptual structure interacted (or not) with the lecturer’s presentation of material (figure 25).

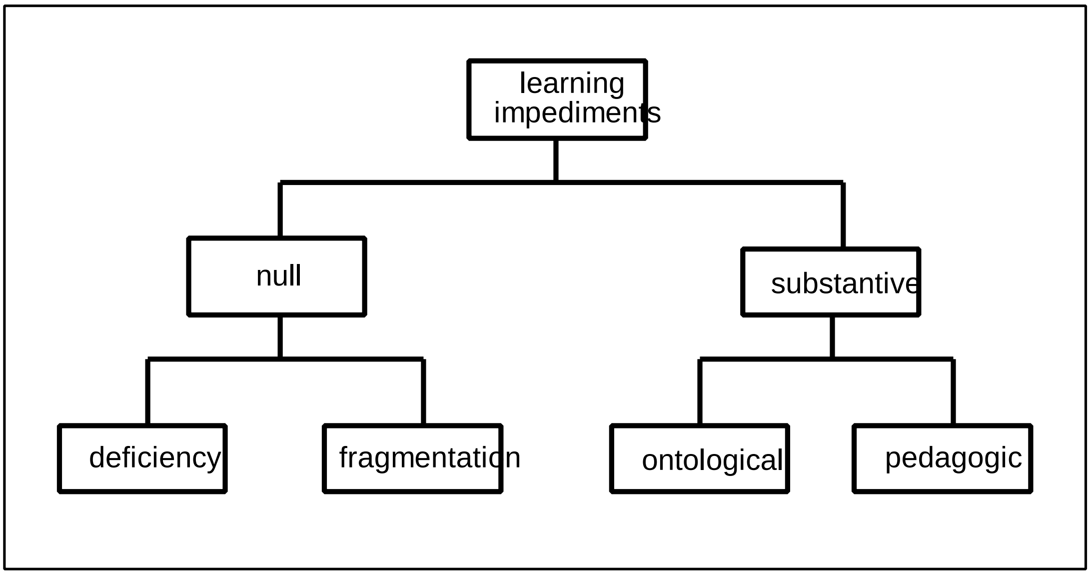


Figure 12: a typology of learning impediments

Substantive learning impediments were those alternative frameworks which caused the learner to misinterpret new teaching because of existing ideas. (Whereas *null* impediments were where the learner was unable to make sense of the teaching because it could not be related to existing ideas: either because prerequisite knowledge was missing - a *deficiency* impediment - or because it was not accessed in the new context - a *fragmentation* impediment.) *Substantive* learning impediments were divided into two broad classes. Those that derived from the learner’s earlier experiences of the world (whether of a direct physical nature, or mediated by language or culture), labelled *ontological*, whereas *pedagogic* learning impediments referred to those alternative frameworks which derived from earlier teaching. Clearly, alternative frameworks are not always likely to fit neatly into such clinical categories, but it was thought to be *a useful way to conceptualise the different ways that learners could fail to make the intended sense of teaching*.

In particular, pedagogic learning impediments could be avoided by changing the way we teach early topics, to save ourselves a lot of trouble later in the curriculum!

The octet framework was judged to be, at least primarily, a *pedagogic* learning impediment. In the absence of careful explanations of how bonds came about (and why reactions occur), and in the presence of some dubious diagrams and explanations in many text books, school pupils look for a rationale in what they *are* taught. The octet rule, a useful rule of thumb for spotting stable chemical species (Cl^{2+}? no, Cl^{-}? yes; NH_2? no, NH_3? yes), becomes elevated to the prime explanatory principle for chemistry.

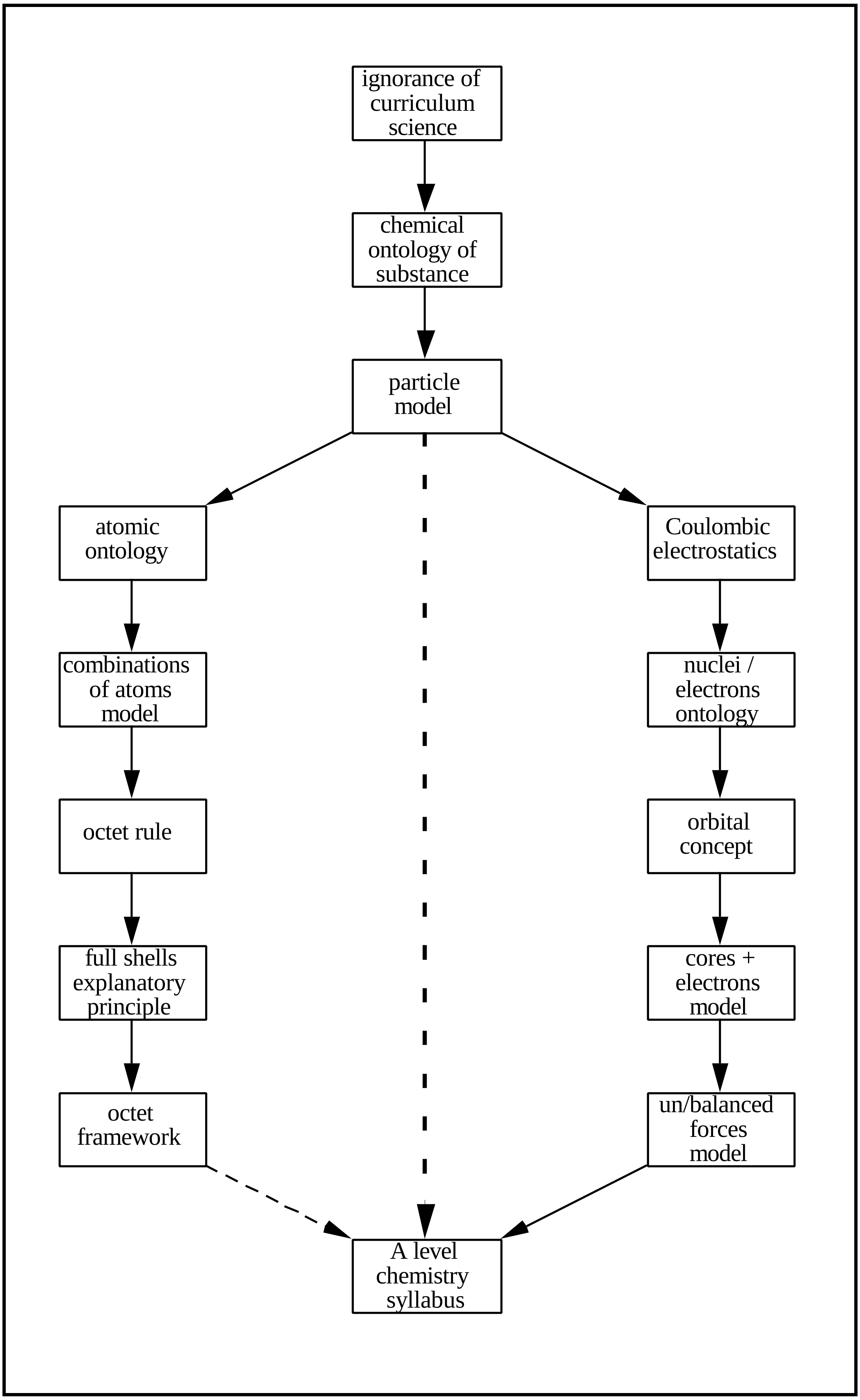


Figure 13: An alternative conceptual trajectory informed by research into learners' ideas.

Advice deriving from the research.

As the octet framework is considered to be a pedagogic learning impediment, it is possible to provide advice for teachers on how it might be avoided in future. By changing the order in which certain ideas are presented, and the emphasis given by teachers, it should be possible to prevent students getting to the end of their school chemistry believing that chemistry is about isolated atoms reacting by forming bonds with the sole purposes of obtaining full outer shells. The key recommendations[6] would be:

- Introduce electrostatics early.
- Avoid over-emphasis of the octet rule, octets, full shells etc.
- Present an ontology based on systems of nuclei and electrons.

By making sure that chemical processes are conceptualised in electrical terms pupils should appreciate the types of explanation that are acceptable. Although the octet rule is useful, and certain electronic configurations are associated with particular stability, it is important not to give pupils the impression that these ideas are chemical panaceas. If chemical species are seen as systems of nuclei plus ‘shells’ of electrons, then molecules and ions can be seen to be just as fundamental as atoms - and potential starting points for thinking about chemical changes.

There is not time to discuss these ideas here, and as these recommendations have not yet been adopted (to my knowledge), it is not yet possible to say how successful they would be. My point is that it is possible to look at the ways things are presently done, and to suggest an alternative approach that may be more effective in helping students construct chemical ideas that match orthodox thinking in the subject. Figure 26 compares the way learners in school current develop ideas about bonds and reactions (left hand side), with my recommended alternative trajectory that derives from research.

I hope I have convinced some of you that the type of research I have been involved in does not just report students’ odd ideas, but looks at how understanding develops, and therefore can provide useful input at two points of the teaching triangle.

[6] Taber 1997.

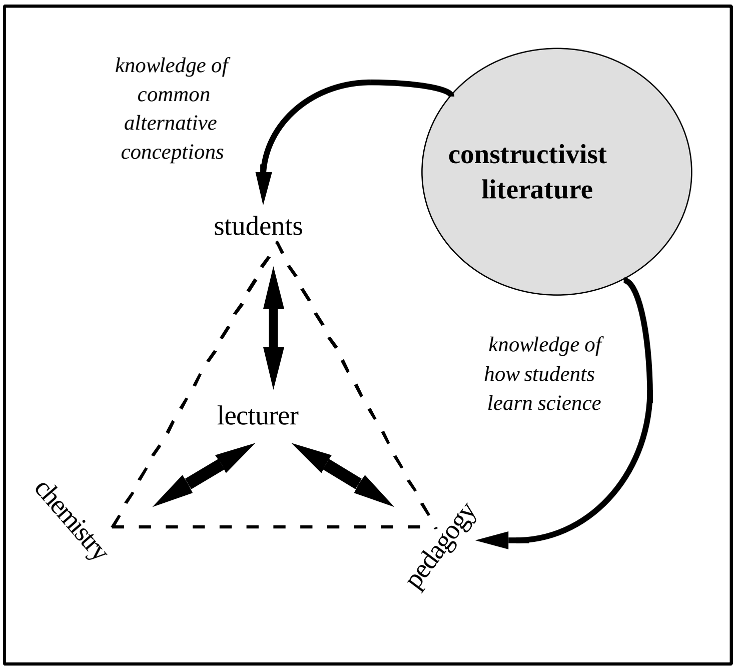


Figure 14: Constructivist research informing teaching

The RSC project.

This brings me to the RSC funded project that began a few days ago (on 1st September). Each year the RSC funds a *Teacher Fellow* to work on some aspect of supporting the teaching of chemistry/science. During the current academic year I will be seconded to the RSC as Teacher Fellow to develop materials to support classroom teachers (at secondary and sixth form level) challenge common misconceptions.

The intention is to provide materials that will be sent (free of charge) by the RSC to UK schools and colleges. These materials will hopefully include a variety of exercises for use in the classroom, as well as supporting information. The exercises will be designed to help teachers find out if their own pupils hold some of the alternative conceptions reported in the literature. The supporting materials will explain the 'misconceptions', and their significance, and provide support in challenging them. It is expected that many of the exercises may act as suitable starting points for classroom discussion that can compare the scientific models with the alternative views suggested by pupils.

Although there will not be the time to produce complete teaching schemes (and the intention is to provide exercises that will slot into existing teaching programmes), it is hoped that materials will be provided that will address some of the key concepts in chemistry, and related general science, where research suggests alternative ideas that block intended learning are commonly encountered.

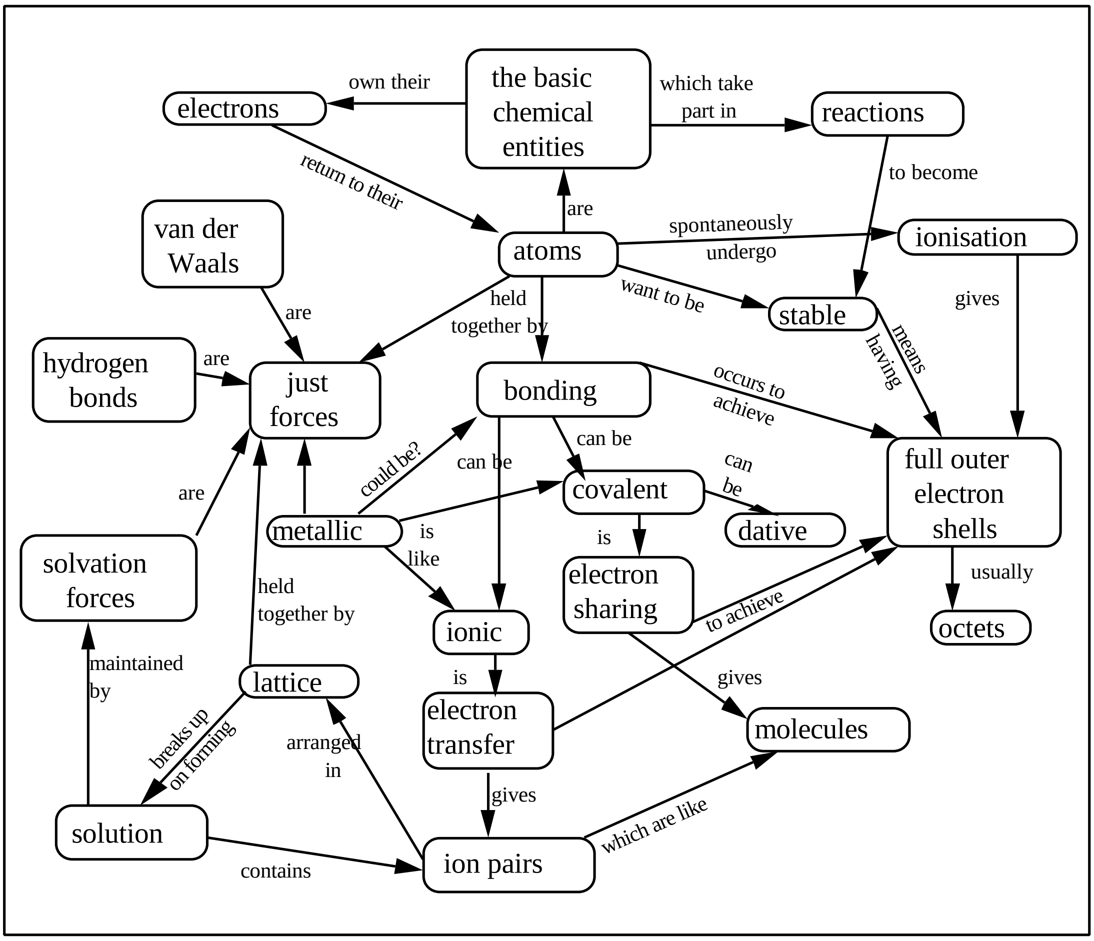


Figure 15: The octet framework

As I have only just started I do not yet have a wide range of materials to talk about. However, I can use the research I have discussed above as an example. The octet framework is more than just an isolated alternative conception: rather it is a complex of inter-related ideas, that are - in some learners at least - integrated into a consistent and mutually reinforcing framework for making sense of the subject (figure 28).

It would clearly not be that useful to teachers just to describe the alternative framework, and advise them to be vigilant. It is also quite unlikely that most teachers would have the time to actively devise ways of exploring the extent to which their own students held these ideas. [7]

Yet, it is possible for someone who *does* have the time to set about producing such materials for classroom use. As part of the research discussed above two diagnostic instruments were written, simply comprising of thirty statements (each) to be judged as true or false.

When these instruments were undertaken by A level chemistry students it was found that some of the alternative conceptions were popularly supported (tables 6 and 7):

[7] This, of course, echoes the points Onno (de Jong) made in his lecture last year

statements reflecting ‘conservation of force’ (relates to a diagram of a sodium atom)	respondents judging statement as ‘true’ (n=110)
“the eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons”	72%
“if one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus”	69%
“the third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus”	70%
“after the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus”	79%
“the force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed”	74%

Table 2: A common alternative conception

Table 6 shows that about three-quarters of A level students find the idea of force from the nucleus being shared among electrons as acceptable.

Table 7 shows that over half of the A level students questioned believed that ions with a single charge can only form one ionic bond. Perhaps even more significant, was how for these two items, this proportion did not seem to change as a result of teaching (although it should be pointed out that there was no attempt to ensure the two cohorts were matched).

It is hoped that these diagnostic instruments, which have been described in the practitioner literature, will provide a *useful starting point* for classroom discussion.

item statement (about NaCl lattice)	support for *valency conjecture* before teaching (n=81)	support for *valency conjecture* after teaching (n=128)
A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.	57% selected TRUE	60% selected TRUE
A chlorine atom can only form one ionic bond, because it can only accept one more electron into its outer shell.	60% selected TRUE	58% selected TRUE

Table 3: Support for the valency conjecture

Long lists of statements that are to be judged as 'true' or 'force' are perhaps a little boring for students, and I have been thinking about more student-friendly approaches to the materials to be produced in the RSC project.

Consider figure 29 which is presented in one such exercise:

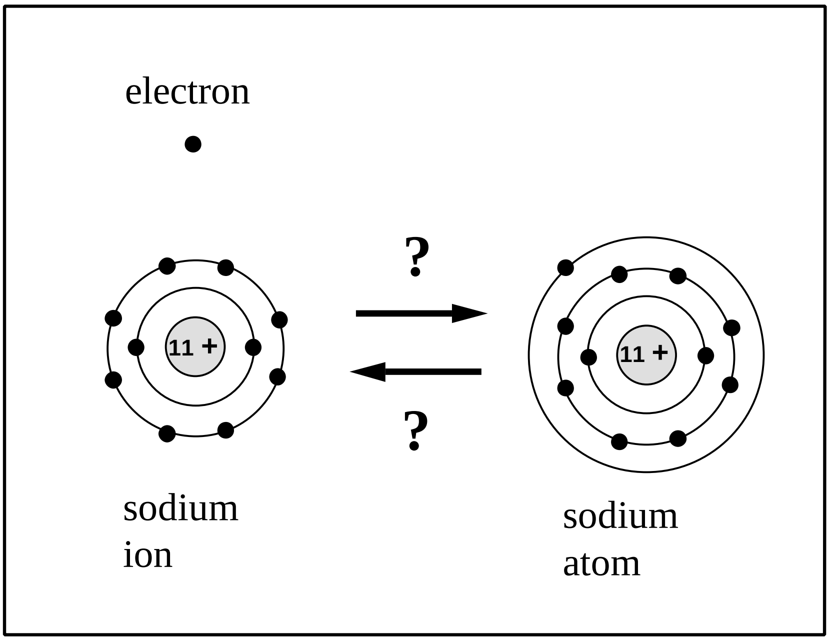


Figure 16: spontaneous changes?

This probe was intended to elicit students' notions of 'stability' - and 'reactivity'. As part of this exercise students are asked to consider the notion of which process is seen as likely to occur. The format is a multiple choice section of four options (including a 'I do not know' option), and space for an explanation.

For this part of the exercise the four options were:

- The sodium atom will emit an electron to become an ion.
- The sodium ion and electron will combine to become an atom.
- Neither of the changes suggested above will occur.
- I do not know which statement is correct.

This exercise has been undertaken by over fifty Y10 pupils in one school. Of 54 pupils answering that item, 3 did not know what would happen, 7 thought neither process would occur, and 1 thought the atom and electron would combine. 43, that is *four-fifths, thought that the atom would emit an electron*. Many of the reasons given were variations on the theme of:

> "To be stable the sodium atom needs to get rid of an electron to make it stable. It then becomes Na^{1+}"

Consider another probe, which provide a more realistic chemical context. This commences with some information about a reaction:

Hydrogen reacts with fluorine to give hydrogen fluoride. The equation for this reaction is:

$H_{2(g)} + F_{2(g)}$ ® $2HF_{(g)}$

The word equation is:

hydrogen + fluorine → hydrogen fluoride

Then a diagram is presented:

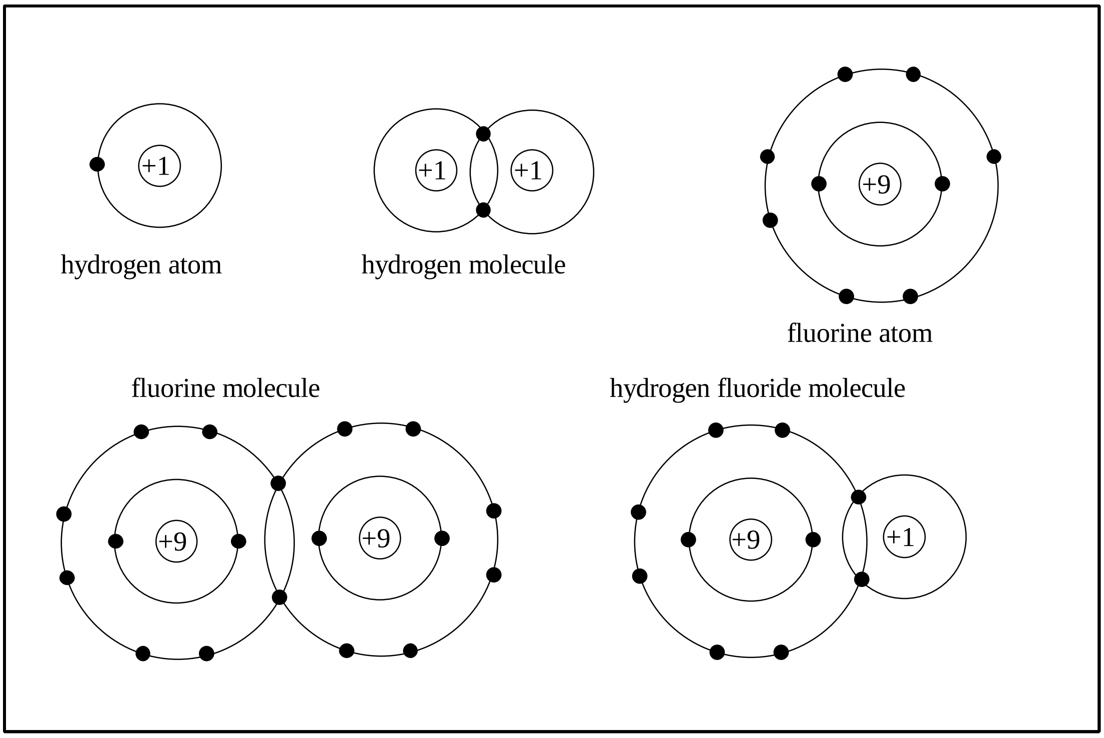


Figure 17: why do H2 and F2 react?

The respondents are then asked:

"In your own words, explain why you think hydrogen reacts with fluorine:"

This was undertaken by 29 A level students in a school sixth form. Here is an example of the explanation given by one student:

> "Fluorine is a halogen and has 7 outer electrons. To be stable it would like 8 electrons in its outer shell. By covalently bonding with the hydrogen atom which would like 2 electrons in its outer shell they form hydrogen fluoride which is stable"

Yet, the reaction equation given clearly refers to H_2 and Cl_2. The figure shows the *molecules* of chlorine and hydrogen where chlorine already has "8 electrons in its outer shell" and hydrogen already has "2 electrons in its outer shell".

If explaining chemical reactions is important in chemistry then this student does not seem to have a very sensible explanation. In that particular group of students there were 24 explanations much like this - four fifths of the group think they know why this reaction will occur, but their explanations are contradicted by the information given in the question! Again, as a classroom teacher, this reveals a significant source of misunderstanding among most of the students, that may not have been obvious to the teacher without using the exercise.

I hope that during my year as Teacher Fellow, I will be able to develop a range of such materials as resources for teachers - supported by documentation to explain the alternative responses to be expected, and suggesting how to respond.

6. A vision of constructivism as one facet of a progressive research programme in science education.

The nature of chemistry - and the limitations of processing power?

It has been recognised that part of the difficulty that many pupils and students have mastering chemistry is due to the inherent complexity of the subject. Alex Johnstone[8] has referred the chemistry as a subject which "exists in three forms": the macro and tangible; the submicro; and the representational.

[8] e.g. Johnstone 2000a.

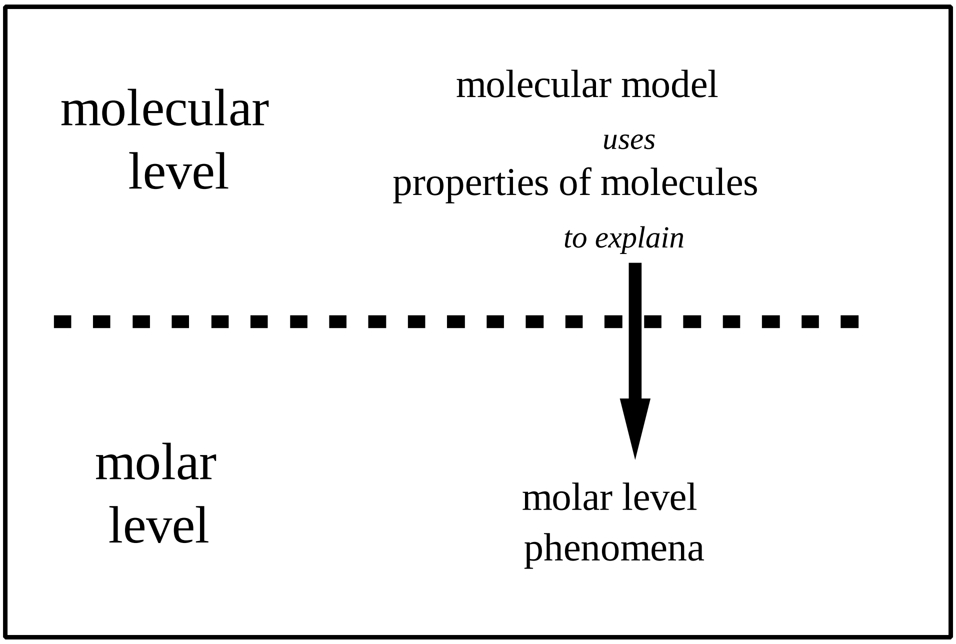


Figure 18: two levels of analysis

Students must be able to grasp the molecular level model of what is going on, and see how that relates to the bench reactions they observe, with the model often being represented in formulaic terms. Much of the chemistry that students observe at a molar scale has to be explained in terms of a molecular level model:

William Jensen has made a similar point, but further distinguishing between the molecular and electronic levels:

> "We are basically engaged in forcing students to absorb a set of theoretical answers at the electrical level, which they do not understand, to a set of questions at the molar level, which, from their point of view, do not exist."
> Jensen 1995: 71.

He suggests that mastery of the subject requires students to understand the subject at these three levels along three dimensions:

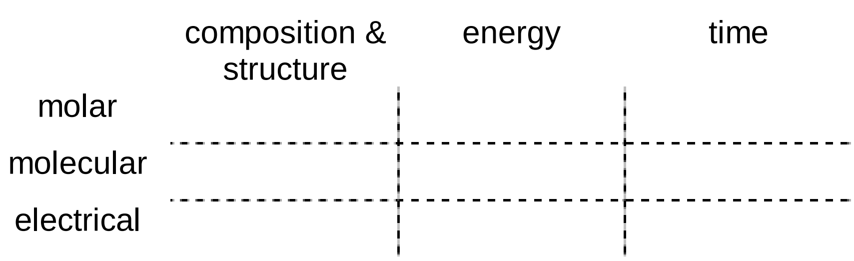


Figure 19: Jensen's analysis of chemistry

Alex (Johnstone) points out that as psychology tells us that humans have very limited 'working memory', expecting learners to be able to cope with working at several different levels all at once may often be unrealistic.

Certainly one common area of 'misconceptions' in school chemistry has been the tendency of pupils to discuss chemistry in molecular terms, but to see the molecular world as being a smaller version of their macroscopic experience.

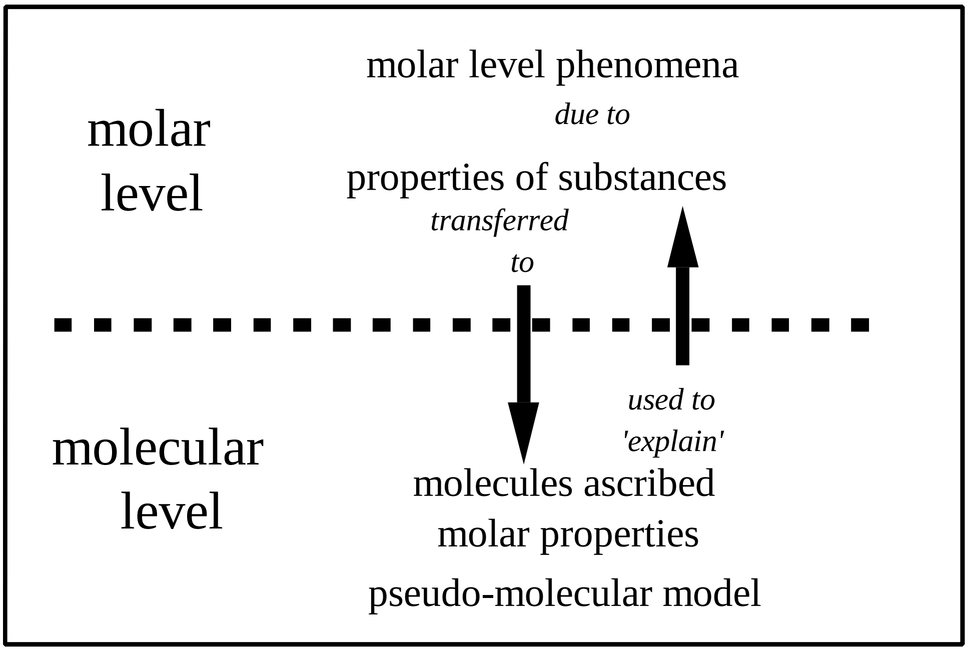
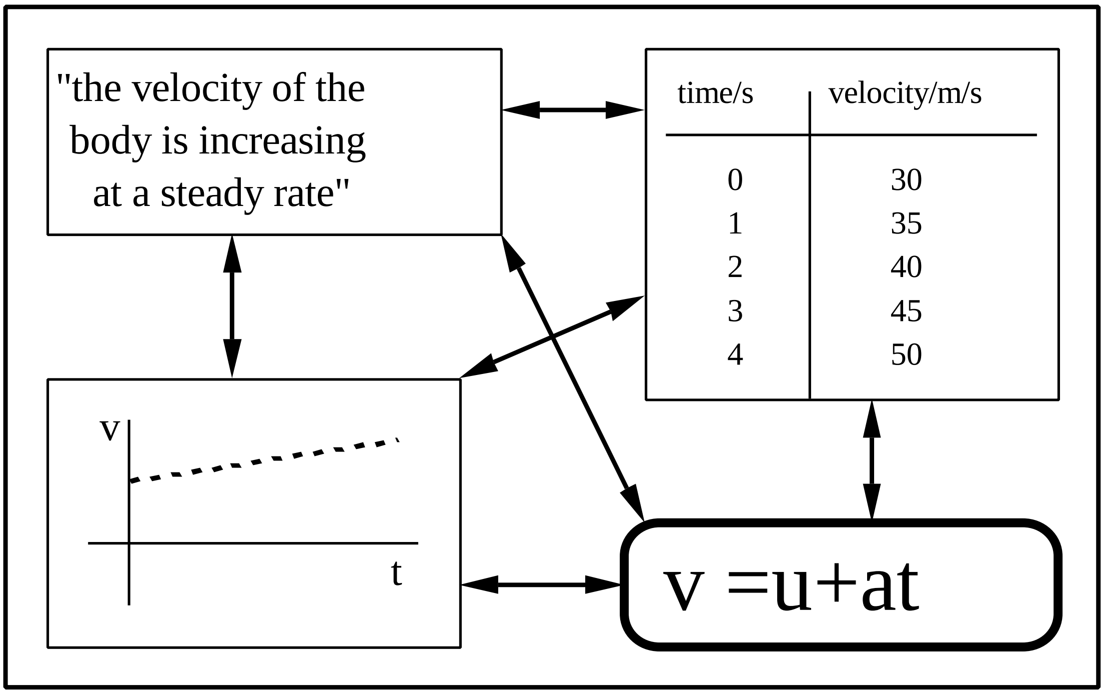


Figure 20: tautological molecular explanations

So instead of macroscopic phenomena being *explained* in terms of the properties of molecular level systems: pseudo-explanations are given where the properties to be explained at the molar scale are simply transferred to the molecular level. For example, an iron rod expands on heating, because it is made of atoms or molecules which expand on heating. (There are many examples of this sort of 'logic' in the literature.) I find the argument that working memory is being exceeded convincing: but of course we do have to *find ways* of getting out students to be able to make transitions between the different levels, whilst ascribing the right set of properties to both the molar and molecular 'worlds'. I have a lot of experience teaching physics as well as chemistry. In physics there is a *similar* set of transitions that is made between verbal descriptions of phenomena, formulaic representations, actual numerical data sets and graphical representations.



Understanding what “v=u+at” means in words, being able to use the equation to solve numerical problems, and knowing how it can be represented on a graph require the skills of being able to link and translate between different types of representation. This is not the same as explaining molar chemical phenomena with molecular models: but I suspect similar higher level cognitive abilities are required.

I believe Onno (de Jong) is right to suggest that much work based on general psychological theories may have limited application to science education: but I also suspect that research into aspects of cognitive functioning: attending, perceiving, interpreting, etc. may be invaluable. As Alex (Johnstone) points out, limited working space in memory puts a severe limitation on what students can cope with: and so we have to find ways to chunk material to help pupils work within the limits.

Jensen’s distinction between the molecular level and the electrical level may not seem immediately useful, as most of us (i.e. experienced chemists) would probably equate the two.

However, the research discussed above gives pause for thought: many of the students I worked with were very happy discussing the molecular world - they could describe and draw various sorts of atoms, ions and molecules with little difficulty - but tended to imbue that world with a busy social or political life. In the molecular world of my students there were power struggles, and social contracts, and an almost moral principle that as an atom you had the right to expect your electrons are returned to you when they were no longer needed for bonding with another atom. They explained chemistry at a molecular level, but *not* at an electrical level. Perhaps Jensen’s three-fold division should be given more attention.

Certainly if we look at the nature of chemistry as a subject, it seems clear that we can distinguish descriptive and theoretical aspects. Both inorganic and organic chemistry have extensive descriptive aspects. Yet, I am sure that most of us would agree that chemistry is a science because it puts this information *into a theoretical framework*.

Some of this theoretical framework can - at least partially - be understood without molecular level models: metal/non-metal; acid-base behaviour, redox; saturation in organic compounds, and so on. However, it is difficult for us, from our standpoint to consider these notions *without* thinking at the molecular level. And it could be argued that chemistry only became a full science when atomic and electronic structure became known, and provided a basis for the modern periodic table.

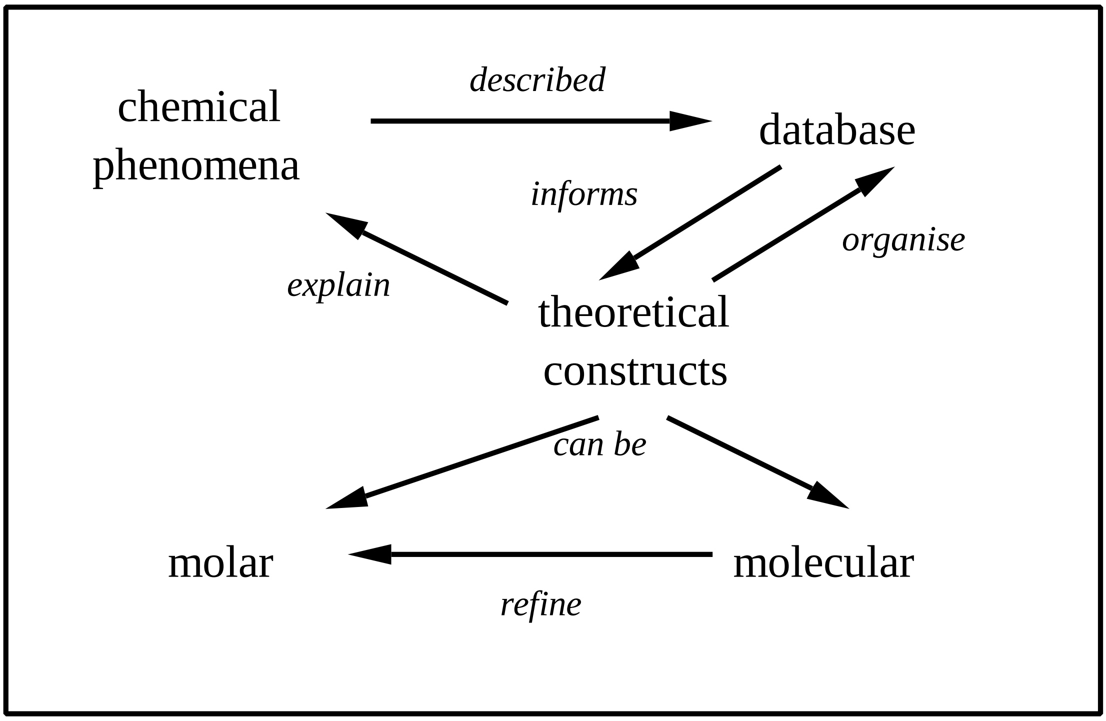


Figure 21: Description and explanation in Chemistry.

What I am going to suggest is that the nature of chemistry could provide a useful analogy for a progressive research programme in chemistry education.

This programme will build upon the vast amount of descriptive work that has already been undertaking collecting information about learners' ideas. The constructivist programme has already moved beyond this, and has its own theoretical organisers - although they are not (yet) as well accepted or as clearly defined as chemical concepts like acidity or oxidation[9]. These concepts are notions of 'alternative conceptions', 'alternative frameworks', 'conceptual trajectories', 'multiple frameworks', 'conceptual ecology', etc.

Yet this research programme can be considerably enhanced if it is related to work into how the brain actually processes information. This area has its own conceptual framework with organising concepts such as 'working space', 'long term memory', and so on.

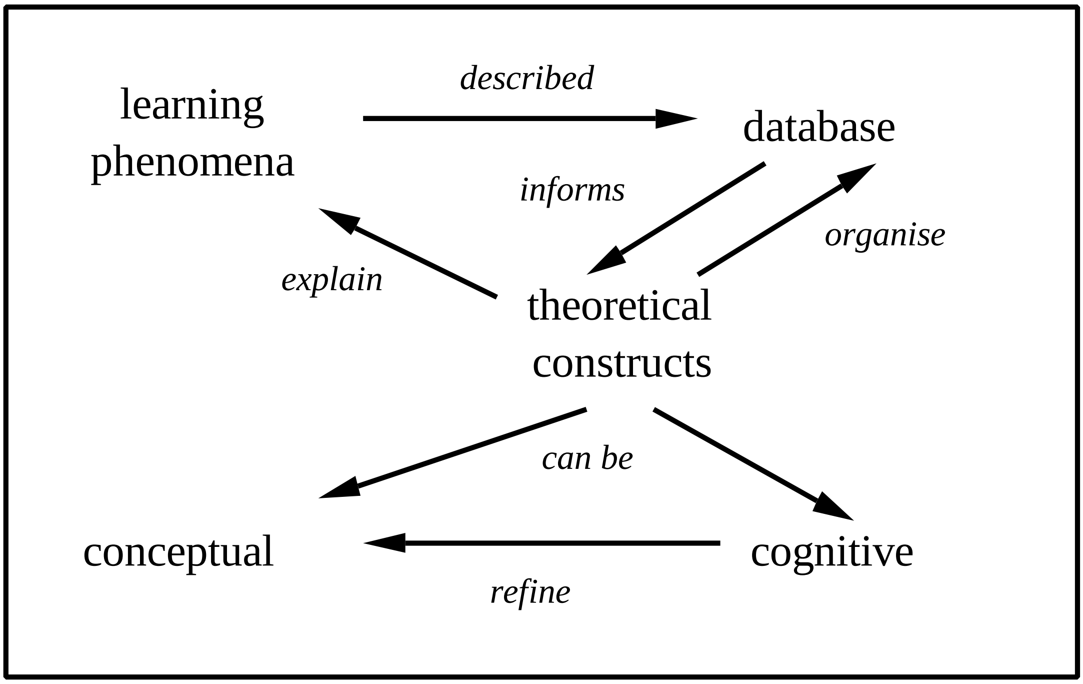


Figure 22: Description and explanation in science education?

Chemistry as a science needed to be developed by exploring reactions at the bench level, and by modelling the processes occurring at the molecular level during those reactions.

Similarly research into the learning of chemistry needs studies into student conceptions and how they evolve, *and also* the development of models that explain what is happening in terms of cognitive functioning. We need to understand the minds of students, and particularly how they change their minds, and to appreciate how what is happening in their brains limits and facilitates their conceptual development.

[9] Of course education is a social science and not a physical science. I do not expect something as complex as learning to be as *well* understood as physical systems. But, on the other hand, I would hope that we can achieve a more evidence-based status than some of our social sciences!

Perhaps one day, this ‘brain’ study will be at a neuronal level. (Perhaps akin to understanding molecular phenomena at the quantum level?) However, at present it is largely in terms of conjectured brain structures and cognitive apparatus rather than actual brain circuits. Nevertheless, an understanding of what the available cognitive apparatus could be, how it operates, and how it is constrained is a key part of a science of science learning.

Of course the analogy with the nature of chemistry is only a useful image, and should not be take too literally. But it may be a fecund image.

In chemistry the vast amount of descriptive data provides little more than recipes unless it can be organised into a meaningful system.

In a similar way, in science education, the vast catalogue of alternative conceptions is of little value *on its own*: out of context it represents the “approach which was negative and offered few solutions to the problems exposed.”

I have argued that the constructivist programme has offered much more than this. It has provided a theoretical framework into why students have alternative conceptions, why they are significant for learning, and why they generally should be taken into account by lecturers. It has also provided models of how conceptual change occurs.

Yet, I would concede that this has not yet reached a ‘scientific’ stage. It is more akin to those subjects where, once the data is in, it is possible to fit them into your preferred scheme, than a subject where it is possible to make successful predictions before data collection has begun. (Or, rather, I should say successful *specific* predictions: it is usually safe to predict that *many of the students will have some alternative conceptions in this topic area, and some of these will not be changed by instruction*.) Perhaps it is too much to hope that we can ever have a predictive science of learning, but I suspect, and hope, we can go much closer than we are now.

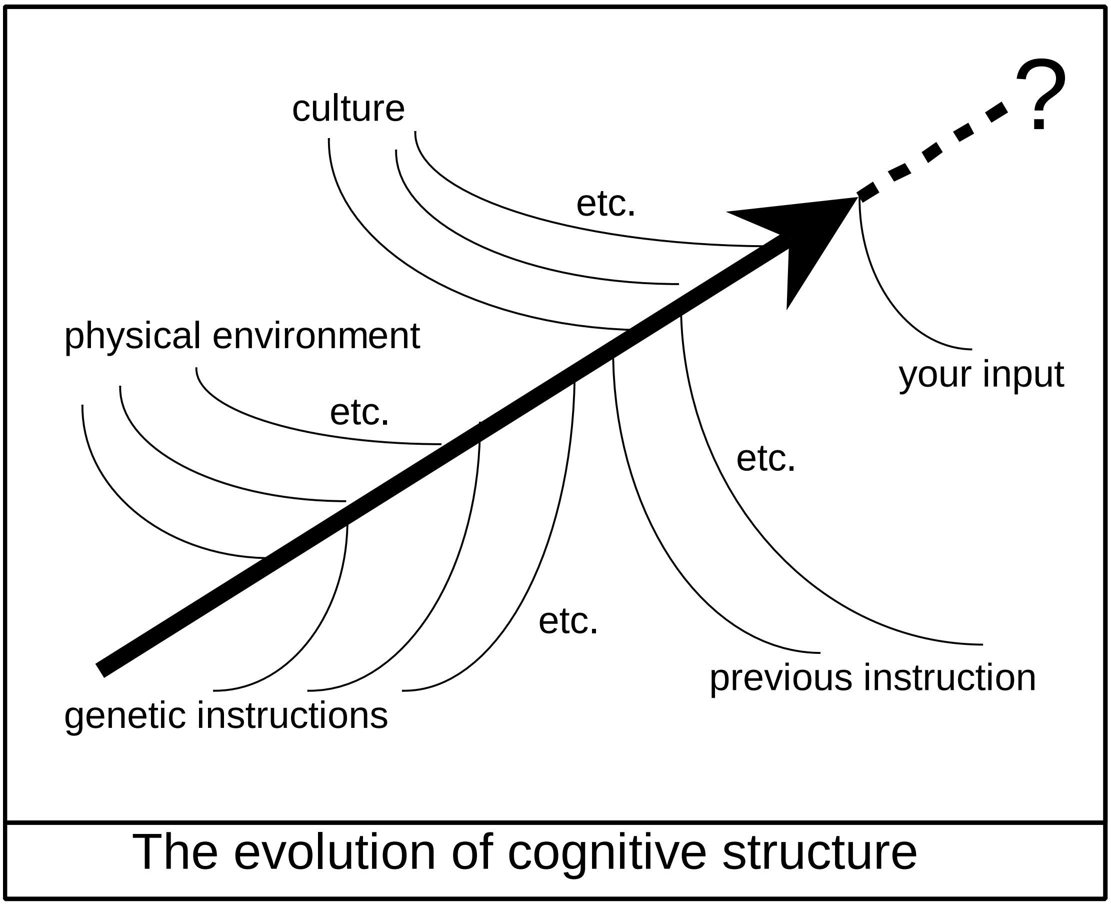


Figure 23: factors influencing conceptual development

On its own, the constructivist approach is a bit like chemistry before a successful atomic theory. It provides ‘molar level’ descriptions and explanations of the learning process.

This is akin to explaining how altering pressure or temperature changes the progress of a chemical reaction, in terms of a simple quantitative pattern, without having a model to explain why. What is needed is an understanding of the cognitive processes at a deeper level, which occur when students develop, evolve and access their conceptions.

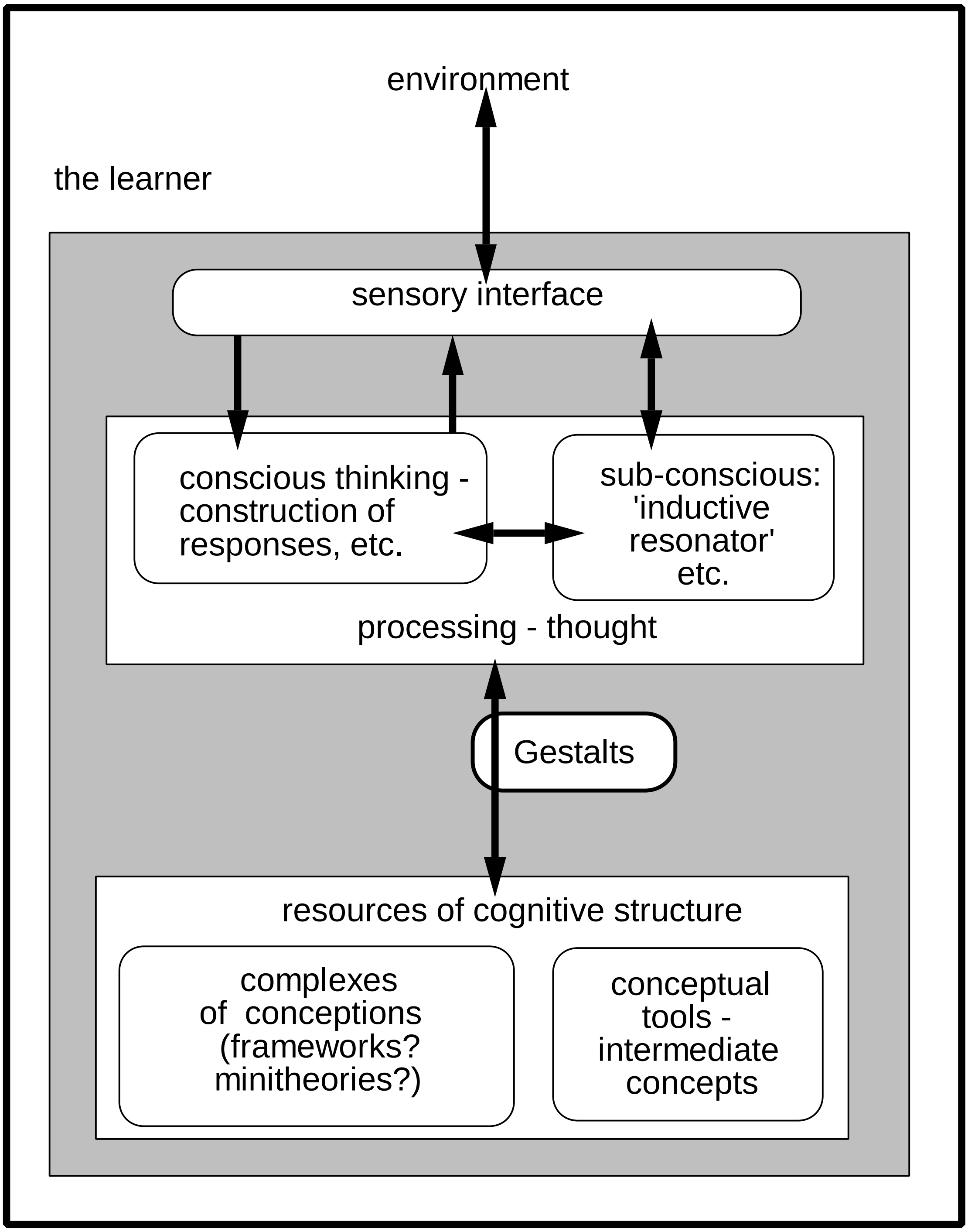


Figure 24: A (vague) model of the learner as a system

We know that perception is more than just 'taking in' sensory messages, if involves a lot of processing: filtering, selecting, interpreting. We also know that a lot of thought processes are at a subconscious level: and much processing takes place when we are not aware that we are thinking about that particular problem or issue. We know than students' responses to questions (in class, in educational research, in examinations) are likely to reflect a construction process in situ - calling upon, but not usually simply recalling material in memory. Material that is learnt may sometimes seem to be stored piecemeal, whereas at other times it seems to be tightly integrated with other learning. We believe that early tacit learning (and genetic instruction) may lead to cognitive apparatus that later influences how we construe information. (For example, the idea of 'natural kinds' of object that seem to be recognised across human cultures; and the proposal of the establishment of 'gestalts' that act as templates for later learning.)

It is easy to draw schematics which show how complicated the learning process is in the light of all of this (figure 37). Yet, it seems to me that we (the science education community, if not the psychologists and neurologists themselves) know very little about these boxes and arrows that offers practical advice. Alex (Johnstone) champions the notion of working memory, and the 7±2 rule is probably one of the most applicable findings we have[10]. Indeed, what else is there of real use to teachers at the present time?

7. An agenda for future research?

My starting point was last year's CERG lectures, where two distinguished colleagues offered their criticisms of research programmes into learning in chemistry.

What I have tried to do today is suggest that the two types of approach that were criticised - general psychological theories and alternative frameworks research - should be seen as complementary streams in a progressive research programme.

expert	*wants more*	*aspect of research programme which could provide this*
Onno de Jong	domain-specific studies	conceptual studies
Alex Johnstone	work informed by a psychological model of how we process information	cognitive studies

Table 4: caricature of synthesis of expert views

[10] i.e., that the limit to most people's ability to process information is set by a 'buffer' that can only hold between 5 and 9 data at an one time.

The notion of ‘cognitive structure’ may be a useful bridge between these two levels of analysis. ‘Conceptual studies’ provide information reflecting the content of cognitive structure and how it changes. ‘Cognitive studies’ can complement this by showing how cognitive structure is built, altered and utilised.

Both studies into how the brain processes information, and research into the nature and development of learners’ ideas have valuable contributions to make. Both of the approaches offer fruitful research questions that can ultimately help us work towards a science of science teaching (figure 38).

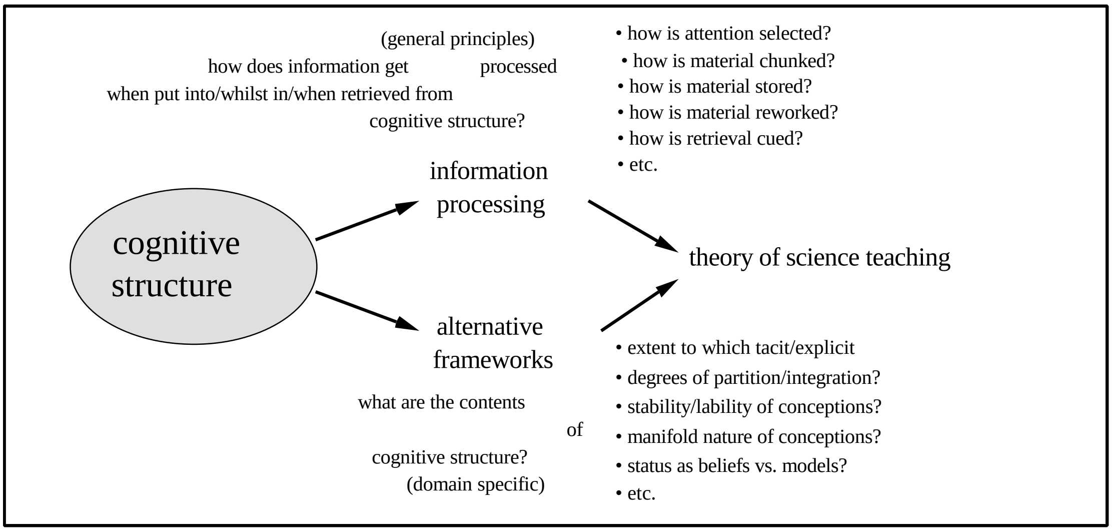


Figure 25: two strands of a progressive research programme?

Teaching will always be a skilled craft, with room for creativity and personal flair: but we can aim to *inform* it with a more rigorous body of knowledge about how students learn science.

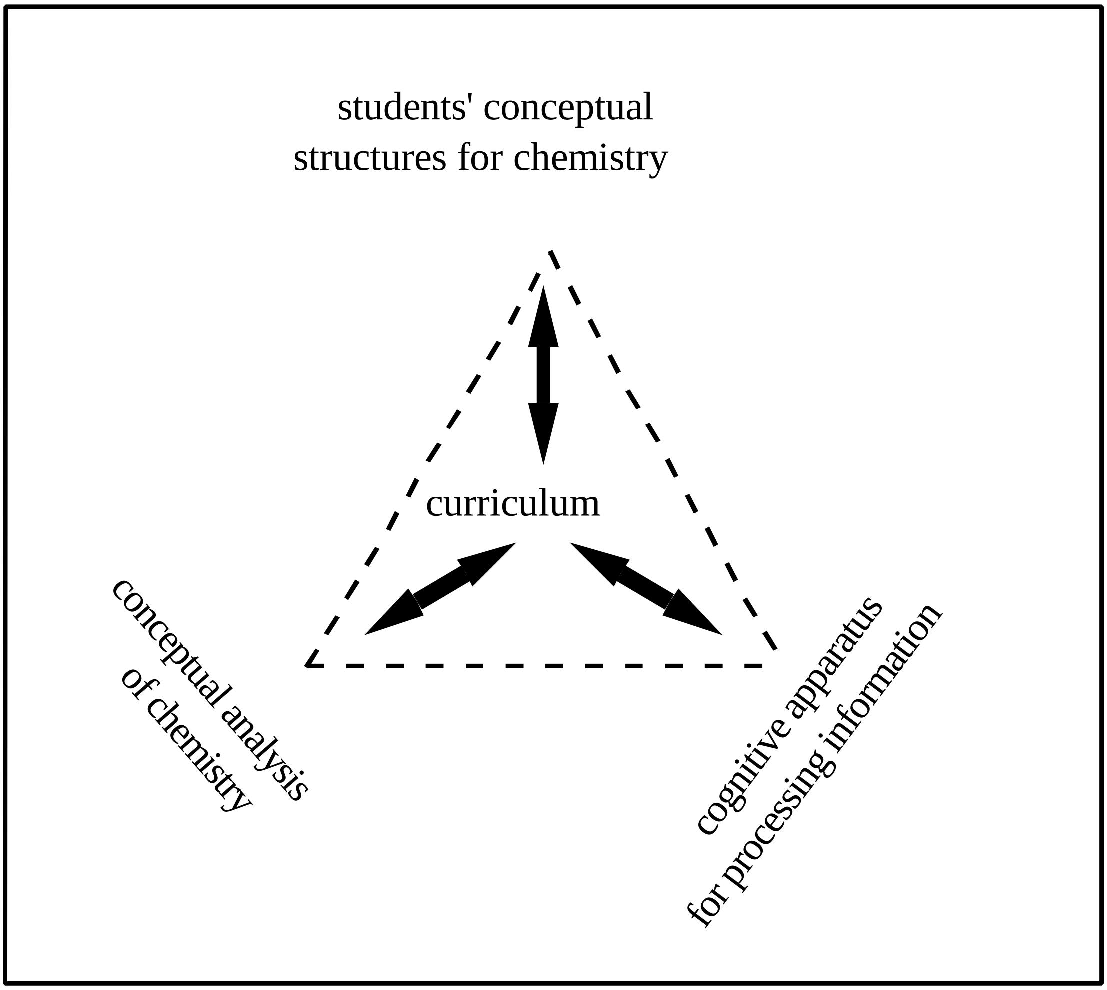


Figure 26: Curriculum planning informed by research.

I hope you have found what I have had to sat this afternoon of interest. I have not had time to go into detail about all of the work that has been undertaken into students' ideas in chemistry, nor to set out a detailed prescription of how we can ensure the future research programme is progressive. However, I hope you will tend to agree with me that:

- alternative frameworks research need not be viewed as negative;
- work ground in general psychological theories can be helpful in planning teaching.

What has perhaps been missing (besides an effective translation of much of our research into a form that teachers can use) has been an overt attempt to produce a synthesis from these two distinct approaches.

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