'... And some fell on good ground'[1]

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In many of our day to day activities we operate efficiently on an input-output model. We press the switch and the light comes on. We depress the accelerator and the car speeds up. There is a simple cause and effect relationship which operates more than satisfactorily until something goes wrong. Then we have to ask questions about what has happened to the switch, the bulb or the circuit. In the case of the car, we may pass the problem to another, because the car may be a 'black box' which we can operate when all is well, but beyond us when things go wrong.

Education can also be run on an input-output model. The teacher provides the input and the student produces the output behaviour in exams or tests or in some kind of overt performance.

Indeed, educational and psychological research in the earlier part of this century regarded the input-output view of education as the only legitimate one since the input and output could be measured objectively and inferences and predictions could be made. This approach was seen in the Behaviourist School and in the work of its proponents such as Skinner[2]. What happened between the input and the output, the mental 'black box', was thought to be unamenable to scientific enquiry.

But the very fact that changing input can change output behaviour, must raise the question why and set us off on an exploration of what goes on in the 'black box' of the mind of the learner. An understanding of the internal workings of a car may very well change the way we drive and inform our actions when things go wrong and direct us to a solution to our problem. Similarly, an understanding of the learning process may well influence the way we teach and the way we seek to remedy things when learning goes wrong.

In the parable[1] from which the title of this paper is taken, the three components were recognised two thousand years ago: the seed (the input), the harvest (the output), the soil (the receiving, transforming processes). This paper will be concerned with what is known about the learning processes in the 'black box' and how they might help our thinking about the teaching environment which will be conducive to a 'good harvest'.

The quality of the seed is important, but the nature of the soil plays a part in the quality of the harvest. It is tempting to assume that the teacher is not at fault when students produce bad results and that the fault lies in the intelligence (whatever that may mean) of the student.

One lecturer, having a bad time with a class, said "This is like casting pearls before swine". The retort from the class was "Ah, but these are not real pearls!". The lecturer's reply was, "They are real pearls and you are real swine!!".

There can also be an implicit assumption that knowledge can be transferred intact from the mind of the teacher to the mind of the student i.e. input = output, but any teacher knows from bitter experience that students can transform what we teach into ideas we never intended and never thought of. The processes in the 'black box' of the mind play their part in producing what are called misconceptions[3] or alternative frameworks.

Looking inside the 'black box'

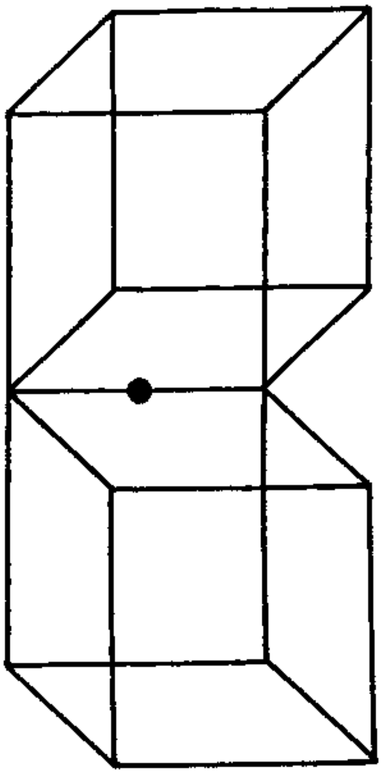
The first step in human processing and learning is *perception*, in other words, what we admit through our senses. There is no doubt that this is a selective process in that we do not *attend* to all of the incoming stimuli, but choose what is of interest or of importance or of greatest impact. To try to respond to all stimuli would be an instant recipe for confusion. However the selection process must be driven by criteria which we already have in mind: previous knowledge, interests, prejudices, misconceptions. In other words, *our previous learning has an influence on new learning*[5].

Since much of our communication is verbal, students take out of words things which are meaningful to them and this is a prime source of misconception. In a large study sponsored by the Royal Society of Chemistry[6], nearly 100 words were identified which were a potential source of misunderstanding in chemistry. The word *volatile* has a specific meaning in chemistry, but its other meanings in common speech such as 'unstable', 'flammable' or 'explosive' also make sense in chemistry. If the teacher asks if the students know the meaning of volatile, all of them will say that they do, but there is no guarantee that the students' meaning and the teacher's meaning coincide. Their previous knowledge is already interacting to change what the teacher is providing. Common words such as *variable, average, simultaneous, rate* and *valid* have been shown to generate misunderstanding[7]. Other words appear to be invented by students and appear as verbal 'chewing gum' in essays; examples are 'bienlarge' and 'to all intensive purposes'. In laboratories, the best constructed manuals are open to misinterpretation, where 'clear' no longer seems to mean 'transparent' but 'colourless', where 'molar' means 'concentrated', where 'a little' can mean anything from a single crystal to a tablespoonful!

Words are, of course, labels for concepts and teachers are only too well aware of how a concept like *resonance* can be misconstrued.

Students are using previously held concepts to perceive and interpret what they receive. Every examination script bears evidence to what students can do with what they were taught!

Figure 1



Some of their efforts are wrong, but are based upon a kind of logic; some are compartmentalised and lacking the linkages to make deep sense of an idea; some are insightful and go beyond what was taught and some are just a jumble of ill-digested ideas indicating utter confusion.

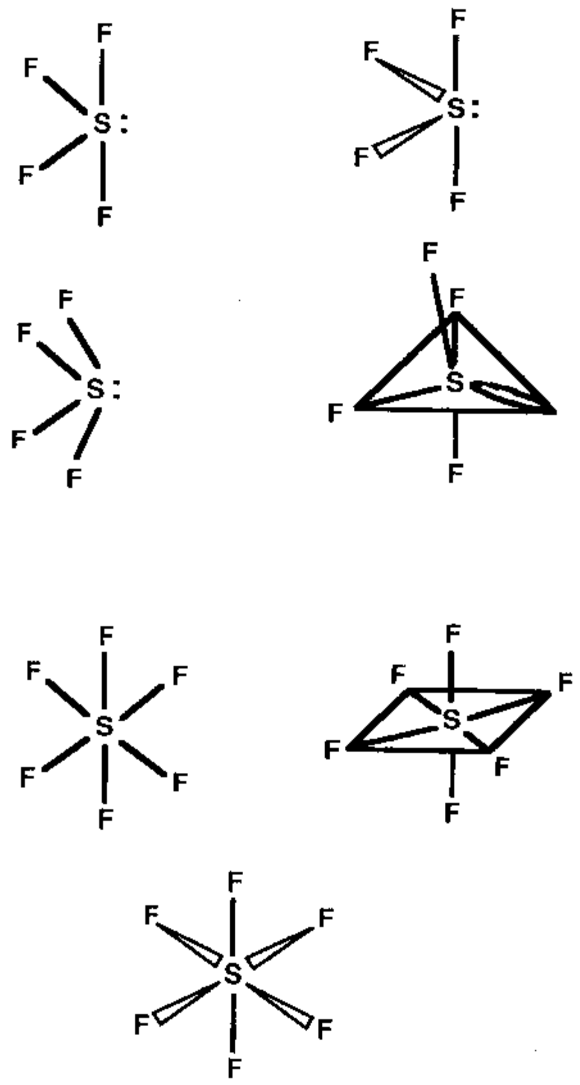
These students are not unintelligent, but they are using previous knowledge and understanding in an attempt to perceive and make sense of what is taught. The evidence is that once students have constructed these ideas for themselves, it is exceedingly difficult for them to undo them and take on the 'correct' idea[8].

However, perception has another function, that of *enhancement*. For example, the images coming on to the retina are not sharp and need to be enhanced and cleaned up like the electronic processes applied to signals from satellites to give a sharp image. Previously stored information is needed to flesh out the imperfect signals. Interpretation is part of this process, particularly when we receive information about three-dimensional objects in a two-dimensional medium such as figures in a book or on a computer screen[9]. Try to make sense of the diagram in figure 1. There are several solutions, all of which are consistent with the incoming signals. If you know what the diagram is meant to convey, you can see it quite clearly, but if you are presented with the diagram for the first time the signals are ambiguous. This is made even worse by the orientation of the figure. Turn it round and you will probably see several versions of the figure: two boxes both coming towards you; two going away from you; the upper one going and the lower coming and so on. The one who draws the diagram does not have this problem. It is obvious to the teacher, but not necessarily so to the learner. This is an acute problem for learners trying to interpret chemical structures, especially where there are several conventions in use in the literature and in lectures (figure 2). When the representation of the 3-D situation is itself in 3-D (i.e. a model) the multiple options are reduced to one. More than 20% of students have severe difficulty in this aspect of perception[9].

Unless the rules and conventions of representation are well understood (previous knowledge) much stereochemistry is a closed book to many students. It is a sobering experience for teachers to ask a class, even at honours level, how many of them have difficulty in this area! With specialised help, about half of the students with difficulty can be rescued, but about 10% (mainly girls) have a residual problem.

Let us move further into the 'black box' to see what happens during the next stage of processing.

Figure 2



Working space (memory)

Having admitted and tidied up the new information we set about a more careful, conscious perusal of it in Working Space where we reshape it, organise it and allow it to interact with already held knowledge brought into consciousness from Long Term Memory (LTM)[10]. We may decide to hold the information for a short time and then dispose of it (e.g. a phone number held until we have dialled and then forgotten). On the other hand we may decide to think about it with a view to storing it for later use. There is a problem, however, in that Working Space is limited in how much information it can hold and process. The concept of a limited Short Term Memory with space for only 7±2 pieces of information has long been established[11]. The concept of Working Space places even greater limitations because it is a shared space with a trade-off between holding information (new, and old from LTM) and working on it. If we have too much to hold we have no room for processing[12]. For this processing to work we need temporary stores where we can dump material while we think about other things. The commonest temporary store is a piece of paper! This processing dilemma is at its most obvious when someone bombards us with information, particularly at high speed (as in a lecture). We tend to make notes with almost no conscious thought. It is very likely that little is learned in the course of a lecture in which students are being confronted with lots of new material[13].

It is worth examining students' notes at the end of a lecture to see how they go about the task. In the face of the rapid stream of information coming at the class, students record only about 10% of what is said. Lecturers deliver about 5000 words per lecture while students record about 500 words per lecture. How do they select the 10%? What drives their perceptive filter to choose the important and ignore the peripheral? Clearly, previous knowledge must play a part, but a more pragmatic system is used. They assume that what the lecturer deems to be important will be written on the blackboard or on overlays and this is a sensible assumption. If, instead of words, one looks at units of information in the lecture e.g. formulae, equations, diagrams, definitions, between 60 and 90% of these find their way into students' notes and almost all of these are copied from the blackboard. However, copying is a haphazard business. In a study reported recently[13] about a quarter of students copied from the blackboard, but inaccurately; another quarter copied only what was on the board but accurately; another group recorded the blackboard work plus some of the spoken information; a final group copied accurately and annotated their notes with linkages, references etc.

Using the information from the blackboard is a sensible device for conserving working-space, but not all the information in lectures is on the board, and overlays are often taken off the projector before students can record their contents. At least the writing on the blackboard is at a pace students can emulate, but the pre-prepared overlay can be difficult to handle. Information is easier to record and process when a diagram is built up stage by stage rather than when it is presented in its entirety. This gives time for understanding and recording.

During a lecture Working Space can be so overloaded that students take breathers in micro sleeps[14]. The length of these periods of inattention can range from 30 seconds to several minutes. These are measurable periods of non-learning which can occur as often as four times per lecture, their frequency and distribution being a function of the lecturer's teaching style.

Laboratories are also places in which working space can be grossly overloaded[15,16,17]. Students are working against pressure of time to follow instructions from work sheets or manuals, recall theory and techniques, observe phenomena, learn new hand skills, read instruments, record data, process data, and to make sense of the message of the laboratory.

In practice, to avoid overload, students can follow instructions blindly, resenting probing questions from demonstrators and maintaining their thinking brains in neutral. It is possible to reach the end of a laboratory period having learned nothing with the exception of some hand skills. It is even possible to obtain 'the right answer' or good crystals without knowing why. As teachers we can provide good input in the form of sound chemistry and observe a good output in terms of result or yield, but this should not lead to the assumption that what happens in between is satisfactory.

The other activity when the processing limitation is felt acutely is in *problem solving*. In problems other than those amenable to algorithms, we can easily overload with the data and leave no space for the processing necessary to find a solution. Even in a fairly routine question on the mole, a few moments reflection reveals how much we have to hold and process.

How many grams of chalk are required to neutralise 25 cm^3 of 0.1 mol dm^{-3} (M/10) hydrochloric acid?

Basic Student procedure

Chalk is calcium carbonate $CaCO_3$ (recall)

Equation is: $CaCO_3 + HCl \longrightarrow CaCl_2 + H_2O + CO_2$

Balance it: $CaCO_3 + 2HCl \longrightarrow CaCl_2 + H_2O + CO_2$

Mole ratio: $CaCO_3$: HCl is 1:2

Gram molecular weight of $CaCO_3$ = 40 + 12 + 48g = 100g

2 moles HCl ≡ 100g $CaCO_3$

$2dm^3$ M HCl ≡ 100g $CaCO_3$

$$\frac{25}{1000}\,dm^3 \text{ of } \frac{M}{10}\,HCl \equiv \frac{100}{1} \times \frac{25}{2000} \times \frac{1}{10}\,g\ CaCO_3$$

$$= 0.125g\ CaCO_3$$

Compare this with the teacher's approach

G.M.W. of chalk = 100g

Obvious 1:2 ratio between $CaCO_3$ and HCl

$2dm^3$ M HCl ≡ 100g chalk

$$\frac{25}{1000}\,dm^3\ \frac{M}{10}\,HCl \equiv 0.125g$$

The teacher's *previous knowledge* has made possible a number of shortcuts, by a process called 'chunking'[18], which has reduced the problem to a trivial level. Some chunking devices can be taught, but others come with experience and a large store of previous knowledge. It is estimated[19] that, in any discipline, it requires about five years (or 10,000 hours) of study to gain a sufficient body of knowledge to be a proficient chunker and efficient problem solver. There is no easy shortcut to move from the novice to the expert state, but the teacher can help by sharing his approaches with his students.

There is some recent evidence at secondary level that some acceleration can take place[20,21] in learning and problem solving, but there is need for teachers to be introspective about their own learning and their own mental connections and to share these with their students.

"Teachers are more expert learners whose understanding about how to ***learn*** *the subject matter is what students need at least as much as they do the factual information."*[22]

In tutorials it is essential to let students see not just the solution, but the thinking leading up to it. For example, in a problem dealing with structures, have an early attempt to visualise a likely structure and then test it and modify it against the rest of the data. This drastically reduces the amount of processing necessary at any one time. For example the students may be asked to work out the structure of SF_4 and are given a collection of physical data. They tend to overload by trying to process all the data at once. Encourage them to build or visualise a trial structure or structures e.g. tetrahedral, square planar, modified trigonal bipyramid. Now look at the n.m.r. with two main signals. This eliminates two structures. Now look at the population of the two environments and any coupling and the structure emerges. Check against the Gillespie-Nyholm prediction.

In a large seemingly intractable problem encourage students to avoid trying to process it all and look for smaller bits they can do. When these solutions are achieved and reinserted into the problem, it now looks less formidable. This is good use of a limited working space. This is 'chunking' in action.

Group work is not just valuable as a so-called transferable skill, but it helps us to use a group of working spaces together and separately. By this means, work is sub-divided into workable (or working space sized) pieces, then brought together, rearranged and then, if need be, reallocated.

Chemists have a wonderful chunking device in the Periodic Table to seek for patterns and trends, but students can lose the thread and overload if the table is used for too much simultaneously. Physical properties, chemical reactivity, electronic configuration and electronegativity can all be summoned together to provide confusion. The table is so rich that the temptation to overdo it is often there and students can lose confidence in a magnificent tool.

Teachers can also share things which are obvious to the initiates but obscure to the novices.

The way in which chemistry has grown historically into three main branches has generated three languages and students are not aware of this. Therefore they may not see the connection between ligand, nucleophile and base which would greatly simplify and unify their ideas. The concepts of hard and soft acids and bases are often lost in discussions of polarisability, whereas their place on the Periodic Table shows clear patterns. If water is a hard base, the common cations in the sea must be hard acids and other things they complex with, such as carbonate ion, must also be hard bases.

Insights such as this can help greatly in the learning, storing and retrieving processes which form the third part of this paper.

There are many factors such as learning style and facility with language which place limitations on the efficient use of Working Space which are a rich field for research. These are outside the scope of this brief paper, but they may in future give us better insights into the processes of learning.

Storage and retrieval

The third stage in this brief look inside the 'black box' is that of putting learned material away in a form that is easy to retrieve and use.

Ausubel et al[5] describe two extremes in the memorisation processes. At one end is 'rote learning' where students attempt to learn by placing information in memory by repetition and in isolation from any other learned material. The other extreme is 'meaningful learning' in which new information is attached to existing learning, making it richer, more interconnected and accessible through many cross-references. These two extremes are similar to, but not quite the same as, the 'shallow' and 'deep learning' described by Entwistle and Ramsden[23]. The latter also includes an attitude to learning. Too many students and maybe teachers also see Chemistry as a subject of mainly rote learning and fail to see the interconnections and the rich picture which are so much a part of our subject.

Some examples of this rich texture of linkages have been outlined above and these can be pursued in lectures, tutorials and laboratories. To break down the compartmentalisation of knowledge and cause it to interlink can be achieved in a number of ways. Perhaps the simplest is the 'mind map'[24] constructed with the help of students. An example might be beginning with the ideas of *electronegativity* and *bond polarity* brainstorm connections into *hydrogen bonding, solubility, electrophilic attack, physical properties.* There is no point in giving this as a handout, but the active engagement of students and tutors to **build** such a network can convert rote into deep learning and this in turn enhances problem solving because ideas can be reached in many ways through multiple channels.

Tutorials and lectures specifically given over to such exercises are invaluable in helping to rescue chemistry from its bad reputation of mindless rote learning. Laboratories can also be adapted to look for patterns. Instead of every student making the acac complex of Cu(II) why not give a group of four students a challenge? 'If you believe in the Periodic Table, the behaviour of one first row Transition Element must be similar to the others. If an acac complex can be made for Cu(II), can a similar complex be made for Ni(II), Zn(II), Co(II)?' Set the team off to find out. The same recipe will do for all. The infrared and uv-visible spectra for these complexes have similarities but they are by no means the same. Then comes the discussion!

If we want our students to have meaningful learning, our teaching has to create the atmosphere and the opportunities for such learning to take place.

We have come almost full circle in this brief overview. Let us gather the ideas together.

Summary so far

1. How we perceive and what we attend to in the information coming to us, is controlled by what is already in Long Term Memory – previous knowledge, skills, beliefs, misconceptions and preferences.
2. How we consciously process new information is controlled by existing material drawn from Long Term Memory as we search for patterns (make sense), recognise surprises and test beliefs. All of this happens in a restricted mental space which operates more efficiently when we use previous knowledge to chunk information and find shortcuts.
3. The storage processes control the retrieval, meaningful learning being easier to access than rote learning.
4. Poor storage and retrieval will affect all the other steps in learning by introducing errors of perception and processing. This will in turn lead to further poor storage. Here lie the origins of misconceptions and crazy ideas, and so-called Alternative Frameworks are born here. There is an extensive literature, mainly in physics, given over to the isolation of these Alternative Frameworks (or Student Science), but little has been reported of how to avoid them in the first place! Chemical examples are less common in the literature, but Taber reports some[4]. Any Chemistry teacher will recognise common examples from their own experience. *"The larger the negative value of ΔG^{θ}, the faster the reaction"*; *"The mole ratio in reactions is 1:1 despite the balanced equation"*; *"Increasing the temperature on the left hand side of an endothermic reaction, drives it further to the right"*.

These ideas have never been taught, but have been *constructed* by the learners out of what they have been given and processed in the light of their existing knowledge (or misknowledge) and understanding. They 'make sense' to the learner.

This can be condensed in the diagram in figure 3.

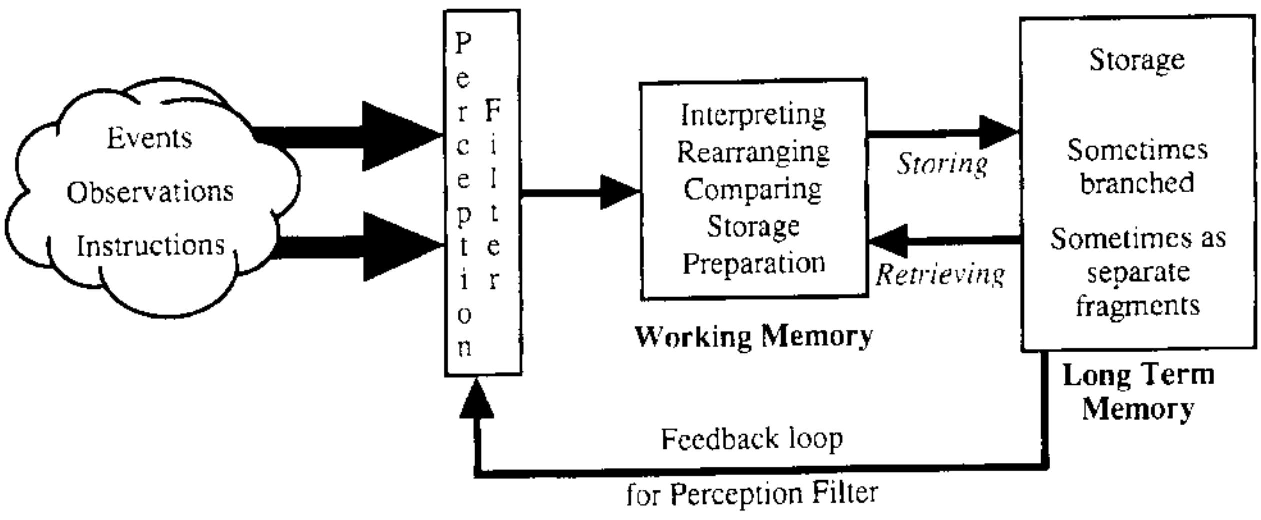
Lessons to be learnt

1. If what is already in the students' Long Term Memory is so crucial to the processing of new material, the preparation of LTM before learning is **absolutely essential** to enhance learning and to minimise mislearning.
2. There is just no point in putting a student into a lecture course, a laboratory or a tutorial without mental preparation.
3. The nature of that preparation has to be as carefully thought out as the course itself.

Prelabs: The purpose of the lab session has to be spelt out and then the student has to be led to ask questions such as: 'What theory do I need to put in place? What instruments will be used? Do I need to get practice using X again? Do I understand the terminology? How will I recognise the product? What maths do I need? What planning am I expected to do?' and be helped to find answers by reference to texts etc. The plan should be recorded, checked by a demonstrator, discussed with the student and given a score which counts.

Some prelabs are more ambitious and involve the student in simulating the experiment on the computer, not to get the result but to familiarise him with procedures and variables. For example, the kinetics for the decomposition of hydrogen

Figure 3



peroxide are to be investigated. There is to be a choice of temperature, peroxide concentrations and catalyst. The student can simulate the experiment several times with changes in variable to come up with a set of conditions which will provide satisfactory results within the length of the laboratory period.

Prelects: Before a set of lectures students can have a short self-marked test to indicate the preknowledge necessary to make sense of the lectures to come so that the new knowledge can be anchored on to a correct base of previous knowledge. A tutorial can then be devoted to remedying the deficiencies and completing the preparation.

This preparation takes time, but amply compensates for 'lost time' by better learning[25].

4. **Storing** can be helped if time is set aside to facilitate it. Postlabs and postlects are there to take the new learning and help students to link it correctly on to existing knowledge and understanding. Here is the place for the teacher to do as Coppola[22] recommends: to share his learning skills as well as his knowledge expertise with his students.

Some of this linking will be helped by Problem Solving, carefully graded to build confidence and to make students seek for multiple cross-referencing. This is helped by group work in which students have access to each other's Long Term Memories and can share out tasks over several Working Spaces. But group work does not happen just by creating physical groups, it has to be taught. The content of this paper could form the basis for sharing with students explicitly how they learn and how they could learn better. Students have intuitive feelings about this, but explicit systemisation of the processes is usually well received. When they understand this, the point of *prelabs*, *prelects*, *postlabs* and *postlects* is accepted and students see them, not as a chore but as an aid to their learning and lead to enlightened self-interest.

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