Science Education: We know the answers, let's look at the problems

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Abstract. Thirty years of Science Education research has found that the areas of the science curricula, which cause students trouble, are the same all over the world suggesting that the problems have a common psychological source. This lecture sets out to develop, with the help of the audience, two learning models, which can account for the problems and suggest ways of improving science curricula for students in secondary schools and beyond. The international phenomenon of students deserting the sciences at a time when scientists are needed, more than ever, to solve problems of international importance, is alarming. A thorough re-examination of what and how science is taught in schools is desperately needed. There will be a supplementary workshop to this lecture which will enable teachers and curriculum designers to get practical experience of how to use the models to bring about new thinking in the teaching and learning of science.

Διδακτική φυσικών επιστημών: Ξέρουμε τις απαντήσεις - ας κοιτάξουμε τα προβλήματα

Περίληψη. Τριάντα χρόνια έρευνας στη διδακτική των φυσικών επιστημών έχουν αποκαλύψει ότι οι περιοχές των αναλυτικών προγραμμάτων που προκαλούν πονοκέφαλο στους μαθητές είναι οι ίδιες σε όλον τον κόσμο. Αυτό μας οδηγεί στο συμπέρασμα ότι τα προβλήματα έχουν μια κοινή ψυχολογική αφετηρία. Η διάλεξη αυτή έχει σκοπό να αναπτύξει, με τη βοήθεια του ακροατηρίου, δύο μοντέλα μαθήσεως που μπορεί να εξηγήσουν τα προβλήματα και να προτείνουν τρόπους για τη βελτίωση των αναλυτικών προγραμμάτων των φυσικών επιστημών στα δευτεροβάθμια σχολεία και πέρα από αυτά. Το διεθνές φαινόμενο όπου οι μαθητές εγκαταλείπουν τις φυσικές επιστήμες, σε καιρούς που υπάρχει ανάγκη για φυσικούς επιστήμονες, περισσότερο από ποτέ, για να λύσουν προβλήματα με διεθνή σημασία, είναι ανησυχητικό. Μια ενδελεχής επανεξέταση τού τι φυσική επιστήμη πρέπει να διδάσκεται και πώς στα σχολεία είναι εξαιρετικά απαραίτητη. Θα υπάρξει ένα συμπληρωματικό εργαστήριο (workshop) σ' αυτήν τη διάλεξη, το οποίο θα δώσει τη δυνατότητα σε εκπαιδευτικούς και συντάκτες αναλυτικών προγραμμάτων να αποκτήσουν πρακτική εμπειρία στο πώς να χρησιμοποιήσουμε τα μοντέλα (αυτά) ώστε να πετύχουμε νέους τρόπους σκέψης στη διδασκαλία και τη μάθηση των φυσικών επιστημών.

Introduction

There are various views of the educational process, which can be summarised in table1.

Table 1. Views of the educational process.

PROCESS			*RESULT*	
LEARNER	**TEACHER**		**LEARNER**	**TEACHER**
Empty head	Scientific Knowledge	→	Gains Scientific Knowledge	Scientific Knowledge
Own Ideas of the World	Scientific Knowledge	→	Gains Scientific Knowledge	Scientific Knowledge
Own ideas of the World	Scientific Knowledge	→	Retains own ideas	Scientific Knowledge
Own ideas of the World	Scientific Knowledge	→	Confusing Mixture of own ideas and teacher's ideas	Scientific Knowledge

Some imagine that the learner is an empty vessel waiting to be filled so that there is the implicit expectation that the student will gain the teacher's knowledge and skills. The second view allows for the fact that learners do not come with an empty mind, but have their own views about the world and how it works. These ideas may not accord with the teacher's knowledge and so they have to be "put right" and be replaced by the teacher's ideas. This also carries the assumption that the change of mind can be achieved and that the end result is a learner who is now thinking "correctly".

The third possibility is that the educational process fails to achieve the desired transformation and the learner is so attached to his own ideas that the teacher's efforts are in vain.

The fourth possibility, and maybe the most in agreement with experience, is that the learner ends up with a mixture of his own ideas and those of the teacher. It has been the author's frequent experience to ask a learner for an explanation of a phenomenon and to get the reply, "Do you want my explanation or the teacher's one?"

The question has to be addressed: "Why is the second situation in the table above not the commonly experienced one?" It would seem to be an eminently reasonable expectation of the educational process and it may even be one we delude ourselves into believing actually happens. When it does not happen, it is easy to assume that the learner is either stupid or lazy.

Empirical Study on the learning of Science.

Over the past 30 years, there have been many studies (Johnstone, 2006) to find out the parts of school science, which seem, from the students' point of view, to be very difficult to learn. The studies have gone further to find reasons for the existence of these problem areas. These areas are set out in table 2.

Table 2. Parts of school science which are very difficult for the students to learn.

BIOLOGY (1980)	CHEMISTRY (1972)	PHYSICS (1975)
Chemical energy from food	Stoichiometry ,mole	Units
Function of enzymes	Balancing equations	Levers and couples
Hormones	Ion-electron equations	Inertia
Aerobic and Anaerobic respiration	Bonding	Resolution of forces
Water transport: diffusion, osmosis, turgor, plasmolysis, cell wall pressure, symbolism	Dynamic equilibrium	Electricity and magnetism electric fields, electromagnetic induction, AC circuits, capacitance, inductance
Genetics	Electrochemistry	How electric motors work
	Reactions of carbonyl compounds	Diodes and triodes
	Hydrolysis, condensation and ester formation	Sound: relating frequency, pitch, wavelength and velocity
	Radiochemistry	Wave/particle duality
		Optics: lenses, magnification

Some of these may have changed since the dates shown above as the curricula have altered, but a persistent core of these remain today. We can ignore these findings and declare that these topics are so fundamental that we must continue with them or we can try to understand the origins of these findings and seek means to make them more accessible. We may also have to face the fact that some of these topics have no place in schools and need to be left till later. This would necessitate a re-examination of the idea of “fundamental”. Much of what we think is “fundamental” may not be based on any logic, but may have arisen by common use from a historical perspective. They may even be artefacts of our own education!

Taking a purely scientific approach, an analysis was done to find common factors among these varied topics to enable the formation of hypotheses. How this was done for chemistry is set out in detail by Johnstone, (Johnstone, 2006).

What clearly emerged from the analysis was the common factor of high information. The content of each topic was rich in information of facts, concepts and specialist language. The solution of problems in these topics involved the manipulation of many pieces of information, some given, some to be recalled as well as strategies to be recalled.

One example from chemistry may suffice to illustrate the general point.

How many grams of chalk would be required to neutralise 50mL of 0.2M hydrochloric acid?

To be recalled or worked out:

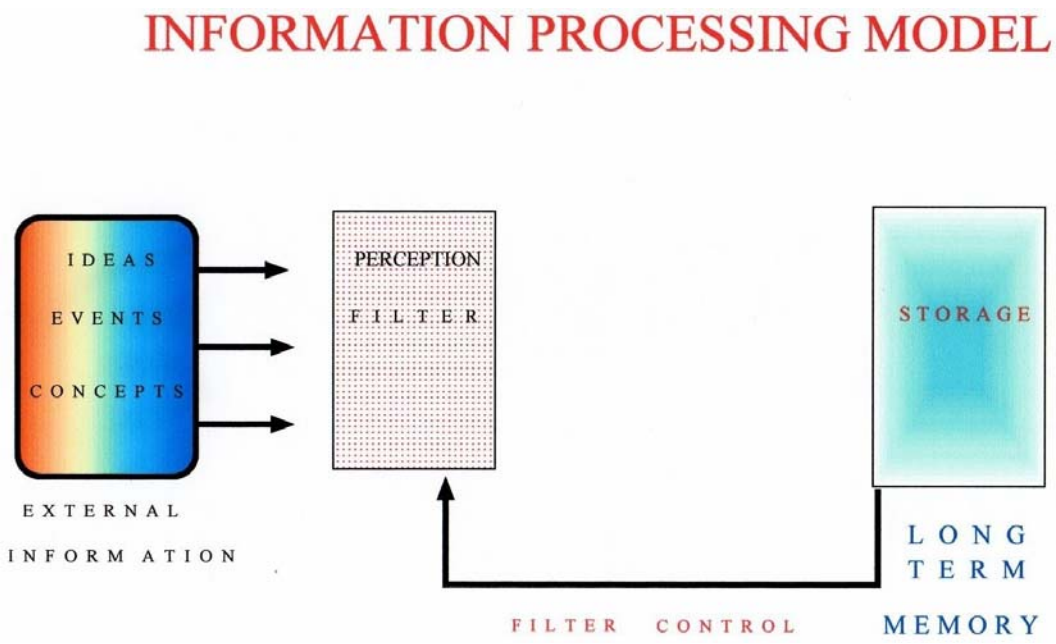
1. Chalk is calcium carbonate
2. Its formula is $CaCO_3$
3. The formula for hydrochloric acid is HCl
4. The products of the reaction are $CaCl_2$, CO_2 , H_2O

5. The balanced equation is: $CaCO_3 + 2HCl = CaCl_2 + CO_2 + H_2O$
6. One mole of chalk will need two moles of acid
7. Number of moles of acid 50/1000 x0.2 =0.01
8. This will be able to neutralise 0.005 moles of chalk
9. 1 mole of chalk weighs 100g
10. Weight of chalk required is 100 x 0.005g
11. Answer is 0.5g chalk

What looks like a simple calculation is not simple at all in terms of the amount of information to be recalled and manipulated? Similar analysis for other topics yielded similar complexity. This drove us to find a theoretical framework in learning psychology to help us to rationalise these findings.

Information Processing Model

Figure 1



This incomplete model (Figure 1) highlights the importance of how a learner initially handles incoming information such as that presented in a lesson. The new information is perceived and filtered in the light of what the learner already knows, believes and understands. It follows that information is not transferred intact from the mind of the teacher to the mind of thee learner. It undergoes an initial selection (filtration) process and what is admitted will vary from person to person. Students with a similar background will tend to select in a similar, but not identical, way.

Let us think about the consequences of this by using a scientific example. Students, who have studied the ideas and conditions for equilibrium in physics, have in mind a set of ideas about balance and static equilibrium, Along with this is a collection of language with specific meaning. Now these students come to a chemistry class and the teacher introduces the topic of equilibrium. Students respond by activating what they learned in physics about equilibrium, but soon they are puzzled because their interpretation of what they are receiving is at variance with what they already know. This results in mental chaos. Table 3 shows the differences between the two treatments of the topic “Equilibrium”.

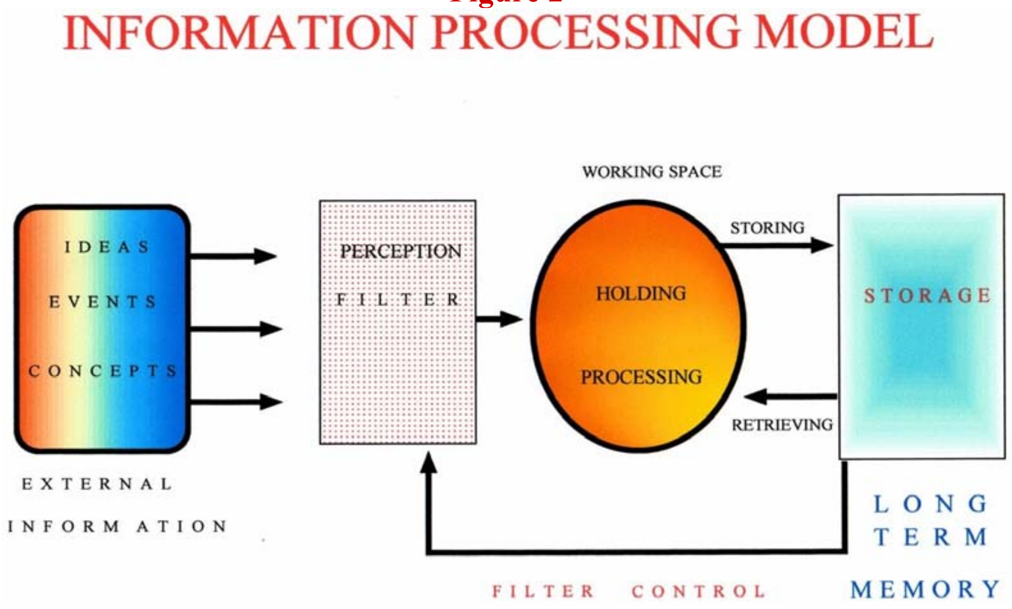
Table 3

Equilibrium Confusion

	Physics	Chemistry
1.	When masses or moments are the same on both sides	Masses or moles need not be the same on both sides
2.	Adding to one side makes the balance tip to that side	Adding reactants "tilts" towards products
3.	A balance has "sides"	There are no "sides" in an equilibrium mixture
4.	You can do something to one side only	Changes of T or P affect both sides
5.	Static	Dynamic

Let us now look at a more complete representation of the model (Figure 2) because we have to consider, not only what the students admit through their perceptive filter, but also what they do with the information.

Figure 2



The information admitted through the filter now goes into Working Space, the part of the mind where new information interacts consciously with what is already known and understood, with the aim of processing it into a form which can be stored for later use (or it can be rejected and discarded as being of no further use because it makes "no sense"). However, this Working Space has a severe limit upon the amount of information it can hold and process at any one time. It operates on a "trade off" system in that, if it has to hold much information it can do little processing or if much processing is required, little information can be held. If the reader casts an eye back to the "simple" mole calculation earlier in this paper, it will become obvious why so few pupils can do even "simple" mole calculations. For most people, the maximum number of pieces of information or operations, which can be successfully manipulated at one time, is five.

Figures 3, 4 show a piece of empirical evidence for this. The data were gathered from

Figure 3

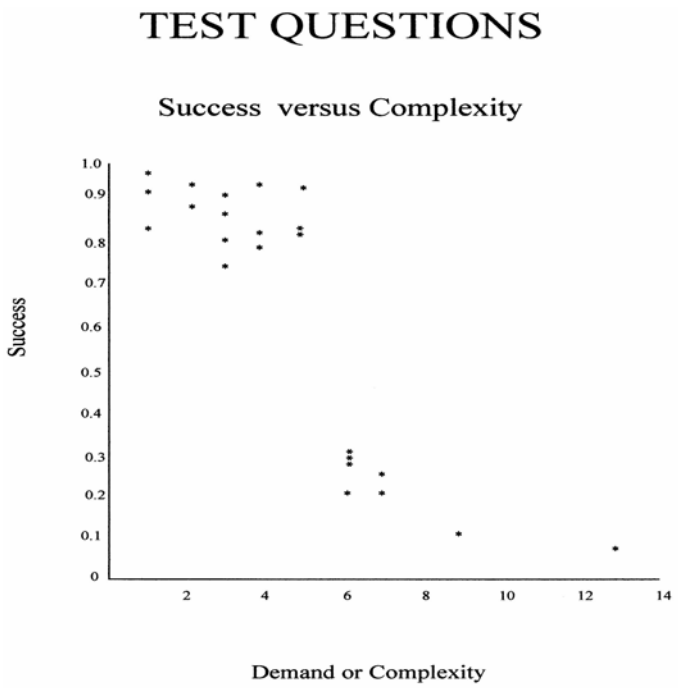
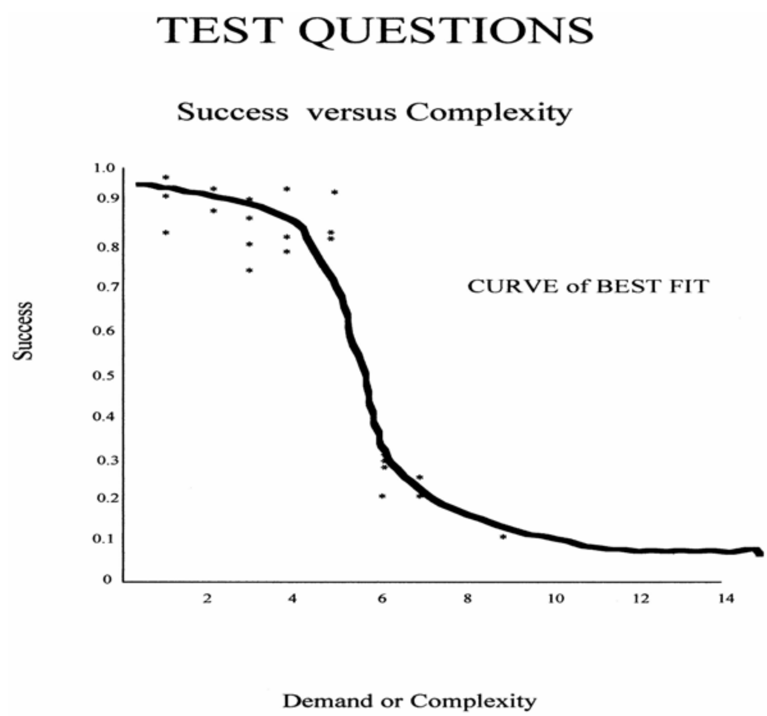


Figure 4



a sample of 20,000 sixteen-year-old pupils in Scottish schools. Twenty-five problem questions were each analysed for their complexity (demand) by adding the number of pieces of information given in the question plus the pieces of information to be recalled plus the operations required to arrive at a solution. The demand is plotted along the horizontal axis and the proportion of the sample achieving the correct answer is plotted on the vertical axis.

As one would expect, the less complex questions get the best response and the more complex get the poorest response (Figure 3), But the decrease in performance is not linear (Figure 4), but rather an "S" shaped curve showing that performance in problems of complexity 5 or less is quite good. However, for problems of complexity greater than 5, the performance drops very rapidly. *The clear implication of this is that, complex problems are no longer testing science, but are testing a psychological artefact, Working Space.*

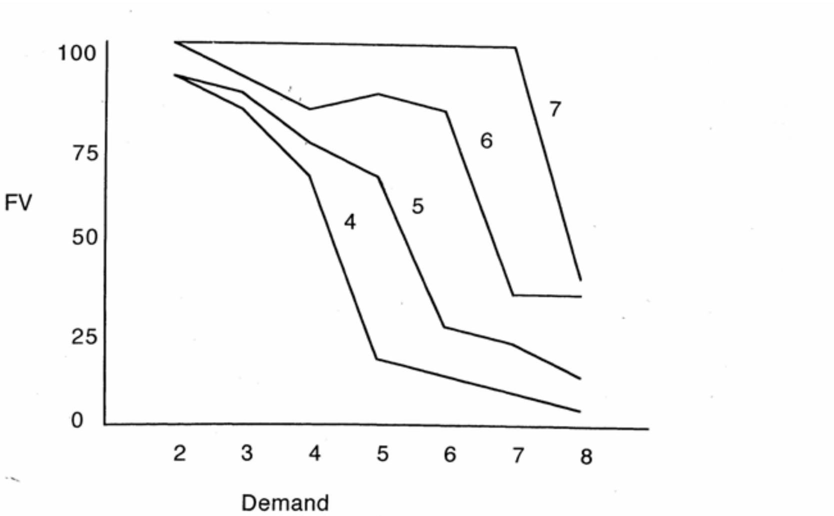
The other thing to note is that performance in complex questions does not drop to zero. A small proportion of the pupils are having success with the more complex questions. There are two reasons for this:

(i) Not all pupils have the same Working Space Capacity. (Figure 5)

(ii) Some pupils have been taught, or have learned for themselves, strategies for reducing the complexity of questions to bring them within the size of their Working Space Capacity. This process is called "chunking".

Figure 5 shows a nest of curves (Tsaparlis, 2000) generated by separating the student performances on the basis of an independent psychological measure of their Working Space Capacity. Students of each capacity begin to perform badly as soon as the complexity of the questions exceeds their capacity.

Figure 5. Facility value versus demand for various working-memory capacities (4-7). The data are for organic-synthesis problems (Tsaparlis, 2000). .



One last look at Figure 2 above, leads us to the box on the right, the Long Term Memory Store.This is a vast store of information: facts, skills, techniques, beliefs, prejudices and attitudes. It is into this store that processed information from the Working Space is placed. It is also the store from which previous ideas are brought out into consciousness in the Working Space to interact with new material coming in through the filter.

The storage process can take three forms:

(i) The new information can be linked correctly to existing material. This storage is successful and has a good chance of being retrieved for later use. The more it is linked with existing experience in a network, the more easily will it be found in the mental filing system.

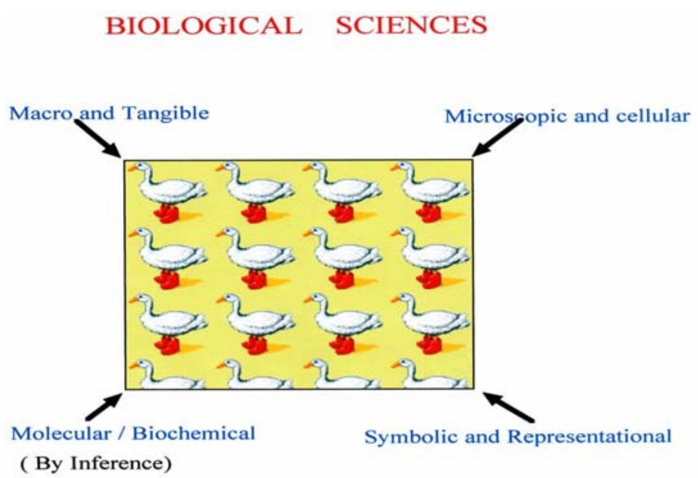
(ii) The new information can be linked incorrectly with existing material. Often language is the source of this trouble. The example of Equilibrium above, is a perfect situation for wrong linkages to be formed and lead to gross misunderstandings. Research in this particular area has uncovered alarming misconceptions. Similar findings have been isolated in topics related to the particulate nature of matter and physical properties.
(iii) Students who cannot find a linkage between their existing experience and the new knowledge resort to rote storage. They try to store information as free-standing, unconnected facts which are difficult to retrieve from the mind's filing system and are often useless for later work. Sadly, many students of science in schools (or even in university) use this rote technique to store unconnected and undigested material, which they can perhaps retrieve for an examination, but can be lost immediately after.

Another related model

The model we have examined above is applicable to any kind of learning, but there are particular problems associated with the learning of the sciences. These stem from the very nature of the sciences.

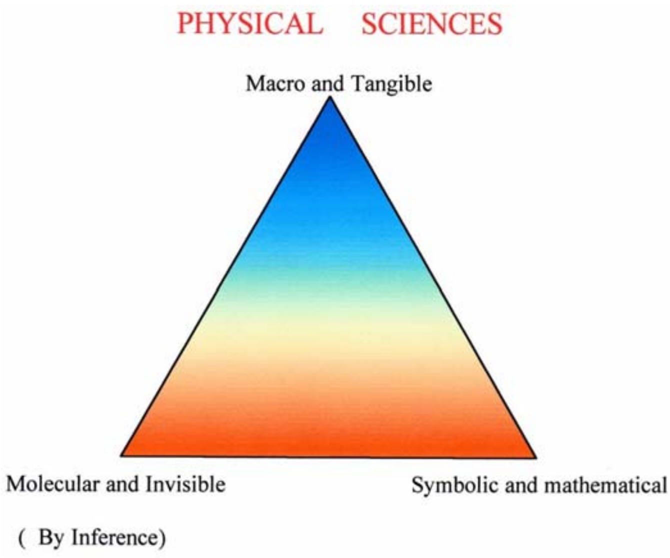
Most of the concepts we develop in everyday living are based on tangible things; things we can touch, see, smell and taste. Although bread comes in various shapes, colours and textures, we can still group them as" bread". The same applies to cars, trees, houses, dogs and flowers. However, concepts such as element, enzyme, atom, gas, resistance, molarity, entropy and many others cannot be constructed directly by our senses. Some are one or even two steps removed from direct sensory perception. Figures 6 and 7 attempt to make visual the various levels on which we operate as scientists.

Figure 6



In the biological example, there are four levels on which we, as practicing scientists, work. These are:
(i) The Macro and tangible, in which pupils can see and touch an animal or a plant
(ii) The Microscopic. We are still directly observing with our own senses, although with the aid of a microscope
(iii) The Molecular/Biochemical which cannot be directly observed and which depends on deductions from indirect measurements.
(iv) The Symbolic, by which we attempt to record or systemise our science using symbols and special language and mathematics.

Figure 7



In the physical sciences, we have three levels corresponding to (i), (iii) and (iv) above, but the emphasis we give them varies between physics and chemistry. As scientists we jump from level to level as we deal with the ideas we are trying to communicate. This is a result of our training and way of thinking and it is very powerful. However, learners cannot do this at first. To try to use all levels in combination is a sure way to overload the pupils Working Space and to bring about poor learning.

To avoid this overload, we must stay with the Macro until pupils have formed new concepts before we attempt to introduce "explanations" based on Micro considerations. Laboratory experiences, to keep things tangible, are essential throughout science education. Almost all the areas of difficulty reported by pupils (see Table 2) and which have been studied by researchers over the past 30 years, are attributable to the early introduction of the levels other than the Macro. It has to be a gradual process by which we lead students into the intellectual world we inhabit.

There is clear experimental evidence that, thinking about our teaching and our students' learning in this way can make large gains in their learning and increase their enthusiasm for science. There are some topics in school and university science, which ought to be removed partly because they serve no useful purpose, since they are no longer of central importance in modern science, or they are so specialised that they are used by only a few scientists for very specific work. This reduction in content would make time for the more gradual establishment of good learning.

Much of what we call Problem Solving is really a measure of pupils' Working Space and could profitably be eliminated.

In summary there are a number of messages from research which, if applied, would make our students' experience of science more meaningful, enjoyable and yet intellectually demanding and satisfying (Table 4).

Table 4. Main Research Messages

- **What we learn is controlled by what we already know**
- **Learners can process only a limited amount of information at one time**
- **Science concepts exist on more than one intellectual level**
- **Many scientific concepts are of a different kind from everyday concepts.**
- **Learners need to start with concepts built from tangible experience and developed later to include inferred concepts.**

Consequences for the curriculum

The ideas set out in this paper have consequences for the curriculum. Some of the ideas could be implemented immediately in any classroom, but there needs to be a complete overhaul of the curriculum to allow all of the ideas to be fully accessible.

The following action is needed by curriculum designers and subsequently by textbook writers:

(i) There needs to be a considerable introductory period in which students get familiar with *thinking in a scientific way through the use of Macro and tangible experiences only*. There is plenty of good science to be learned without the "interference" of sub-micro considerations. In physics, there is much to be learned using nothing smaller than a brick! Chemistry as a macro material science, dealing with the things of every day experience, has much to offer. Biology lends itself wonderfully to the macro experiences of observation, classification, animal and plant care and field and environmental studies.

(ii) To support the ideas of (i), there is good evidence that an *Applications Led Curriculum* is the ideal medium for their achievement. Beginning where the students are and leading them towards the underlying science is very much in keeping with the evidence in this paper. Perception is able to function efficiently because the students recognise the starting point and already have good attachments in Long Term Memory ready to receive the new material.

(iii) There has already been a survey done of the International Science Education literature (Reid and Mbajiorgu, 2006) to distil out the main findings. This should be the basis of any curricular revision. The same learning difficulties have been found throughout the world, suggesting that *many parts of the existing curricula are intellectually unsuitable for students.*

(iv) *Practicing scientists should be consulted* about the science that they have found to be useful (and useless) in their professional lives and to suggest what should be eliminated from curricula and what should be incorporated. Removable of redundant or unsuitable material would give more room for understanding.

(v) *A new approach should be taken to Problem Solving.* Much of what passes for problem solving is so complex that it ceases to measure science and is conflicting with Working Memory space. Group problem solving and problem solving in the laboratory eases the load on working memory and at the same time encourages other desirable skills. (Johnstone, 2000; Johnstone and Al-Shuaili, 2001; Wood, 2006; Yang and Reid, 2002)

(vi) *Examinations*, which are heavily based on multi-step calculations, are almost certainly not measuring scientific ability alone. The validity of such examinations must be in doubt. (Johnstone and Ambusaidi, 2000; Danili and Reid, 2005).

References

To obtain a fuller account of the material in this paper, the reader is referred to a suite of papers produced in Chemistry Education Research and Practice (CERP), Volume 7 issue 2, 2006. The journal is electronic and can be freely accessed at the website: www.rsc.org/Education/CERP This issue contains a wealth of references to enable the reader to follow the evidence more thoroughly. The references below specifically apply to those cited in the text of this paper.

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