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# Debugging teaching

## *Improving the teacher's mental model of the learners' mental models*

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Abstract:

*This keynote addresses discusses an approach to thinking about why teaching goes wrong that can be applied to support classroom teachers charged with teaching conceptual curriculum material. The perspective applies to any situation where a teacher presents material of a conceptual nature - but has been informed by research and examples from science teaching. The science learning doctors approach is based on a typology of learning blocks or impediments, that can help diagnose the nature of problems when there are breakdowns in the teaching-learning process such that learners do not seem to have successfully understood what the teacher has intended to teach. This applies to those situations where a teacher has presented curriculum material to a learner who was attending to teaching intending to learn, and was not obstructed from hearing or seeing teaching; yet the teaching is not understood as intended. This certainly does not apply to all teaching-learning system failures, but is relevant to a great many of them. This type of system 'bug' can be understood as due to a 'mismatch' between two mental models - the existing mental model the learner has of the subject matter and related topics, and the mental model that the teacher has of the learner's cognitive system. This perspective will be illustrated with some examples of where science teaching-learning has gone wrong.*

**Keywords**: alternative conceptions; diagnostic assessment; mismatched mental models; learning doctor; teaching-learning bugs; typology of learning impediments

# Introduction

In this keynote I will discuss a perspective on teaching and learning which can provide insights when learning goes wrong, and can be used by the teacher who sets out to be a 'learning doctor' by diagnosing and de-bugging learning impediments. I am using the term 'bugs' because I am considering that teaching-learning is a system, and so when the process breaks down we can look for the bugs in the system. I am going to start the talk by setting out the general idea, so you appreciate the approach I am describing - so, this may seem a little theoretical. However, hopefully most of these ideas will be familiar to you already, as they are well-established, and I am simply shaping them into a particular perspective that may not be so familiar. So, I trust that this will be as if I am introducing you to a structural formula for a compound you are not familiar with, but where you will recognise all the components (see Figure 1).

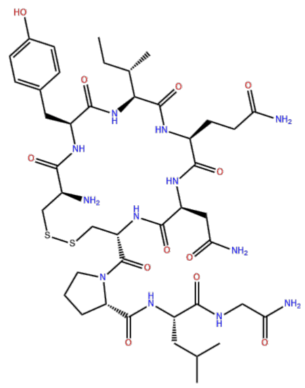

Figure 1: A complex molecular structure that can be understood as a configuration of simpler, more familiar, elements.

Apologies to those of you who *do* recognise this (see Figure 1) as oxytocin, but even if you have never seen this structural formula before, most of you will appreciate it is just built up from very familiar elements.

Then, once I have organised these familiar ideas to explain the learning doctor approach and its typology of learning impediments, I will discuss some examples of where teaching-learning can go wrong, and relate these examples to this model.[1] Time only allows a modest range of examples, but I think these should be sufficient to illustrate the application of the idea. I hope this will persuade many of you that this model is useful enough to add to your mental toolbox of pedagogic perspectives, as a tool to apply in teaching or in analysing learner thinking.

## *The range of application of the model*

However, it is important to first set out the range of application of this model. There are many reasons why students do not always learn what we would like them to. Students may be absent from class - but this perspective will not help there. Or, a student may be present but for various reasons too tired, or too hungry or thirsty, or too scared or sad, to be able to effectively engage in learning. In these situations, then the causes of that state need to be addressed, and these may often be outside the direct control of the teacher. Indeed, sometimes, as in bereavement, there may be nothing a teacher can do, in regard to the

[1] My examples derive from science learning. The approach should be applicable in any context where teaching seeks to bring about conceptual learning.

students' learning, but allow the learner time. Again, the approach to be discussed today cannot help in these situations. Or, there may be an attitudinal issue that relates to the breakdown in the relationship between the teacher and the student, such that the student disengages with learning in that class; or some prior experiences which have led to the student concluding they do not understand this subject, and will never be any good at it. Here, the teacher may well be able to address the issues, at least given time, but, again, the model I am discussing today will not be the tool to employ. Finally, perhaps communication is not effective for some practical reason that degrades the communication channel - perhaps because the student is too far away from the teacher to see clearly, or has an obstructed view of the board or screen, or has forgotten or lost eye-glasses, or the environment is too noisy to allow the student to hear clearly, or the board is obscured by reflected sunlight - or whatever - in which case that is the problem that first needs to be addressed. In a sense those are issues that prevent the teaching-learning system being engaged. My concern today is more with what often happens when the system *is* engaged but does not produce the learning hoped for.

Figure 2: Classroom teaching - the teacher is faced with a range of learners of diverse characteristics (interest in the subject matter, level of background knowledge, range of alternative conceptions, etc.)

Normally we are concerned with class teaching, in a classroom or lecture hall with 20, 40 maybe a hundred learners (see Figure 2). That is a very important consideration, and complicates teaching immensely, but for the purposes of our analysis today we will consider the teaching-learning system as involving a teacher and one learner (so the teacher may be part of many such systems at once). The system may include *inputs* from classmates or maybe textbook authors, and so forth, but the key elements are the teacher and a learner who are able to clearly communicate information to each other. So, I am talking about the teacher-learner system, but the actual teaching-learning context facing the teacher is actually a manifold of these unitary systems (see Figure 3).

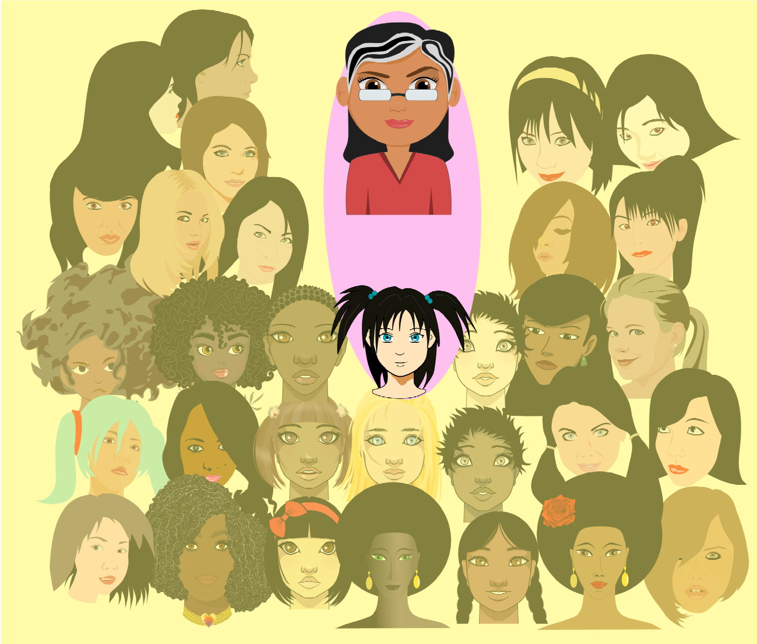

Figure 3: The 'system' is composed of a teacher communicating with a learner, but in the classroom this will be only one of many such systems the teacher is part of.

So, the system I am discussing is based on assuming there is

- a teacher who wishes to teach some curriculum material that has been prepared for the class; and
- a learner who is present;
    - willing, and
    - in a fit state, to learn;
    - who is paying attention in class; and
- where there is a good communication channel, which will normally mean that the learner and teacher can see and hear each other clearly (see Figure 4).

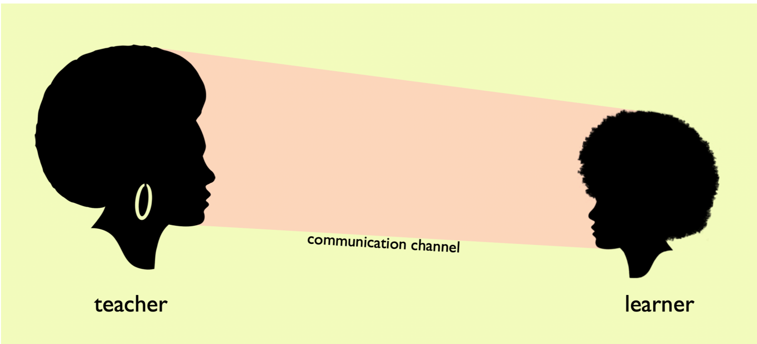


Figure 4: The basic 'teaching-learning system' - a teacher and a learner able to exchange information [2]

[2] Having a 'clear' communication channel allows the exchange of **information**, but this may not be sufficient to lead to sharing **understanding** (Taber, 2019). The teacher might, for example, say "molybdenum is paramagnetic", and the learner may be able to hear, repeat, and, perhaps, even later recall, this information. Yet, if they have never heard of molybdenum and do not know what 'paramagnetic' means, this transfer of information would not lead to a sharing of meaning.

I will call this *the teacher-learner system* (or *the teaching-learning system*), and, as I am sure you will agree, even when this system exists, we cannot be confident the learner will always understand what is being taught in the manner intended.[2] Sometimes that happens, but sometimes not. So, there are sometimes, perhaps even often, bugs in this system. We can either just accept that is the nature of teaching - 'some you win, some you loose' - or we can see it as a situation to analyse and address.

I should also point out that even when teaching *does* lead to the intended understanding of curriculum material, that does not mean the learner will still understand it the same way by the time of the next lesson, let alone by the time they may be formally tested in an examination. Abstract ideas met in science teaching usually need to be regularly revisited for learning to be consolidated effectively. There are strategies and tactics teachers can employ to reinforce initially fragile learning so that it becomes robust - but they are only relevant once the student initially understands the new material. So, today my focus is on that immediate aspect of teaching, and what can go wrong at that stage.

## *Some useful ideas*

Before proceeding, I am going to set out how I will use some key terms. I am talking of conceptual learning rather than, for example, teaching manipulative skills such as using a burette or focusing a microscope. My notion of concept is quite inclusive. By concept, I mean any kind of mental category (Taber, 2019). Let me explain that. If a student has some basis on which to suggest whether something can be categorised in some way, then I consider that a concept: so, if they could respond meaningfully (not necessarily canonically) to a question such as: is this/that

- an atom?
- an example of oxidation?
- a food web?
- a test-tube?
- a resistor?
- a tangent?

*etcetera,* then they have some concept associated with that label. They may also have concepts that do not have such labels attached. All concepts are in a sense abstractions - the abstraction of a commonality from across different examples, but these concepts met in school science can be at very different levels of abstraction.

There are different types of concepts. Here is a simple system suggesting four groups (see Figure 5). Some concepts refer to things, or types of things; some refer to process that occur; and some to the qualities we use to describe. That may sound quite straightforward, but of course in science the *things*, *events*, and *properties*, that we discuss may be invisible or even imaginary! That is, some of these concepts may seem *very* abstract to learners.

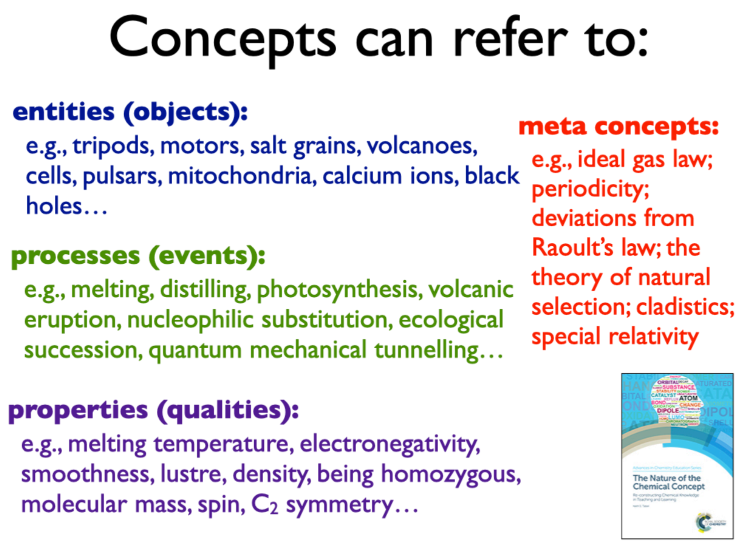


Figure 5: Concepts met in science classes vary in their degree of abstraction from what learners can directly experience.

I referred to four categories. The fourth, metaconcepts (Taber, 2019), is for those concepts which do not refer to anything with a direct referent - not even a very minute referent like an electron or an imaginary one like an ideal gas - but only relationships between other concepts. So, this includes all our principles, and laws, and theories, and so forth. It was thinking about and with ideas of this kind that Piaget (1970/1972) suspected only became fully available at the end of adolescence - which is a reason why teachers often need to use similes and analogies and models and representations to help make such abstractions of abstractions seem more concrete for learners (Taber, 2021).

I assume that a person has a conceptual structure, which we can imagine as an extensive web or net with concepts as nodes, and the links being the perceived connections between nodes. These can be represented by propositions, such as for example, '*mammals are vertebrates*', or '*metals are electrical conductors*', although again I am not suggesting that a person can always verbalise a connection they are at some level aware of. Each of these aspects of a person's concept might be labelled a conception. So, the canonical conception that '*all metals conduct electricity*' and the alternative conception that '*all metals are magnetic*' might both be part of a learner's concept of metals. We might suggest the content of a concept is the sum of all those propositions, all those conceptions; that is, all those connections embedding the concept in the wider conceptual structure. A person's concept may be more or less canonical according to how well the component conceptions match the scientific account.

The actual connectivity is presumably related to the synapses between nerve cells in the brain, with patterns of neutral firing and inhibition determining what ideas come to mind as associated with others. However we can model the conceptual structure in a simplified way as a kind of concept map where the propositions linking associated concepts are shown as the connections between concept labels. It has probably not escaped your notice, that in a sense I am reflecting these ideas as a kind of concept map here (see Figure 6).

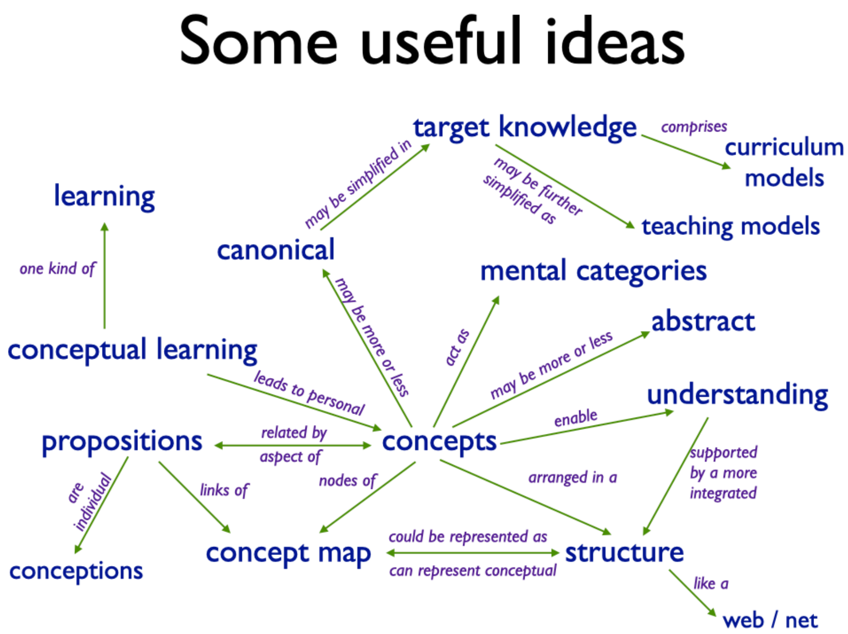


Figure 6: Some useful ideas for understanding the 'teaching-learning system'.

It is worth noting that there is a kind of conceptual inductive effect (Taber, 2015), named by analogy with the inductive effect in large molecules, in that the total content of a concept depends on its association with other linked concepts, but the meaning of these concepts is also dependent on their other associations with further concepts that are only indirectly linked with our original concept.

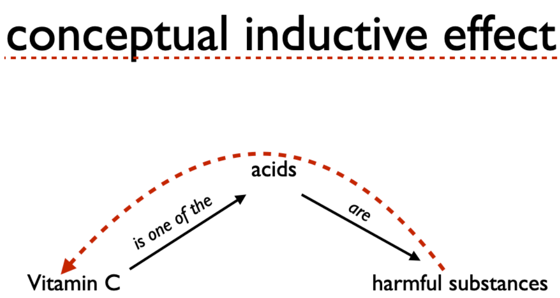


Figure 7: The conceptual inductive effect: a learner who thinks (correctly) that vitamin C is an acid but also believes (incorrectly) that all acids are dangerous will be wary of ingesting vitamin C.

If that should a little obscure, think about the conception that '*vitamin C is an acid*' (see Figure 7). That is a perfectly canonical conception. However, if a learner who held this appropriate conception also had the conception that '*all acids were harmful and would be dangerous to touch or ingest*', then that would be an unhelpful alternative conception. Because the learner incorrectly sees all acids as harmful, this colours their view of ascorbic acid, vitamin C - as correctly knowing that vitamin C is an acid can lead to the inference, the logical deduction, that vitamin C is a hazardous substance which should not be ingested. [3] That is what I mean by the conceptual inductive effect, where the content of a person's concept is influenced by the other concepts *indirectly* associated with it. Now, by 'understanding' I mean making sense of something. Again I use the term inclusively. A student may have some understanding of, say, electrical fields, but this understanding may be neither extensive nor canonical. Usually in teaching we are intending to develop a learners' understanding both in terms of deepening understanding, and in terms of increasing the match to the canonical account. Deepening understanding may refer to better appreciating the correct range of application of a principle, or being able to correctly *apply* it more widely, but could also mean embedding a concept more thoroughly in a web of other related concepts. As Albert Einstein (1994) commented on a number of occasions, science seeks to encompass the greatest range of phenomena under the least number of basic principles, and I think increasing learners' levels of conceptual integration is a key aim of an authentic science education (Taber, 2006).

The concepts met in the curriculum may be very complex and sophisticated and nuanced, so in teaching there is often a simplified more limited target version of the canonical concept set out - a curriculum model of the scientific idea. In presenting these ideas, teachers sometimes use teaching models which may simplify things further if the teacher judges this is needed for students to make good sense of the topic (Taber, 2021). Ideally, after the teacher has taught the curriculum model, the learner's understanding matches that target. Sometimes it does. But often, it does not! And in my experience that is true of even the most skilled classroom teachers. We come to expect students to obtain a wide range of scores or grades in terminal examinations even when the exam has been carefully designed to only test what has been taught. Perhaps we first enter the classroom with idealistic expectations, but we soon become realists. Perhaps we give top grades to those who only get a fifth of the questions wrong, and a pass mark to some who do not even get half the questions right.

## ***Construction of knowledge***

Now the model I am going to present today is underpinned by the perspective known as constructivism . This word is used in various ways in a range of fields, but the pedagogic notion of constructivism is much supported from work in the learning sciences and science education. The basic idea is that human learning is incremental, interpretive, an so iterative (Taber, 2014).

By saying that learning is incremental we mean that human learning tends to take place in small steps. Teaching needs to 'feed' learners new ideas in manageable ('digestible') learning quanta that, then, have to be sufficiently processed before the system can move on to process any further learning. The amount of new material a person can take in during one class session or lecture is limited by their cognitive apparatus. Today I am drawing on a wide range of ideas and examples in my talk, but I am assuming that because of the nature of my audience most of this material will be familiar from either your academic study or professional classroom experience. If I am wrong, there will likely be the kind of breakdown in communicating understanding that I am describing as a teaching-learning-system bug! Let us hope not, and that my mental

[3] One might be tempted to say that this "***will*** lead to the inference…". However, human cognition is not determined purely by logical analysis. A learner might think that vitamin C is an acid, and all acids are dangerous, but that it is safe to take vitamin C. It is possible they would not have noticed the logical inconsistency. Or they may have noticed it, but think this is an exception, or they might speculate that as it is an essential vitamin the body has some special protective mechanism to allow ingestion…or they may simply think - much as scientists themselves sometimes do (Lakatos, 1970) - that here is an anomaly that ultimately needs to be addressed, but which can be ignored for the moment.

model of the interpretative resources you are likely to have available to make sense of today's talk, is at least *reasonably* well-judged.

By saying that learning is interpretive, we mean that what is already known, understood, thought, believed, has a critical role in making sense of new information. Generally, we understand something only if it makes sense in terms of prior experiences, and how we understand it is strongly influenced by that prior learning. This is why Lavoisier and Priestley could observe the same chemical reactions, and yet have such different ideas about them. This is why Lysenko managed to derail Soviet agriculture for so long. This is why two politicians can look at the same economic data and have such totally different takes on what it means, and what should be done about it. Perhaps it is why two keen observers can honestly disagree about the merits of a penalty claim in a football match.

Prior learning here does not just mean school-book learning, but our wider learning from experience of the natural world and social interactions. We understand in terms of the interpretive resources we have already available. Or, at least, that subset of those resources that are triggered as being relevant at any time.

Given that learning is both incremental and interpretive, it follows that learning is accordingly iterative. Our understanding develops by a small step in a direction shaped by its starting point in our existing thinking, and that leads to a revised starting point to shape the next small step. We *can* we change our minds, but the cognitive system is biased towards the status quo. Confirmation bias has probably been advantageous in human evolution, but does not help the teacher trying to overcome learners' alternative conceptions. Our developing thinking is highly contingent on what we already think.[4] I sometimes wonder, not that teaching-learning so often goes wrong, but that it is incredible just how often teaching is effective!

So we might develop our model a little (see Figure 8):

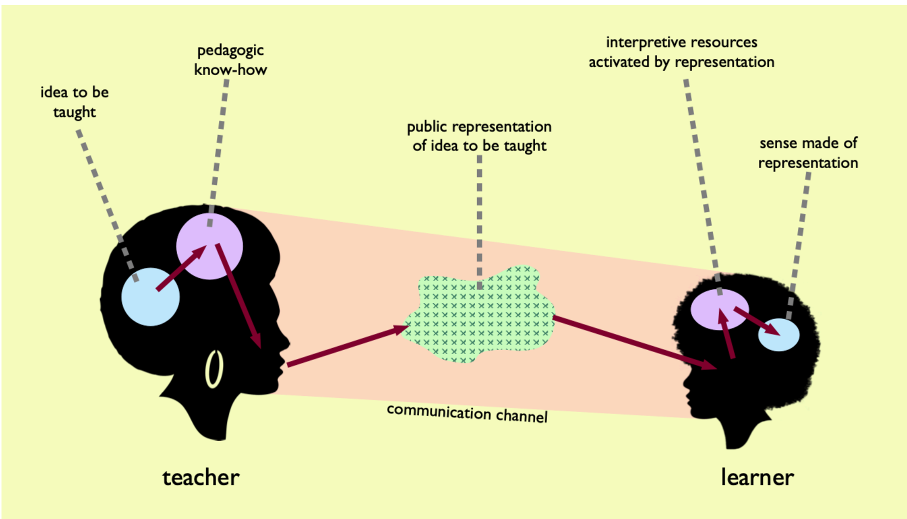


Figure 8. The teaching-learning system relies on cognitive processes at both ends of the communication channel.

[4] Constructivism in education could be seen as based on the core premise that learning is contingent (Taber, 2009b).

## Planning teaching

It follows from what I have said so far that teaching needs to be carefully planned, taking into account the way people learn (Taber, 2018). The teacher has to have a good understanding of their subject matter, but that is not enough. Because learning is incremental, interpretive, and iterative, the teacher has to be able to

(i) sequence teaching logically,

(ii) break the material down into manageable learning quanta, and

(iii) help students relate what is being presented to their existing conceptual structures.

This means that teaching is informed by a mental model of the learner.

### *The teacher's mental model*

The teacher's lesson plan or lecture notes set out what is going to be presented, based on an explicit or implicit notion of what it is hoped learners will have come to know and understand after teaching. Clearly, the lesson plan or lecture notes are more likely to lead to that outcome if they have been designed around an explicit, rather than an implicit, notion. The sequence and level, and parsing, and phasing, and mode of presentation, will be effective to the extent that they engage the learners' interpretive resources in ways that support the development of the intended understanding. It seems then that the teaching presentation will imply some model of the learners' existing conceptual structure - the prior learning, the ways of thinking, the potential 'anchor' points that can help interpret teaching (see Figure 9).

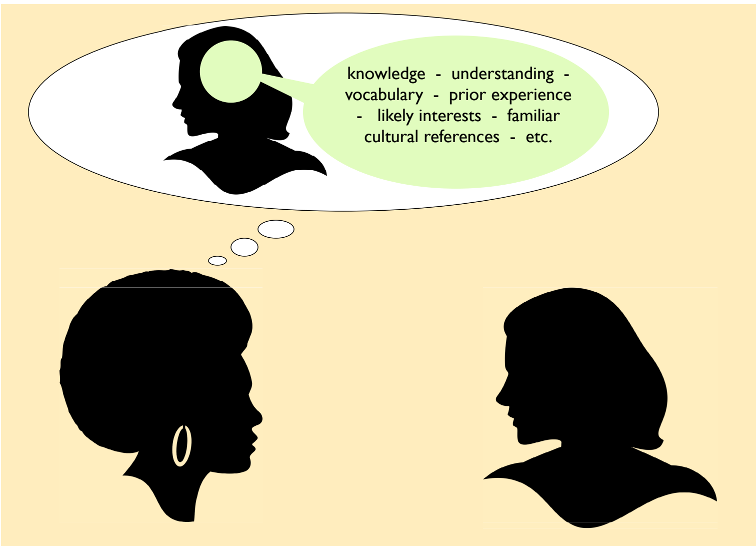


Figure 9. The teacher works with a model of the learner's current state of understanding of a topic which helps plan teaching.

So, given what we know about how learning occurs, teaching implies a model in the teacher's head of what will happen in the learner's head when engaging with the teaching. That model may be implicit or explicit. Teaching is more likely to be successful if it is designed according to a well-informed model, so, again, an explicit model is to be preferred. A teacher's model of the learners' cognitive system will be informed by their working with these present, and past, students as well perhaps as from their teacher preparation and professional reading. In those terms there may seem to be no reason to prefer an explicit model, as long as the teacher is taking their model into account implicitly in preparing teaching. However, if a major cause of teaching-learning failures is an imperfect model then the teacher who works with an explicit model is in a better position to reflect on their model and seek to modify it to make it more effective.

## Teaching-learning bugs as mismatches

The argument made here is that many teaching-learning bugs are due to mismatches: a mismatch between the teacher's mental models of how the learners will engage with teaching in the light of their assumed initial cognitive states, and how the learners actually process teaching given their actual existing cognitive structures (Taber, 2001). Given the complexity of any person's thinking, none of us can ever expect to develop an accurate model of someone's else cognition. Perhaps a researcher working with a person in depth over an extended time, and exploring a limited concept area, might do pretty well, but in any realistic class teaching context I would suggest mismatches are inevitable. And this we should be neither surprised nor too self-critical when they occur.

But if we recognise that the 'bugs' are often mismatches, and appreciate the kinds of mismatches that occur, then we are better placed to diagnose the bugs and address them. That is, a model of how mismatches might occur, can be a useful tool for diagnosing teaching-learning failures and treating them (Taber, 2002). We should not be too critical when teaching-learning system bugs occur, but we should seek to do something about them.

## The typology of learning impediments

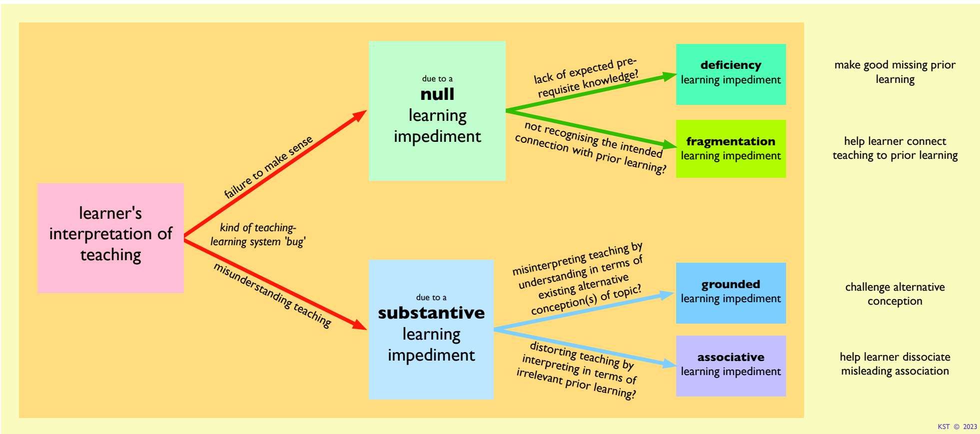


Figure 10: A typology of learning impediment to help diagnose teaching-learning system 'bugs'.

The typology of learning impediments sets out the main classes of learning bug that teachers can look for (see Figure 10). Classifying bugs may allow us to work with the individual learners concerned, as well as informing modifications to teaching for future classes. Meaningful learning requires that, firstly, the learner has available interpretive resources that can help them make sense of the new teaching, and, secondly, that they actually make a link: that is that they perceive teaching as being related to their prior knowledge and understanding (Ausubel, 2000). This offers us some clues at to what can wrong in teaching. Perhaps the student does not make the expected link: they do not perceive teaching as relating to their prior knowledge. This can be for two main reasons. One is that the expected prior learning is simply not there - the prerequisite learning has not taken place. I recall a first year undergraduate lecture where the professor of physical chemistry commented on one of his teaching points that we would remember this from the second year course. We clearly did not.

However, it is also possible that the learner has indeed completed the expected prior learning and does have the relevant interpretive resources available - but does not perceive the teaching as linked to that prior learning, so does not bring it to mind although it is needed to make sense of teaching.[5] These types of problems may be not always be too challenging to spot as the learner may well be aware they do not understand, as teaching does not make much sense to them, and they may express this: whether by hands-up, stating their lack of understanding, looking confused, or disengaging from the communication channel having decided it is only providing them uninterpretable signals - and perhaps instead examining the grain structure of their desk or offering a far−away look reflecting just how far their focus has drifted away from the teaching.

Now, that is perhaps the more obvious half of the story here - a failure to make expected links. Learning is basically associative - we associate the new with the established, and assimilate it into our cognitive systems. If we find links that work for us, then we make sense of teaching; *some* sense, if not always *the intended* sense. But there is another potential source of system bugs, which is where a student *does* make a link with prior learning: but one that is not helpful in bringing about the understanding the teacher seeks.

Again there are two main classes of system bug here. Students commonly have alternative conceptions, and if they already misunderstand the topic area, they may interpret the new teaching as fitting in a distorted understanding of the science. The learner here *seems* to understand, the materials make sense to the learner, but later - perhaps in a test - it will transpire they have acquired a *different* understanding to that hoped for. It is also possible that the learner understands teaching in terms of some prior learning, some past experience, which is perceived by the learner as relevant but which from a canonical view is unrelated. Here the prior learning may itself be quite correct from the scientific perspective, but when teaching is filtered through it, this leads to a new alternative conception.

So, the basic model has four categories, grouped in two sets of types of learning impediments. It obviously helps to have labels for the categories when we are thinking about, applying or talking about the different types. So, some years ago I came up with a set of labels which perhaps could be improved upon, but I think they make reasonable sense as labels.

The first level of division was between **null** and **substantive** learning impediments. A null learning impediment meant the student failed to associate teaching with prior learning - that the teaching did not lead to the learning bringing to mind something that helped them make sense of the teaching. This could be because the expected prior learning had never happened, called a **deficiency** learning impediment; or

[5] It may be worth just emphasising that this would normally be an implicit process, not a reflective one. That is, most of the interpretation of teaching (or any other sensory input) takes place automatically prior to the processed (*i.e.*, worked-up) 'input' reaching consciousness. For example, the ears do not detect language, just sound as vibrations, but usually what we hear, that is, what we are conscious of hearing, when someone talks to us is already decoded into words and sentences. Sounds have been interpreted as phonemes, and fitted within likely words which have been adjusted to fit into feasible sentences and so forth. We do not normally notice how we only perceive highly treated and cleaned up data till something is unclear, or we hear someone talking in an unfamiliar language when we notice the distinct sounds.

because the relevance of prior learning was not appreciated (i.e., not associated), a so-called **fragmentation** learning impediment.

The two main types of substantive learning impediments involve the learner making sense of teaching in a way that does not match that intended, either because the relevant prior learning includes alternative conceptions, and so the learning is distorted by being understood within a conceptual framework that does not match the science; or through the teaching being understood in the context of some *other* prior learning that seemed relevant to the learner, but which, from the teacher's perspective, was not pertinent.[6] These are referred to in the model as **grounded** and **associative** learning impediments, respectively.

Earlier, I used the metaphor of *finding anchor points* in prior learning for new teaching, and in those terms we might suggest that these types of learning impediment are

- not finding anywhere to anchor new knowledge (null impediment), either because
    - the expected harbour had never been built (deficiency impediment) or
    - the harbour could not be located (fragmentation impediment); and
- anchoring the new knowledge somewhere, but not as intended (substantive impediment), either
    - in the right harbour, but one that had not been built correctly according to the plans (grounded impediment), or
    - in completely the wrong harbour (associative learning impediment)

We might suggest Christopher Columbus suffered from an associative learning impediment when he arrived in the Bahamas (Guanahaní) and identified them as part of the East Indies.

Another analogy might be useful to 'catalyse' your understanding of the model might be the binding of a metabolite in a cell with the relevant protein. What could go wrong? Perhaps:

- The target protein is missing, so there is no substrate for the ligand to bind to (or the protein is mutated in such a way that there is no functioning binding site for the ligand); or
- The ligand diffuses to a different part of the cell, and never comes into contact with the protein; or
- The target protein has a mutation, and although the ligand is able to bind, it is strained by the abnormal conformation of the binding site; or
- The ligand comes into contact with another protein with a matching binding site before it reaches the target protein.

Each of these situations has some parallels with what can go wrong in teaching-learning.

[6] Again, it is worth emphasising this does not usually mean a learner consciously thinking to themselves, "this relates to…", but rather that the association is activated preconsciously *before* it reaches conscious awareness - so, to the learner, the perception 'arrives' in mind already accompanied by, and coloured by, the context of the perceived association.

### ***Some limitations of the model***

Now, it is possible to further breakdown our types of substantive learning impediments as we can consider in a little more detail what can go wrong in the learning process. But before I do that I should acknowledge some provisos. Like all models, this model has limitations. A person's conceptual system, their range of different kinds of interpretive resources for making sense, will be complex. Learning is a subtle process in that it tends to be much more nuanced and shaded than any simple model with distinct categories can offer.[7] I do not claim that the teacher-learner systems bugs always fit simply in one category, or even that we can always work out which category best describes a case - as you will see from some of my examples. My claim is that this is *a useful thinking tool* that can help us to look at an instance of a student not understanding or misunderstanding, to see if we can put matters right. A full diagnosis will often rely on talking to the learner, questioning them, and listening carefully to what they say. Just as is often the case in medicine, or in forensic investigations. So, if you prefer, you can think of this approach as being *a learning detective* rather than being *a learning doctor*.

Given that 'health warning', here are some finer categories (see Figure 11). Where students' existing thinking contains alternative conceptions, these can derive from several, or an interaction of several, sources. These include direct intuition of the nature of the world based on experience of living in it (Andersson, 1986). But it can also be due to folk knowledge that has social currency in everyday discourse but does not match the scientific models (Solomon, 1987). Sadly, another source can be science teaching. The science teacher can teach things that are wrong or muddled. Even if *none of* ***us*** has ever done that, we likely know of examples of it happening.

When learners make unhelpful associations, linking teaching to their prior learning, but not the prior learning the teacher had in mind, this can be a completely creative process - making an idiosyncratic link that would not be apparent to most other people. However, sometimes there may be a linguistic basis. Words do not map uniquely onto the world. Sometimes one word has several meanings, or a word may sound very similar to a different word. Many words adopted into use in science have been acquired from everyday language where they may have a somewhat similar, but often more vague referent (Sutton, 1992). Another issue may relate to associations that arise from an over-literal interpretation of teaching (Taber, 2010). Teachers use models and analogies and metaphors and similes and anthropomorphisms and various other ploys to help make the unfamiliar, familiar (Taber, 2021).

That is, often when we need to teach some abstract idea that cannot be directly demonstrated, we either represent it imperfectly using some kind of model or diagram that can be directly shown to the learners, or we describe in terms of something already familiar. This is a perfectly good, indeed sometimes essential, strategy. However, our learners may not have the epistemological sophistication to appreciate that models and simulations and pictures are not realistic accounts of what is being represented; or that analogies and metaphors are only *somewhat like* the target concept, and are not *just like* or even *identical* to it.

---

[7] This subtlety means that representing students' thinking through concepts maps over-simplifies, as such a representation tends to suggest there are, or there are not, associations between specific concepts, whereas realistically there will be very different connection strengths in the cognitive system: from some very well-established links which mean that the association between two concepts is likely to be brought to mind whenever one or other concept is activated; through to such weak associations (perhaps formed years ago, never consolidated by reinforcement since) that they are only likely to be brought to mind under very rare specific circumstances that closely match the original context of learning. At this extreme, the connections are effectively 'forgotten' for all normal purposes (Taber, 2003). This will be relevant, for example, in one of the examples discussed later, where an interview with a student could be mapped out to suggest a high level of integration of knowledge (see Figure 30), yet her thinking actually demonstrated a major disconnection.

I think there is a strong case for teaching children from very young that various kinds of models and representations and analogies have been used *in science* to generate ideas about how aspects of the world might be - to produce hypotheses to test - as well as by scientists to explain their ideas to other scientists (Taber, 2017a). They are also used in teaching; but they are sometimes just thinking tools, and sometimes they are meant as simplifications or partial representation of aspects of the natural world. (I am distinguishing here between posing the exploratory question "*what if* it is somewhat like this?" and making the knowledge claim "*it is* somewhat like this".) We should start introducing this mindset with the very young and continue to push the idea throughout science education, so that learners come to appreciate this important aspect of science and do not end up confusing the representation for what represented, the sign for the signified (Taber, 2010). That could avoid a lot of frustration for both teachers and learners.

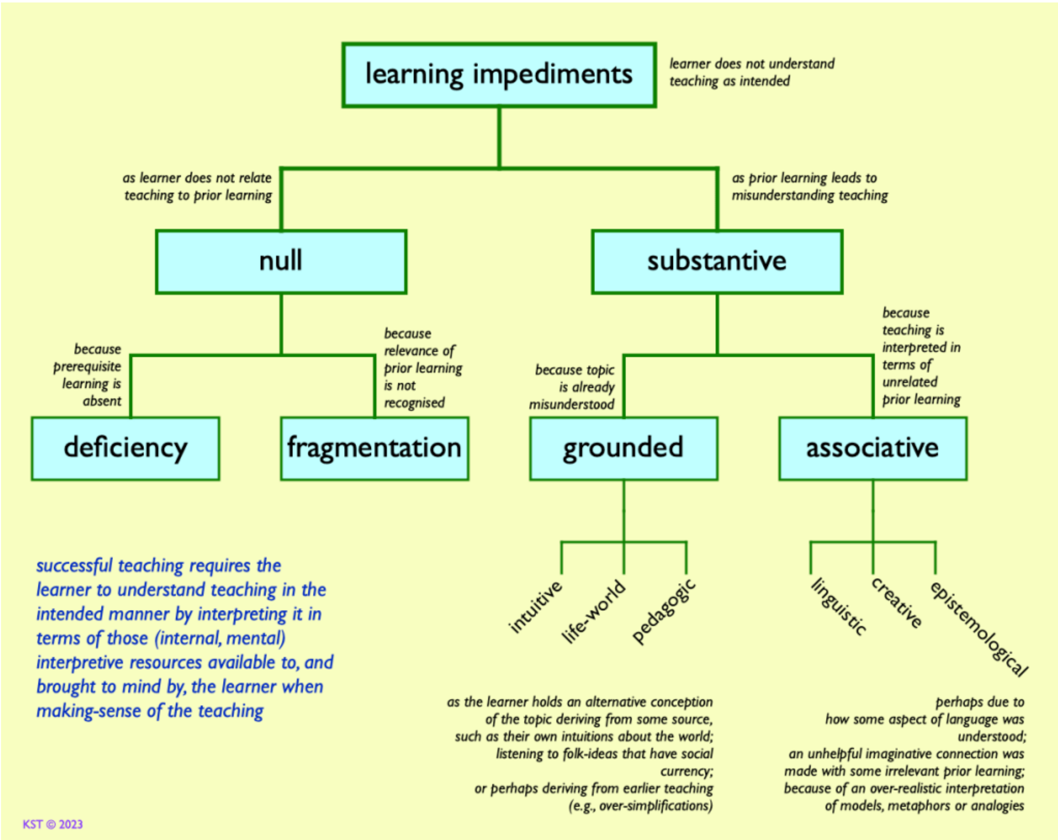


Figure 11: A typology of learning impediments.

So, the learning doctor perspective is intended to de-mystify some of the reasons learning does not always occur when a teacher offers a clear presentation of some curriculum material. Now that we have considered the model, I am going to talk about some examples of students' thinking which did not match the curriculum target knowledge, and see if the model can offer some insights into what might be going on.

### ***Some examples from science earning***

Some of the examples I am discussing have often arisen from my own teaching or research, so I am not suggesting you would *necessarily* meet these specific problems in your own teaching - though, of course, you might. Some of these examples are discussed in more detail in my publications (e.g., Taber, 2014) or at my website [8].

Actually, I think the model here is likely to be most useful when you come across a student who writes or says something unexpected, rather than when meeting a very well-known, common, learning issue that is likely already diagnosed and discussed in the literature. So, the examples are meant as illustrative of the kind of analysis one can undertake to make sense of learners' thinking. Before looking at individual cases of specific 'presentations' of thinking by students, I am going to offer examples of how the model can help us think about common learning issues in some key topics.

## ***Teaching about particles at the atomic/molecular scale***

One area of teaching that is well recognised as a challenge for many students, is making sense of notions of atoms, and ions, and molecules - their nature, properties and interactions, and how these can be the basis of explanations of macroscopic phenomena. This is important across the sciences, but is especially critical in teaching chemistry, where a great deal of the subject concerns understanding how what can be observed at the bench can be explained in terms of models of what it is imagined to be going on at the nanoscopic scale. Indeed, the so-called 'Johnstone triangle', which considers how chemistry is understood at the macroscopic and molecular scales, and represented symbolically, has been described in the subtitle of one book as '*the key* to understanding chemistry' (Reid, 2021). Even if there is some hyperbole there, this chemist's triplet is certainly critical to making sense of chemistry as a science.

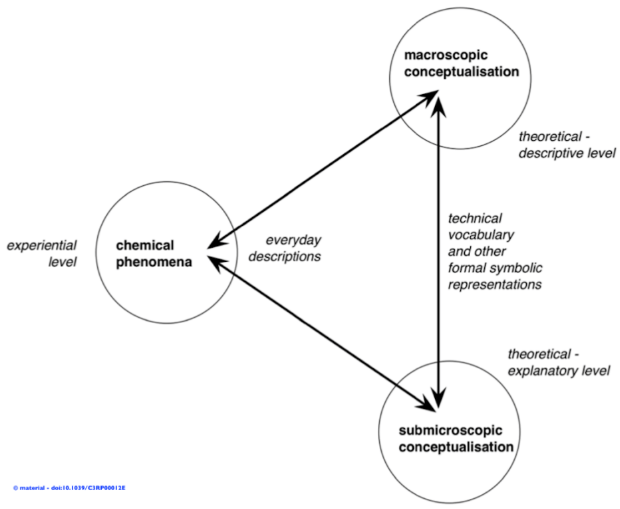


Figure 12. Learning chemistry involves re-descriptions (represented by the arrows) between the everyday language of direct experience and formal representations of the conceptualisation of the subject at two distinct levels. (Figure 5 in Taber, 2013b Reproduced by permission of the Royal Society of Chemistry.)

Chemistry re-describes observable phenomena in terms of abstract concepts such as oxidation and sublimation, and then further re-describes them in terms of a narrative involving completely invisible conjectured entities such as ions and double bonds and distorted electron clouds that have unfamiliar properties (see Figure 12). Electrons cannot be localised in space, and ions do not have distinct surfaces, and

8 https://science-education-research.com

atoms are said to have completely different sizes in different contexts [9] - and if that is not bad enough, sometimes particles can tunnel their way through barriers like fantastical ghosts walking through doors.

Learners who are told that the behaviour of substances they observe in the lab' can be explained in terms of the molecules or ions of the substances often come to assume that this means gold particles must be shiny, and wax particles are soft, and copper particles conduct electricity, and ice particles melt readily (Ben-Zvi, Bat-Sheva, & Silberstein, 1986).

Analysis of this topic suggests there are a number of barriers to student understanding. Indeed, in terms of the typology of learning impediments, it can potentially tick most of the boxes (see Figure 13).

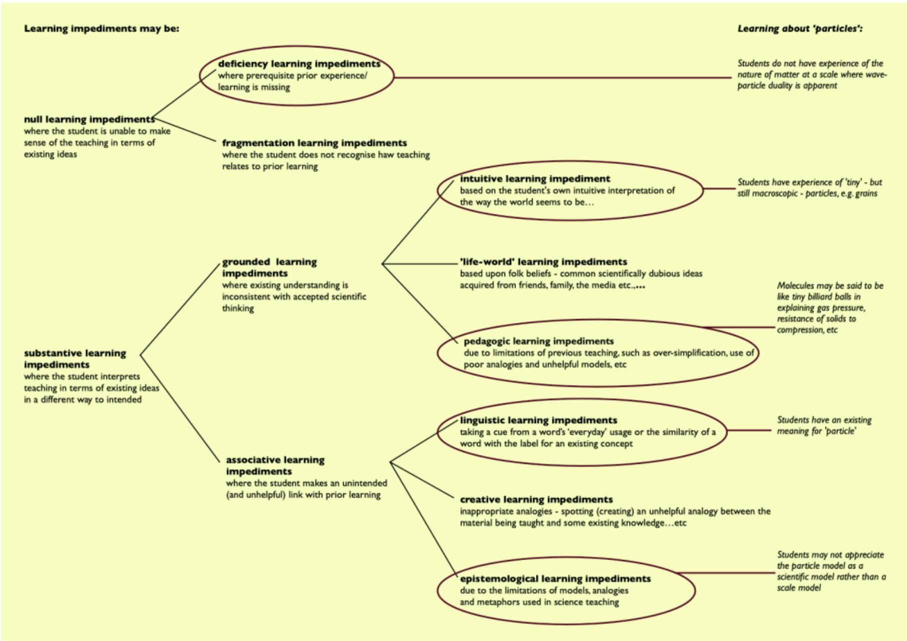


Figure 13: Learning bugs are common in coming to understand the molecular realm (After figure 4 in de Jong & Taber, 2014).

## *Naïve physics*

Probably the most reported alternative conceptions relate to the so-called naïve physics or folk physics (Watts & Zylbersztajn, 1981).[10] People commonly assume that the force on an object must be in the direction it is travelling, so a moving object must be subject to a driving force and moving objects will come to a stop by their own account without any resistive force being needed. An object tossed into the air, according to folk physics, has an upwards force whilst it is moving upward, until gravity takes over then it start to move down. It is typically found that over four-fifths of naïve learners think that way before teaching,

[9] An atom does not have a size in the sense a marble does, as the atom does not have a distinct volume or surface, being more like having an 'atmosphere' which gets 'thinner' and 'thinner' but can never be entirely escaped from. In a sense, a single hydrogen atom is infinite in size (Taber, 1996)! Usually, several of covalent, metallic, van der Waals' and ionic radii can be measured for an element, and can give very different sizes.

[10] A more detailed analysis would look at the specific common alternative conceptions separately. So, for example, '*naïve physics*' might also be considered to include the common notion that no force is required to make an object move in a circular path, which presumably does not develop from early life experience of moving objects in circles without any apparent force. For the sake of today's presentation I am considering some of the most common aspects of naïve physics.

and most probably continue to think that way outside the classroom. The naïve physicist does not grasp the principle of inertia, and children asked to role play dropping something from a plane onto a target will typically overshoot the target assuming the payload will drop vertically. This can prove frustrating, though experience and practice can overcome the initial intuitions. We develop an intuitive understanding of mechanics from our very early experiences in the world (see Figure 14) - but that is a world awash with frictional and other resistive forces that are initially ignored in setting up the scientific formalism. [11]

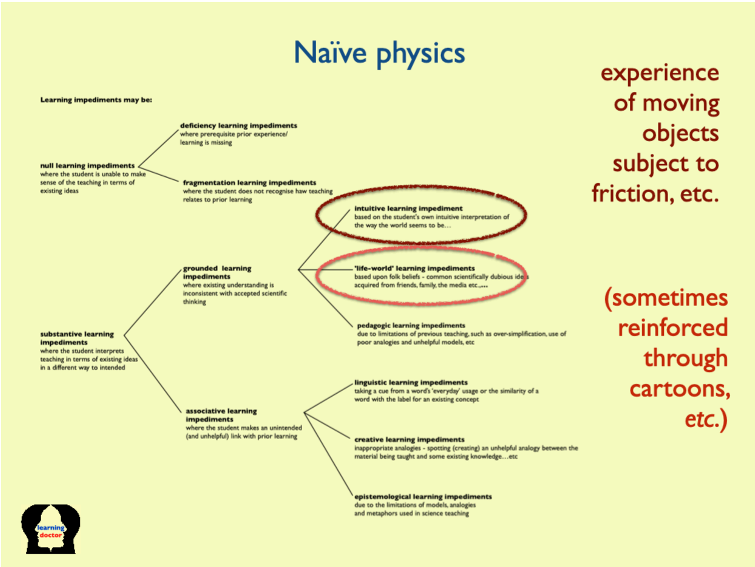


Figure 14: Applying the typology - naïve physics.

### *Evolution by natural selection*

Similar analyses could be made of other topics. For example, many learners struggle to understand natural selection, despite some biologists suggesting it is an obvious and simple notion. (It is obvious and simple to those who have been working with the theory intensely for many years: less so, for those first meeting the theory.)

Actually, fully understanding the theory of natural selection requires the coordination of a range of principles that have to be understood and familiar before they can be brought together in a learner's mind (Taber, 2017b). Everyday notions of '*nature versus nurture*' show some of these component ideas are not easy to grasp. There is also the tendency of the human cognitive system to group and classify things, and so to readily recognise natural kinds in nature, so that the species concept is often assumed to be fixed and absolute, much as was often thought before Darwin. The timescales over which macroevolution occurs are completely outside human experience. Furthermore, even when a community has no ideological reasons to reject evolution, it is common for people to still think in terms of the inheritance of acquired characteristics (see Figure 15).

[11] That is, the scientific approach is to simplify, by first considering an ideal case (uniform fields, point masses, no friction, inextensible strings and non-compressible objects) and then adding in complications. This is perfectly sensible, but humans are born into a world where all those complications are already operating.

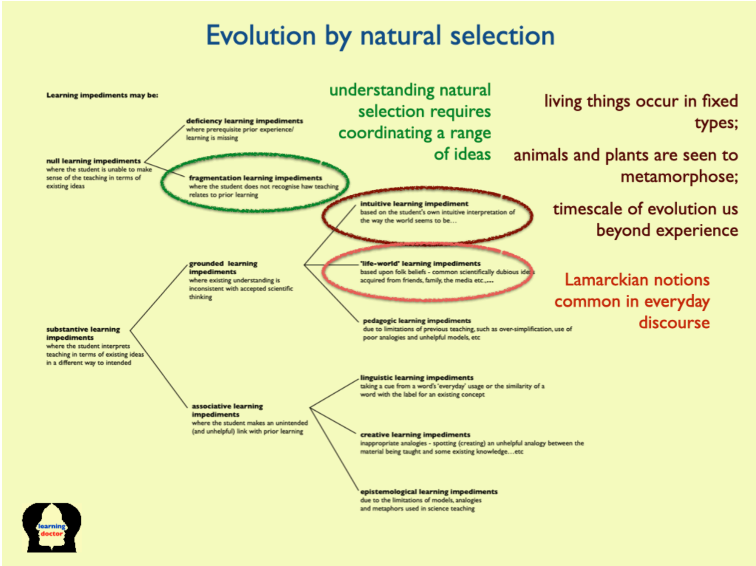


Figure 15: Applying the typology - understanding natural selection.

### ***The product of a neutralisation reaction has pH7***

This ('*the product of a neutralisation reaction has pH7*') is quite a common alternative conception. At core, this seems to be a linguistic learning impediment (Schmidt, 1991) in that given the way in which the English language is generally used, we might expect a process that has been labelled as *neutral***isation** to lead to something '*neutral',* in the way that, for example, *polymer***isation** leads to a *polymer* (see Figure 16). However, if, for example, sodium hydroxide is reacted with ethanoic acid, it leads to a basic salt.

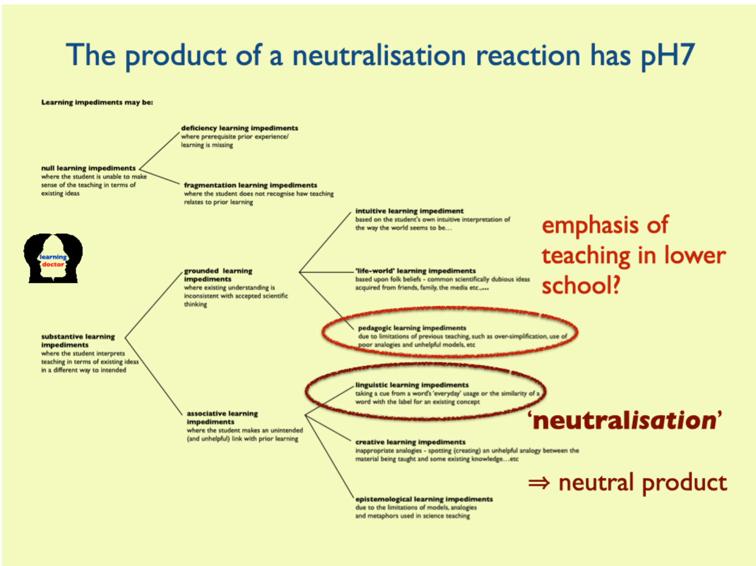


Figure 16: Applying the typology - the product of a neutralisation reaction has pH7.

Moreover, this perfectly reasonable interpretation of language - that *neutralisation* leads to *neutral* products - is often made in teaching contexts where the reagents used to introduce neutralisation reactions are strong acids and strongly alkaline solutions, and where laboratory work may involve finding an end-point by looking for a pH of 7. This therefore provides contexts that reinforce the misconception. It may only be some years later that the notion of acid and base strength is introduced in more advanced courses, and neutralisation reactions which do not lead to neutral products are first detailed. By that time the initial idea has become well entrenched in the learner's thinking.

### *A mineral acid has a pH of 1*

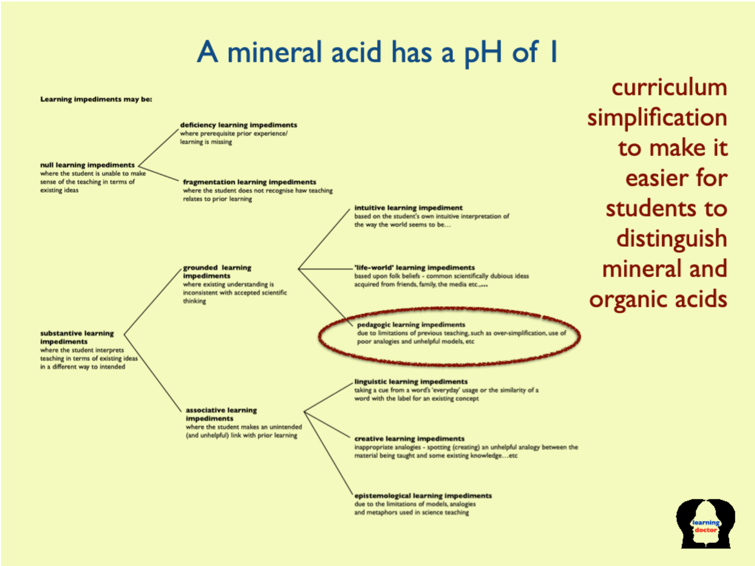


Figure 17: Applying the typology - a mineral acid has a pH of 1.

The pH of an aqueous solution will in part depend on the strength of the acid - but also on the concentration, and strictly also on the temperature (as pure water is only pH7 at about 25˚C). So, any statement that a certain type of acid has - regardless of dilution - a particular pH, is questionable. Yet, I once found an experienced chemistry teacher who was convinced that the mineral acids such as hydrochloric, nitric, and sulphuric acid *always* had a pH of 1.

We actually met in a school lab with measuring cylinders at dawn - well, actually, lunch time - to test the idea with serial dilutions. Many years of teaching a course where pH measurement was limited to indicator colours, and where students were taught the 'simplification' that mineral acids would be found to have pH 1 had led to this teacher accepting the idea himself (see Figure 17).

### *Hydrogen bonding is a type of covalent bond*

I met students in my own college classes who, by the time hydrogen bonding was introduced in chemistry lessons, had already formed the notion that a hydrogen bond was a kind of covalent bond. This was in a curriculum context where school chemistry courses only discussed covalent, ionic and, to a lesser degree, metallic bonding; and so hydrogen bonding was only explained later in more advanced (indeed, post-compulsory) classes. However, students on biology courses would be taught about how hydrogen bonding was involved in various processes relating to proteins and nucleic acids - without (it seems) explaining further what hydrogen bonding was.

Hydrogen bonding was clearly a bond to a hydrogen atom, that was usually represented with a line from the hydrogen atomic centre to another atom in figures. So, in the absence of any teaching on what a hydrogen bond was (a deficiency learning impediment) the students simply assumed that what was labelled this way a type of covalent bond (see Figure 18).

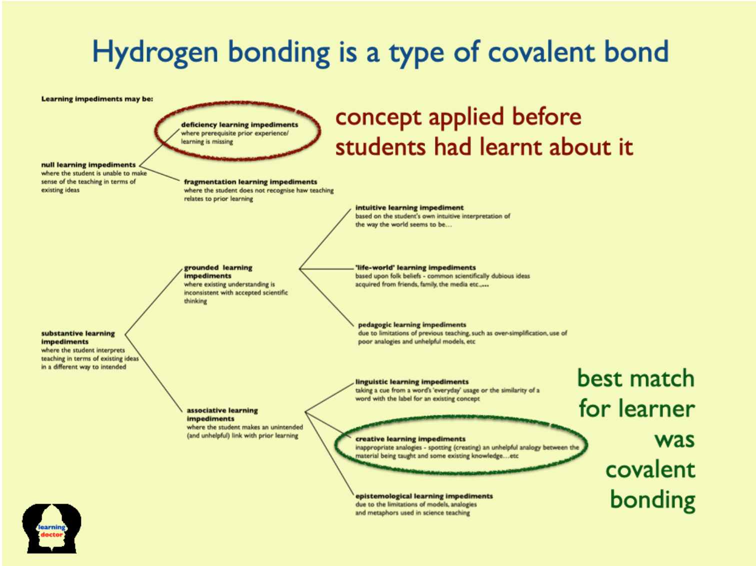


Figure 18: Applying the typology - hydrogen bonding is a type of covalent bond.

### ***Interpreting multiple bonds***

One of the 'learning bugs' I came across in my own teaching, that rather surprised me, concerned a student who was not sure how to relate the notion of multiple bonds to the ideas of covalent and ionic bonding. She suspected there was a link, but was not sure. In my classes on general chemistry topics I talked a lot about covalent and ionic bonds, whilst in the introductory organic chemistry class topics another lecturer talked a lot about single and double bonds (see Figure 19).

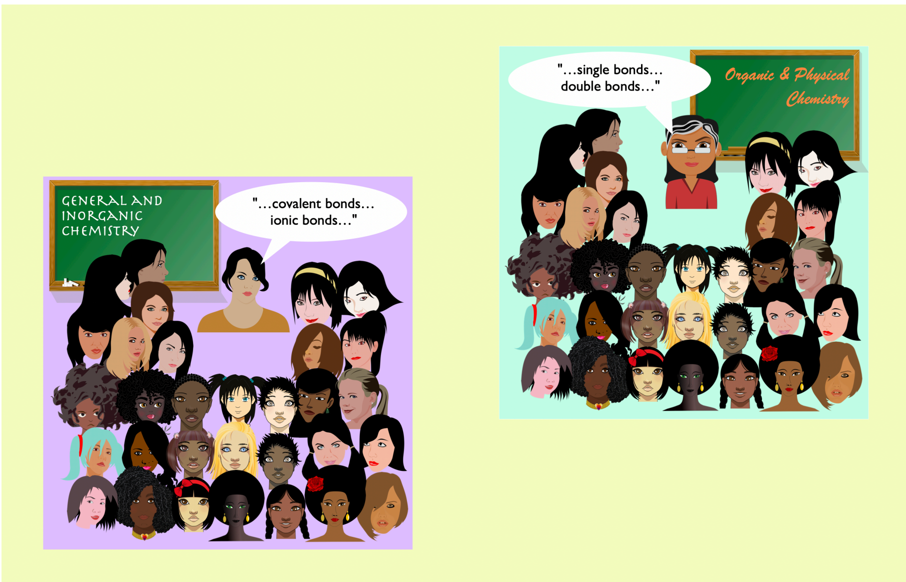


Figure 19: Not sure of the connections between types of bond.

Here there was a kind of fragmentation learning impediment as the student was not able to link up learning from the different parts of the course (see Figure 20). She had not appreciated that the bonds referred to in organic topics were covalent, as either the teacher had not made this explicit, or she had missed this point.

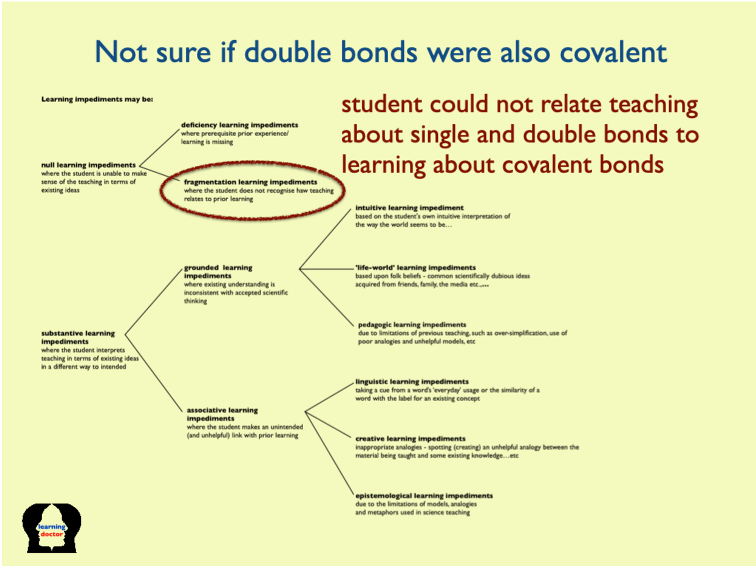


Figure 20: Applying the typology - interpreting multiple bonds.

### ***The stability of ions such as $Na^{7-}$ , $C^{4+}$, $C^{4-}$, and $Cl^{11-}$***

I was also very surprised in my work with my own students to find they often though that the $Na^{+}$ ion was inherently more stable than the neutral atom (so they thought the atom would spontaneously ionise itself), and indeed, even more worryingly that the $Na^{7-}$ ion would also be more stable than the atom.[12] This led to some work which suggested this is very common among learners, and that students will often think that other ions with large charges ($Be^{6-}$, $C^{4+}$, $C^{4-}$, $Cl^{11-}$) will be stable as long as they have outer electron shells that are full or have octets (Taber, 2009a). Many students will even think that an excited chlorine atom (2.7.8) will be more stable than the ground state atom (2.8.7) as the excited atom has an octet in the outer shell.

This seems to be largely a pedagogic learning impediment, where teachers and/or textbooks have either explicitly stated, or at least strongly implied, that species with full shells/octets are more stable than those that that have other electronic configurations (see Figure 21). Of course, the octet rule is a genuine heuristic that can be useful in chemistry - but it only tells us that, more often than not, ions in chemical systems, such as in lattices or when solvated; and atomic centres in stable molecules; will have octet and/or full shell arrangements. Learners will readily extrapolate from this that full shells and octets offer inherent stability in any context.

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[12] This was especially surprising as students never came across any ion with a formal charge of ±7 in their lessons, and were very familiar with the general pattern that metallic elements formed positively charged ions. The alternative conception that octets/full outer shells always made a species stable was so convincing to learners that it could dominate their thinking in spite of other considerations (Taber, 1998, 2009a, 2013a).

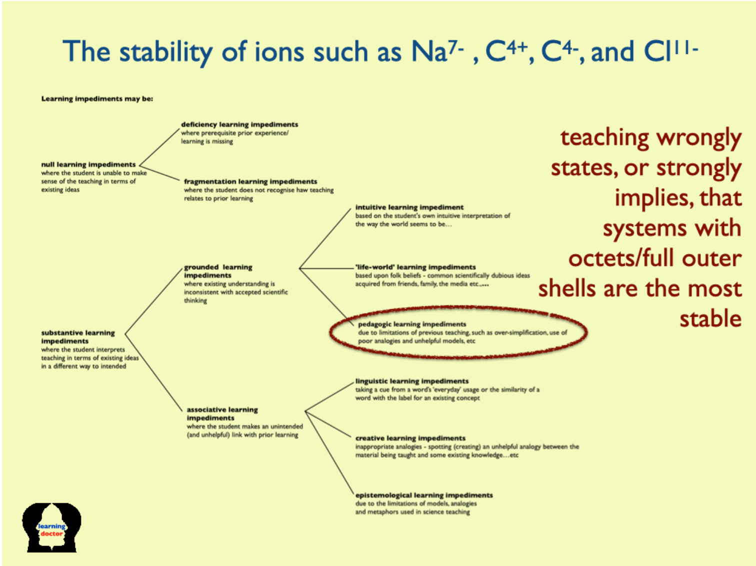


Figure 21: Applying the typology - The stability of ions such as $Na^{7-}$ , $C^{4+}$, $C^{4-}$, and $Cl^{11-}$.

As an analogy, consider the statement that spheres are strong structures. There is some truth in this, but it has to be understood in context. A sphere made of very thin glass, like a Christmas bauble, will readily break. A spherical submarine subject to increasing depth may eventually collapse if the pressure is sufficient. A spherical glass marble dropped from a plane may not survive intact.

### ***Metals do not boil - or freeze***

It might seem that if learners have been taught a simple model of transformations of matter: that pure substances can exist as solid, liquid or gas, with the associated transformations (melting/freezing; boiling/condensing) then once they had acquired this idea, and consolidated it through a range of examples, then it could be universally applied. But just because a learner 'knows' that a liquid will freeze on sufficient cooling; or boil on sufficient heating; this does not mean they 'know' this for all possible examples.[13] Grounded learning impediments may interfere with the application of the principle in some circumstances.

So, for example, if hot wax from a hydrocarbon based candle is seen to solidify, the student may not consider this an example of freezing as in everyday, 'life-world', usage, freezing only occurs when something is very cold. Similarly, while a learner may have no trouble accepting that, like water, many other liquids will become gaseous if heated enough, they will intuitively 'know' that this could not apply in the case of something like iron.

A c.twelve year old school student told me that "*different substances have different freezing and melting and boiling points*" yet thought that iron would melt, but then *stay a liquid* no matter how much it was heated.[14]

---

[13] That is, although the student may know the general rule (and that it is a general rule), and apply it in many cases, they may have blind spots where they tend not to apply it. For example a student who 'knew' "there is particles in everything", was still unsure if chlorophyll would be made up of particles:
https://science-education-research.com/there-are-particles-in-everything-but-maybe-not-chlorophyll/
That said, students may also apply general rules too broadly - such as supposing that as "everything is made up of atoms", then a chemical bond would have to be made of atoms:
https://science-education-research.com/a-chemical-bond-would-have-to-be-made-of-atoms/

[14] This example is discussed at https://science-education-research.com/liquid-iron-stays-a-liquid-when-heated/

For this particular pupil, iron was just not the kind of stuff that could become a vapour. I am not sure how widespread this particular alternative conception might be, but a c.16 year old just starting her advanced chemistry college course told me that

> "It's not that I'm not convinced about it, it's just sound strange, because it's like - well this sounds like ridiculous but, like but before today like none of the people in out class had thought about iron being turned into a gas, and it's little things like that which sound weird."
>
> https://science-education-research.com/iron-turning-into-a-gas-sounds-weird/

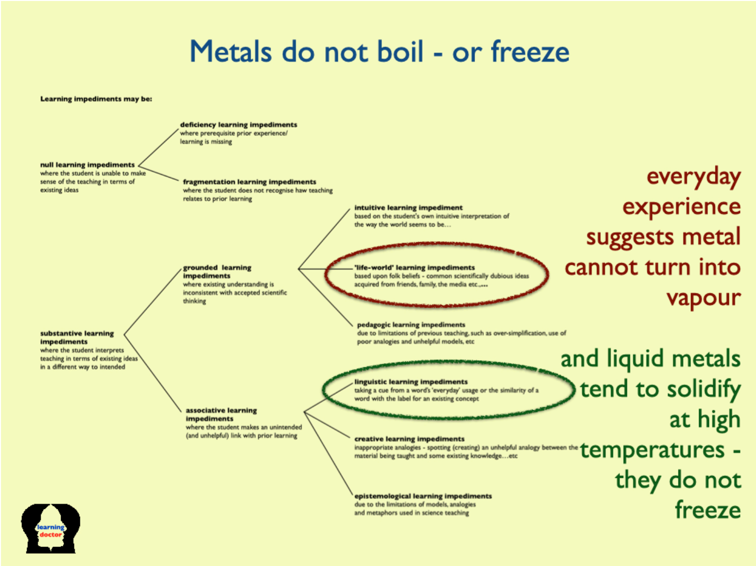


Figure 22: Applying the typology - metals do not boil - or freeze.

I might suggest a paraphrase that "science tells us that iron can become a gas, but it is hard to believe it" (see Figure 22).

## *Sleep, like food, gives us energy*

I recall interviewing a year 7 (c.11-12 year old) pupil at a secondary school who told me that going to sleep, like eating food, could give us energy. When I asked about this he drew an analogy with recharging a battery - a creative association (see Figure 23), though strictly misleading as although sleeping may refresh us, it does not act as a net source of energy.

> "when you haven't got any energy, you can't think, like the same as TV, when it hasn't got any energy, it can't work. So it's a bit like our brains, when we have not got enough energy we feel really tired, and we just want to go to **sleep, *which can give us more energy,*** a bit like food…
>
> it's like putting a battery onto charge, probably, you go to sleep, and then you don't have to do anything, for a little while, and you, then you wake up and you feel – less tired."
>
> https://science-education-research.com/sleep-can-give-us-energy/

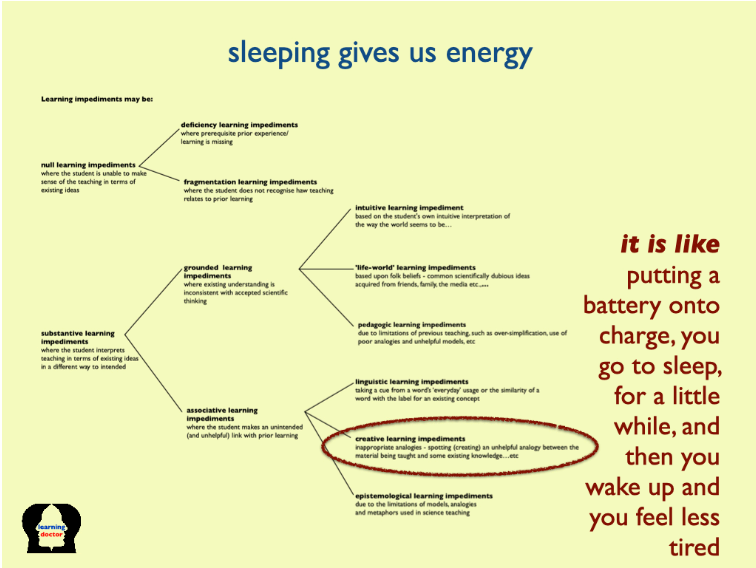


Figure 23: Applying the typology - sleep, like food, gives us energy.

## *A break from electricity?*

Sophia was a Y7 student when she told me about the things she had been learning in the topic of electricity. She also told me,

> "I don't know what, it's not that much to do with electricity, but, yesterday or the day (before) we done magnets."
>
> [Oh right. So that's a new topic, is it, not to do with electricity, or?]
>
> "Well, I think we're still doing electricity. I don't know if it was just something – so we know what might, er, so we know what, what electricity will flow through, and maybe it's something to do with – 'cause magnets like stick to other things, they might be – I'm not sure, I think we might just have had a break from it, I don't know, but"
>
> https://science-education-research.com/magnets-are-not-much-to-do-with-electricity/

There was a sense of stream of consciousness here, as poor Sophia tried to suggest a convincing reason why the class had had a lesson on magnets when they were supposed to be studying electricity. She did not seem to find a sensible option and her best guess was simply that the teacher had given them a break from the topic (see Figure 24).

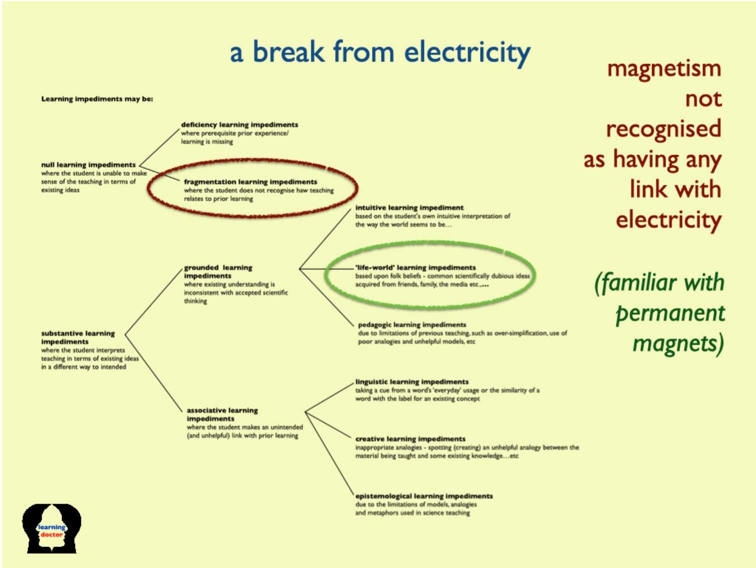


Figure 24: Applying the typology - a break from electricity?

I suspect the teacher would have seen things quite differently (see Figure 25).

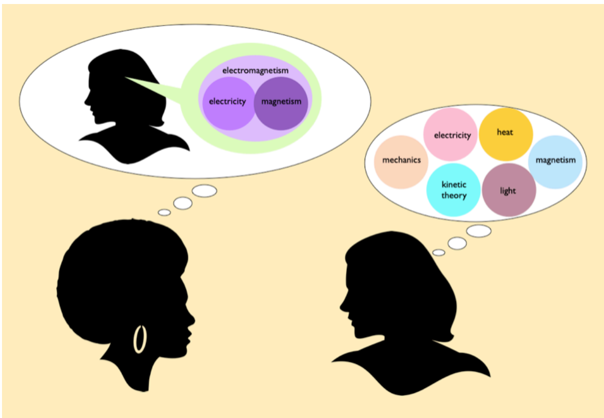


Figure 25: A mismatch between the teacher's mental model and the student's conceptualisation of topics?

### ***Summer occurs when the earth is nearest the sun***

The idea that summer means we are closest to the sun has a clear difficulty, in that the Northern Hemisphere summer coincides with the Southern Hemisphere winter, and *vice versa*. Yet even young children will notice a general pattern that when you are closer to sources; of light, of heat, of sound, of perfume; the intensity is greater.[15]

[15] Children are likely to notice this before they develop language competence, so I am not suggesting they initially form an explicit, verbalisable, conception such as 'when you are closer to sources, the intensity is greater'. Rather, this is likely to be the kind of implicit knowledge element sometimes referred to as a p-prim: a phenomenological primitive (diSessa, 1993). That is, at a preconscious level the brain responds to the similarities in experiences by developing a 'unit' that spots this pattern ('gestalt') in further experiences such that the brain becomes biased to 'expect' future experiences to fit the pattern. Once established, this 'p-prim' can be applied in both predicting what might happen in future scenarios (the child will expect the sound produced by a trumpet to get louder as it crawls towards the source, even if it has never previously been present when a trumpet has been played) and, once language is available, can be recruited into forming explanations, as in this case (Taber, 2008).

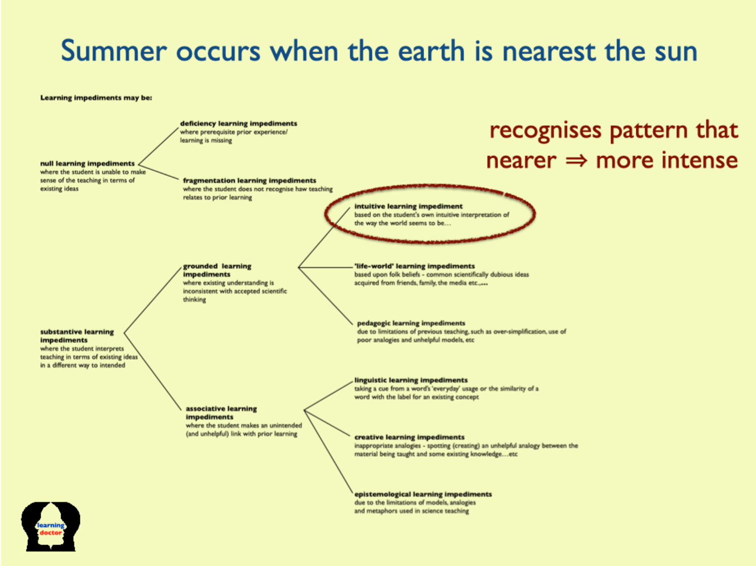


Figure 26: Applying the typology - summer occurs when the earth is nearest the sun.

If a student learns that the earth's orbit is not a perfect circle, then it will be clear that our distance from the sun must change at different points in the orbit. So, it is quite reasonable that this intuitively inferred general pattern would offer a feasible hypothesis for why it is warmer at some times of the year than at others (see Figure 26). Indeed, this is not an irrelevant factor, but simply not the most significant one in determining the seasons.

### ***The nucleus is held together by the surrounding electrons***

Another idea that I was surprised to come across was the suggestion that an atomic nucleus with several positively charged protons would be held together by a force from the electrons. This idea is wrong in so many ways that it seems bizarre from a canonical perspective. This is certainly an example of where, if prior learning from physics is being applied by the learner they would not entertain the conception.

When atomic structure is first introduced in basic chemistry it is likely that the attraction between the positively charged nucleus and the electrons will be highlighted. But nuclear chemistry is a more advanced topic not taught at this level; so although the composition of nuclei as usually being composed of several protons and neutrons *will* be presented, the forces at work there (i.e., the strong nuclear force) will likely seem off-topic and an unnecessary complication. That is likely a sensible judgement, but it does leave an 'explanatory vacuum' as it should invite the (obvious?) question: '*what holds the several protons in a typical nucleus together?*' In my experience, this is seldom raised by learners, which - if reflected more widely in other teachers' classes - may be another sign of the compartmentalisation of knowledge: here, the failure to think of the physics undermining the chemistry. If asked to suggest what holds the nucleus together, students are likely to build an explanation from fragments of what they have been taught.

To a physics teacher it should be obvious to learners that the nucleus is not being held together by the electrons as Newton's third law suggests forces are mutual *and symmetrical* interactions. That is, if the positive protons in the nucleus are 'pulling' on the electrons then the electrons must also be pulling on, not pushing on, the nucleus. Forces give rise to mutual attraction or mutual repulsion, not a combination. [16] Moreover, Coulomb's law tells us that the electrical force diminishes with distance (it is an inverse square law) such that the repulsion between two protons packed into the nucleus could not be balanced by a force due to the relatively much more distant electrons. Even if some science teachers do not keep such physics to the forefront of their minds, they will not expect their students to think that negative electrons could be repelling positive protons to squeeze them together!

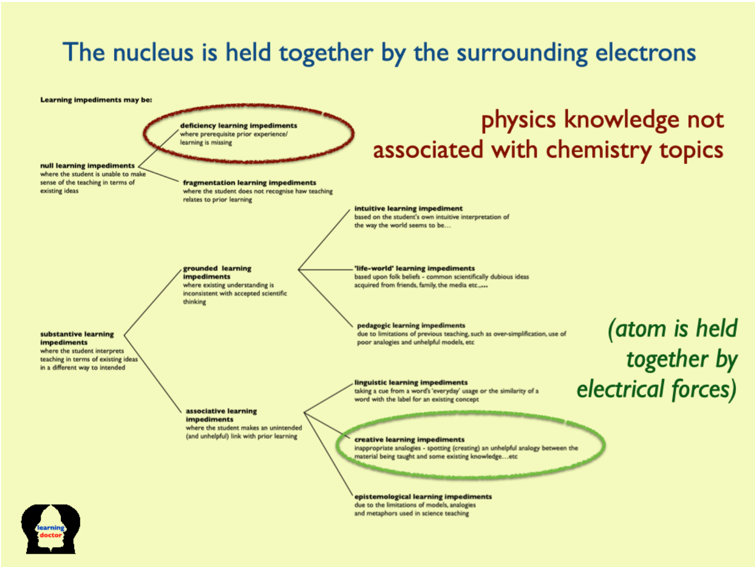


Figure 27: Applying the typology - the nucleus is held together by the surrounding electrons.

Learners seem to 'fill the explanatory vacuum', so to speak, by positing a different kind of symmetrical relation (the atom is held together by the mutual interactions between nuclei and electrons - nuclei pull in the electrons and electrons squeeze together the nucleus) which might be seen as a kind of associative learning impediment as an initially ignored explanandum (i.e., *the positively charged protons in an atom are found together in the nucleus*) comes to be explained by associating the cause of stability *of the nucleus* with the taught reason for the stability *of the atom* itself (see Figure 27).

### *The force attracting electrons to the nucleus is gravitational*

Life for teachers would be more straightforward if all learners developed the *same* alternative conceptions. Other learners when asked about the force holding the electrons in the atom suggested this was gravitational (Taber, 2013c). Although, strictly, there is such a force, it is minuscule compared with the electrical interaction. One likely source of this idea is the common notion, sometimes found in science books, that *the atom is like a tiny solar system* (see Figure 28).

Actually, at one time this analogy was taken very seriously by some scientists, even leading to speculation that the little worlds in atomic systems could be populated and, in turn, made up of their own tiny atoms. Such ideas clearly did not survive the quantum model of the atom with its orbitals replacing orbits.

[16] But I am not sure this alternative conception is that rare in learners. For example, I recall being told by one learner that the distance between the earth and moon remains constant, despite the earth pulling the moon toward it, as the moon was repelling the earth.

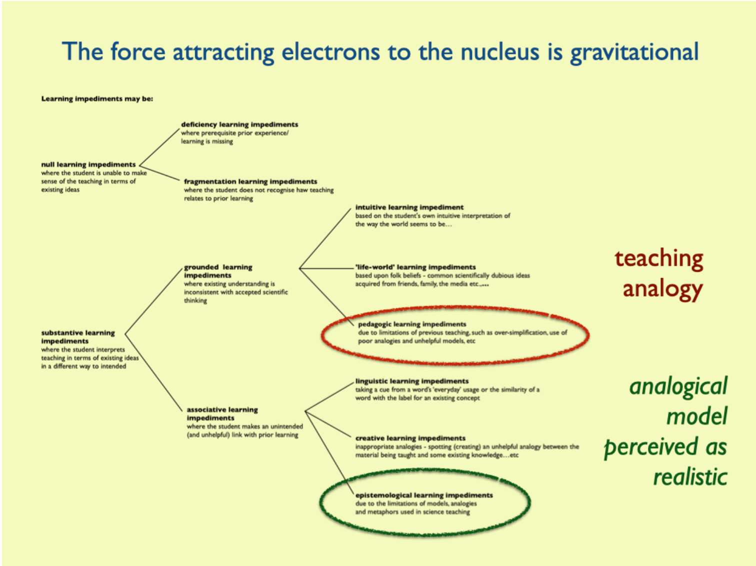


Figure 28: Applying the typology - the force attracting electrons to the nucleus is gravitational.

### ***Plants mainly respire at night***

Mandy, a Y10 student (c.14-15 years of age), told me she got her energy from respiration. She also told me that plants also respire, but

> "they mainly do it at night…because they are photosynthesising during the day…They respire more at night, because – they do it then instead of in the day because they do photosynthesis during the day, but they still respire a little bit."
>
> https://science-education-research.com/plants-mainly-respire-at-night/

Here (see Figure 29) is a summary of what she told me about respiration in plants.

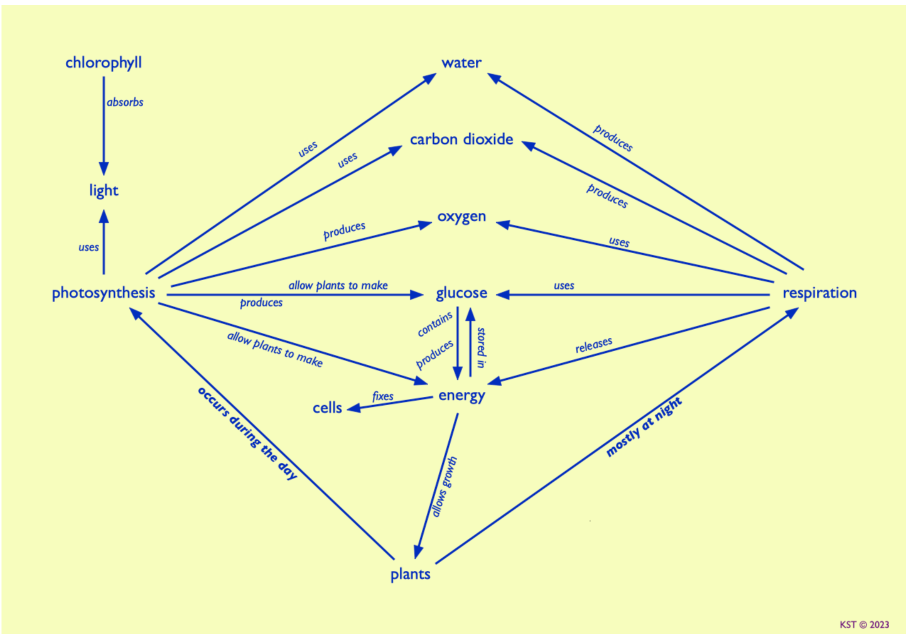


Figure 29: Mandy's conceptions of respiration and photosynthesis in plants.

Now, whilst this graphic helps me map out the comments she made in our conversation, I think it might be misleading as it shows how certain ideas link up, but for a learner this amount of material likely exceeded her working memory capacity. That is, she may have thought these various things, but she was unlikely to be able to bring this all to mind at once (see footnote 6). I accessed fragments of her thinking by asking questions and here I represent these as though they provide evidence that this all linked together for Mandy. I can add to this what she said about how she needed to respire as well (see Figure 30).

We can see that Mandy thought that she and other people need to respire all the time, whereas plants mostly do their respiration at night. Now I think one of the challenges here is that we can talk about respiration at the organism level or at the cellular level, and as teachers we likely shift back and forth. That is legitimate, as respiration for the organism is the aggregate of all that cellular respiration, but it must add to the learning challenge.[17]

Although Mandy talked about energy, the language she used reflected everyday discourse that is often vague when compared to the specification of scientific language (Solomon, 1992). Respiration '*made*' energy; glucose '*produced*' energy; and carbohydrates '*were*' energy. In a sense, the energy concept could be seen as the integrating idea needed to make sense of metabolism, and in particular of understanding how respiration and photosynthesis have a systematic relationship in plants. So, although my representation of Mandy's ideas into a network might suggest otherwise, Mandy felt that she did not know how the energy stored in food we eat or in glucose used in plant respiration got to be there.

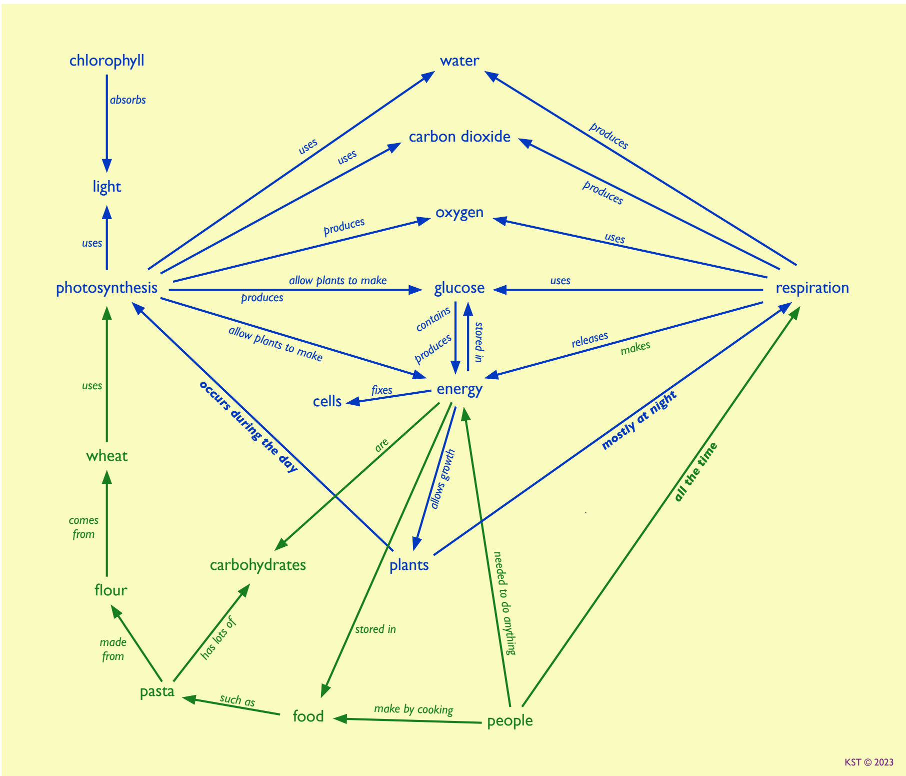


Figure 30: Mandy's conceptions of respiration in plants - and her.

17 In this sense, biology teaching involves similar kinds of shifts (between levels such as molecule-organelle-cell-tissue-organ-organ system-organism-biome-biosphere) as has been much discussed in chemistry teaching (see Figure 12). I acknowledge benefitting from several valuable conversations with Dr Venus Hung about this issue.

Mandy's conception of the two processes were balanced in terms of the substance involved, but not energy (see Figure 31).

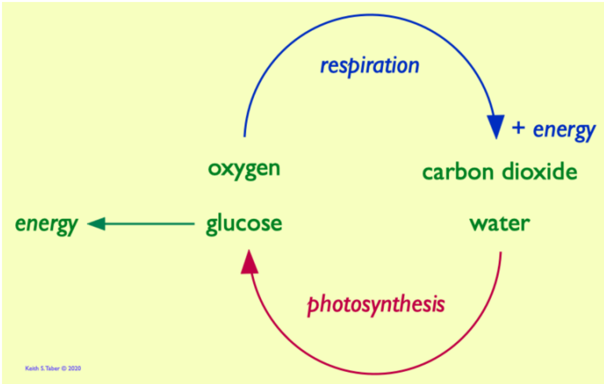


Figure 31: Mandy's notions of how energy fits into respiration and photosynthesis did not recognise that the energy released in respiration was related to the light needed for photosynthesis.

That seems bizarre looking at the concept mapping in Figure 29. Light is used in photosynthesis, when it is absorbed by chlorophyl. So, surely this is the source of the energy? But on reflection I think Mandy meant it when she said that plants *made* energy by photosynthesis. One of her comments was that plants *used* the light *to get the energy*. It seems here that although she knew light was needed for photosynthesis, and that it was absorbed in the chlorophyll, this did not imply to her that this energy somehow became the energy stored in the glucose produced in the process and later released in respiration.

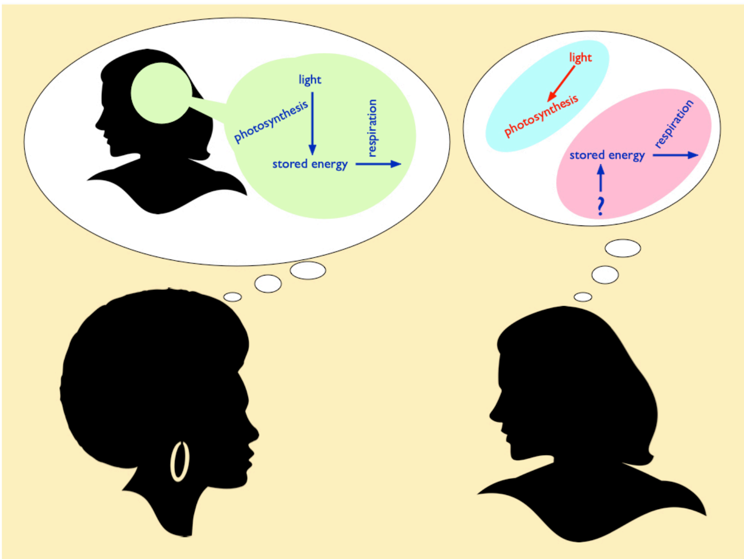


Figure 32: Given what Mandy did know about respiration and photosynthesis, it was not immediately obvious that she had missed a key connection between the two processes.

I think there are several things going on here, include a somewhat fuzzy energy concept, and a suitably vague language for talking about it, but I think the critical issue is that Mandy did not link the light needed for photosynthesis with the energy released from reacting glucose with oxygen in respiration. This link would have seemed so obvious to a science teacher (see Figure 32), that I doubt the issue would have come to light (so to speak) if she had not volunteered to be interviewed. Indeed, I failed to fully appreciate this myself until I revisited this example when preparing the presentation for today.

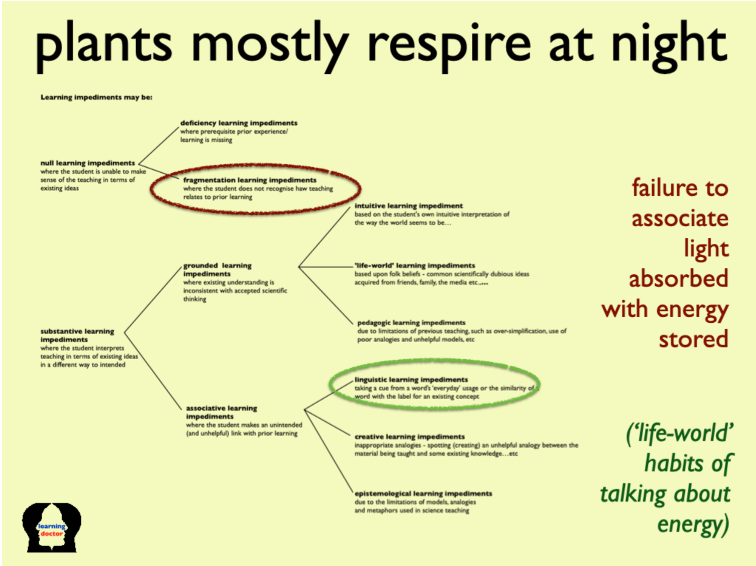


Figure 33: Applying the typology - plants mainly respire at night.

So, I think the main issue here is not understanding photosynthesis and respiration as parts of an integrated system. We can say that the plant gets its energy from the sun by photosynthesis, and we can also say that the plant gets its energy from chemical stores by respiration. Both of these statements are true, but they are related parts of a story, not alternatives that offer options. So there is something of a fragmentation learning bug here (see Figure 33): Mandy had different parts of the scientific narrative, but had not managed to integrate them in a coherent framework. Mandy knew that respiration and photosynthesis were related, but she did not fully appreciate the symmetry of these processes in terms of energy changes.

## Conclusion

I could discuss a good many more examples, but I suspect you have seen enough to either dismiss this approach as not useful to you, or to think it may be something you could find useful in your work. Whichever option you may take, I would like to remind you of my opening premise.

Often students fail to learn as we would wish because they are absent, or distracted, or unable to hear clearly, or demotivated, or in some other way not in a fit state to learn. Yet, it also seems to be the case that often learners come away from teaching when they *could* see and hear and *were* making the effort to understand, but either could not make sense of teaching or misinterpreted it. We *could* put that down to poor teaching, or stupid learners, but I think we all know better than that.

We could claim that science is abstract and teaching it well is difficult. That would be true, but then I assume we have all volunteered to take up that challenge. We could quite justifiably claim that effective teaching would be possible if teachers were able to work in depth and over extended periods with individual learners. But that is not classroom teaching, where, in any case, student-student interaction can be very valuable.

So, we can either dismiss failure to learn as an inevitable outcome of education systems that work with students *en masse*, or we can envisage teaching-learning as something which only works when the components are well tuned to each other and integrated into a system. From that perspective, system bugs may be inevitable, but they can also be analysed so that they can be addressed. This particular model is then intended to address a real problem facing classroom teachers.

Thank you.

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