NYHOLM LECTURE*

Chemical Education Research: Facts, Findings, and Consequences

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1 Introduction

This is by way of a detective story in which the victims and their complaints are immediately evident, but the search for clues and the emergence of a first tentative hypothesis have taken ten years. Whether solutions for all the problems in such a complex field will ever be found remains to be seen.

In 1969 and 1970 all first-year chemistry students entering the Universities of Glasgow and Strathclyde were invited to respond to a questionnaire about the chemistry courses they had just completed at school. Of the annual intake of 1500 students about half of them had been trained in the Traditional Chemistry Course and the remainder on the Alternative Chemistry Course of the Scottish Certificate of Education Examination Board.[1] They were asked to place each topic of their course in one of four categories defined as follows:

(*a*) Never studied—since there were differences of content between the syllabuses.

(*b*) Easy to grasp—understood from the beginning.

(*c*) Difficult to grasp—understood only after much effort.

(*d*) Never grasped—still not understood after effort;—needs to be retaught.

Category (*d*) results were plotted as frequency against topic (Figure 1). The results for two consecutive years are shown together and there is a remarkable similarity between them when one considers the subjectivity of the responses.

As a test of the validity of these results, it was argued that, if the same questionnaire were given to pupils in their final year at school (a broader spectrum of the ability range), the same peaks of perceived difficulty should appear, but be more intense. This, in fact, turned out to be the case.

The main areas which seemed to be raising the problems were:

(*a*) Energetics—including Hess's Law,
—E°'s and cells;

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*First delivered on 28 February 1980 at University College, London.

[1] Scottish Education Dept., Circular 512, Edinburgh, 1962.

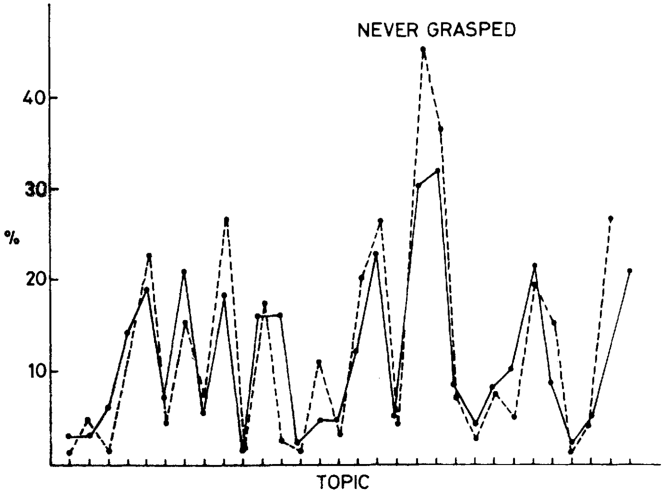

Figure 1

(*b*) Stoicheiometry—writing and balancing equations,
ionic equations,
ion–electron half equations,
moles in solution;

(*c*) Organic—particularly esterification, hydrolysis, condensation, saponification, carbonyl compounds.

A team of researchers began to explore each of these areas in detail by a variety of techniques. The hypotheses which were adopted for each investigation were not tied to any specific school of psychological or educational thought. The aim was to isolate, if possible, the location of the underlying problems in each area and to discover why the problems were there. A mass of data was rapidly accumulated, but it had little clear shape or pattern. However, it gave useful indication of alterations in method and teaching order which led to empirical improvements in learning.

Let us look at some examples of the findings, each in itself of no great consequence, and yet they provided the clues which have led us to propose a working hypothesis of importance to chemical education.

2 The Order of Presentation of Topics

The syllabus and the accompanying texts up to 'O' Grade (15—16 yr) were set out as shown in the left-hand column of Table 1.

In some preliminary work it had been established that pupils did as well if the topics grouped under B were exchanged in order with topics grouped under A.

One further change was made. The block of theory which lay at the beginning of the original version was placed alongside the now reorganized syllabus like a

Table 1

	Original Version	*Experimental Version*		
	Atomic structure	Atomic structure		
	Ionic and covalent bonds	Covalent bonding		
	Binary formulae (ionic and molecular)	Simple binary formulae		
	Equations and balancing	C 4 bonds	B	
	Atomic and molecular weights	N 3 bonds		
	Reacting weights	O 2 bonds		
A	Evidence for ions	H 1 bond		Organic
	Reactivity series	Skeletal formulae		
	Corrosion	Unbalanced equations		
	H^+ and OH^-	First hint of ionic bond		Acids
	Ionic mobility			
	Neutralization		A	
	Mole in solution			
	Acid and normal salts	Ions		
	Precipitation reactions	Ionic formulae		
	Sulphur, oxides, and sulphuric acid	Ionic equations		Corrosion
	Nitrogen, oxides, acids, ammonia, fertilizers	Molecular weights		Neutralization
	Halogens	Mole and balanced equations		
B	Carbon, carbonates	Reacting weights		
	Hydrocarbons	Oxyanions		Sulphur
	Energy foods			
	Alcohol, acids	Ionic equations		
	Proteins			
	Fats, soaps			
	Plastics			
	Silicones			

'soundtrack' down the edge of a film. Only enough theory was introduced at any time to help to make sense of the observations being made in the laboratory. By having the organic topics first it was possible to use only the idea of the covalent bond for several months before it was necessary to introduce ionic bonding. Pupils who followed this experimental programme were compared with similar pupils studying the normal programme and, in every test, the experimental group performed significantly better.[2]

Clue 1. Spreading out the theory seemed to be beneficial.

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[2] T. V. Howe and A. H. Johnstone, Bulletin No. 1. National Curriculum Development Centre, Dundee, 1972, 36—38.

3 The Mole

Much has been written about this.[3–5] Some writers believe it is beyond 'O' level pupils, others advance theories about simple proportion, while others call upon the tricks of new maths or other strategies to solve the problem.

Duncan,[6] investigating the problem, set a series of tests in which the complexity of each question was carefully graded compared with those before and after. In the first test he 'kept his powder dry'—no solutions were allowed to intrude. Pupils were asked to respond to multiple-choice questions in calculating gram formula weights of a series of compounds, given their formulae. The formulae were simply binary ones increasing to those involving oxyanions. The term 'gram formula weight' was then replaced by 'mole' and a similar set of questions was asked. The last stage in the increasing complexity was to ask the questions without supplying formulae. The results for pre 'O' level students were consistently good (about 80%) until the formulae were omitted, when the scores fell to below 20%.

Another text examined the ability to balance and to use equations to find mole ratios in reactions. When balanced equations were supplied results were, on the whole, very good; but the most popular *wrong* answer in every case was that which assumed a 1:1 ratio regardless of the balancing. When students were asked to balance an equation and then use it, performance dropped drastically. In a third test there were a series of questions involving solutions, two of which are shown below with the percentage distribution of student responses shown beside each. The results of these puzzled us until recently.

Which of the following HCl solutions is most concentrated?

A.	500 cm^3 of 2M HCl	5
B.	1000 cm^3 of 3M HCl	19
C.	300 cm^3 of 4M HCl	44
*D.	800 cm^3 of 5M HCl	32

Which of the following solutions contains most NaCl?

A.	500 cm^3 of 2M NaCl	2
*B.	1000 cm^3 of 3M NaCl	41
C.	250 cm^3 of 4M NaCl	5
D.	200 cm^3 of 5M NaCl	52

The work of Cassels[7] has made us much more aware of the part played by language in testing, particularly where words which are familiar in common parlance are used in science with a more precise meaning. The results of those two questions can be explained as follows. In common speech applied to orange

[3] I. M. Duncan and A. H. Johnstone, 'The Mole Concept in Chemistry,' *Educ. Chem.*, 1973, **10**, 213.

[4] M. J. Hudson, 'Introducing the Mole', *Educ. Chem.*, 1976, **13**, 110.

[5] R. Henson and A. Stumbles, 'Mathematics and Chemistry', 1977, **14**, 117.

[6] I. M. Duncan and A. H. Johnstone, 'Chemistry Check-up', Heinemann, London, 1974.

[7] J. R. T. Cassels and A. H. Johnstone, 'Understanding of Non-technical Words in Science', The Chemical Society, London 1980.

juice, for example, 'most concentrated' means 'of the smallest volume', *i.e.* concentrated before dilution. The popular choice of C in the first question was for the smallest volume (300 cm^3). In the second example 'most NaCl' has now deflected pupils either to the *smallest* volume or more likely to the highest molarity. The same phenomenon appears in other similar questions. 'Most' here would correspond to what is normally meant by 'most concentrated' rather than 'largest amount' of dissolved substance.

Clue 2. *High performance* suddenly *dropping to low performance as complexity is systematically increased.*

Clue 3. *There seems to be confusion about the precise use of words.*

4 Ionic Equations

One of the innovations which appeared with the new syllabuses in the 1960's was the use of ionic formulae and ionic equations to describe neutralization, precipitation, and displacement reactions.

$$AgNO_3 + NaCl \rightarrow AgCl + NaNO_3$$

became

$$Ag^+(aq) + NO_3^-(aq) + Na^+(aq) + Cl^-(aq) \rightarrow AgCl(s) + Na^+(aq) + NO_3^-(aq)$$

which reduced to

$$Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$$

Acid-base reactions shared the common phenomenon

$$H^+(aq) + OH^-(aq) \rightarrow H_2O$$

This simplification and rationalization appealed to teachers and it was widely adopted.

Garforth[8,9] was not convinced that they appealed to pupils and set out to explore the situation from the pupils' point of view. It turned out that pupils preferred to use the 'old fashioned' molecular equations rather than the simple net ionic equations.

The reaction of silver nitrate with sodium chloride did not seem to them to be adequately represented by

$$Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$$

The intermediate full ionic equation was not at all popular with pupils. To arrive at the net ionic equation, pupils had to go through the full ionic equation, decide what information was redundant, and then discard these 'spectator ions'. The problem was that, to perform this last step, their concept of ionic reactions had to be well developed and linked to a good working knowledge of solubility rules.

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[8] F. M. Garforth, A. H. Johnstone, and J. N. Lazonby, 'Ionic Equations and Examination at 16+', *Educ. Chem.*, 1976, 13, 41.

[9] F. M. Garforth, A. H. Johnstone, and J. N. Lazonby, 'Ionic Equations—Difficulties in Understanding and Use', *Educ. Chem.*, 1976, 13, 72.

Clue 4. To arrive at a simplification involved going through a more complex stage than the 'molecular' equation.

Out of the same piece of work came another clue. Pupils aged 15, 16, and 17 were set the same test involving ionic equations for neutralization, precipitation, and displacement reactions. The results are shown in Figure 2.

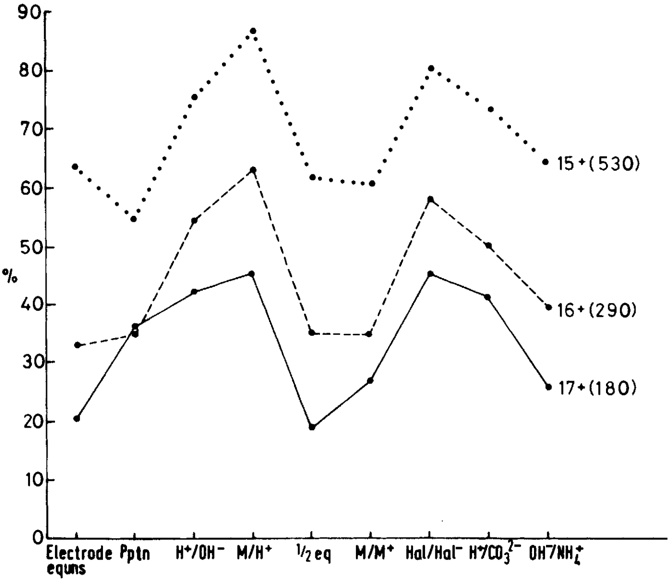

Figure 2

There is an improvement in performance with age, but this may be due to the fact that the selection process at 'O' level has eliminated the weaker candidates at 15+. The fact that the three graphs are almost parallel shows that, what was difficult at 15, is still relatively difficult at 17. On the face of it, none of these test items should be difficult for a 17-year-old and yet there seems to be a 'hangover' from their experiences at 15. This 'hangover' effect was also observed in other parts of our work.

Teachers were asked to estimate how well their pupils would do on the test before the test was attempted by the pupils. Their estimate and the pupils' actual performance are shown in Figure 3.

Teachers who were confident in the use of ionic equations and were keen on their use consistently overestimated their pupils' performance.

Clue 5. Early unsuccessful introduction of a topic may set up insecurity for later learning.

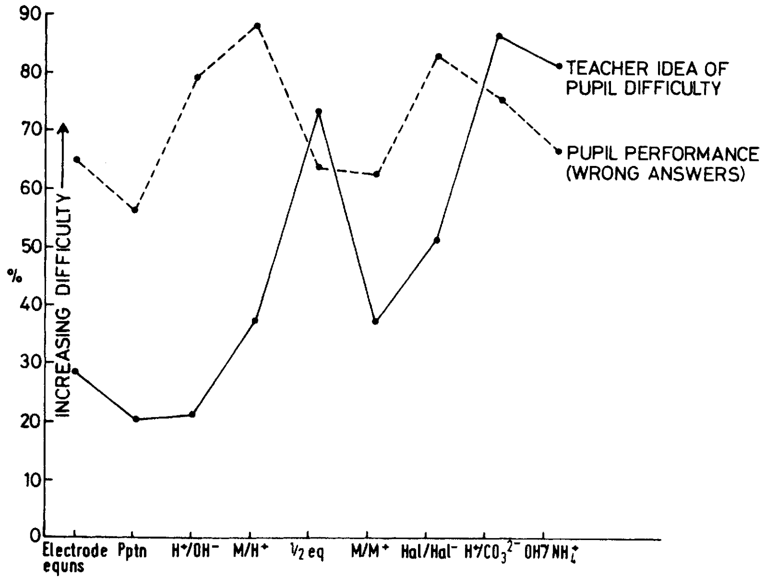

Figure 3

5 Organic Topics

The organic topics which were most often reported as difficult were esterification, hydrolysis, condensation, saponification, and carbonyl compounds. Our first hypothesis was that this was purely an optical effect brought on by writing formulae in a variety of ways and orientations. This was soon shown to be untenable.

A second hypothesis proposed[10] that the students' perception of functional groups was weak. To test this idea a strategy was proposed involving the short-term memory.

If one is shown a series of letters such as AVPNSB and asked to memorize them and reproduce them, this task is well within memory capacity. However, if the list is extended to MQCSLOXBNFZD, the task is normally beyond capacity. Another twelve letter sequence such as CATFINHOPDEW is well within capacity for English speakers because the twelve pieces of information cluster into four words. Miller[11] and many others[12,13] have noted that short-term memory capacity is about 7 ± 2 pieces of information, but what constitutes a 'piece' depends upon the existing knowledge of the individual. Presumably, for non-

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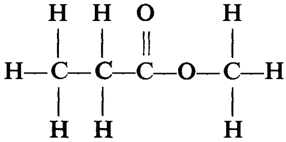
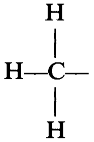
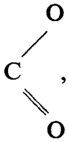
[10] A. H. Johnstone and N. C. Kellett, 'Towards a Working Hypothesis in Science Education', *European J. Sci. Educ.*, 1980, **2**, 175.

[11] G. A. Miller, 'The Magical Number Seven, Plus or Minus Two: Some Limits on Capacity for Processing Information', *Psychological Review*, 1956, **63**, 81.

[12] P. H. Lindsey and A. A. Norman, 'Human Information Processing: An Introduction to Psychology', Academic Press, New York, 1977.

[13] H. A. Simon, 'How Big is a Chunk?', *Science*, 1974, **183**, 482.

English speakers, the second of the twelve letter sequences would be as difficult as the first because they would have no previous knowledge by which to organize the letters by increasing the size but decreasing the number of pieces. This seems a far cry from organic chemistry but the link will now become apparent. Consider a structure such as  $\begin{array}{ccccccccccccc} & & H & & H & & O & & & & H & & \\ & & | & & | & & \| & & & & | & & \\ H & - & C & - & C & - & C & - & O & - & C & - & H \\ & & | & & | & & & & & & | & & \\ & & H & & H & & & & & & H & & \end{array}$. If someone who knew no chemistry was presented with this structure for ten seconds and then was asked to reproduce what he saw, the task would be well beyond his capabilities. Another subject with some slight knowledge of chemistry might group the  $\begin{array}{ccc} & H & \\ & | & \\ H- & C & - \\ & | & \\ & H & \end{array}$ into CH_3 and so reduce the load but the total task would also be beyond him.

A third person with a sixth-former's chemical knowledge might group the formula as C_2H_5,  $\begin{array}{cc} & O \\ & / \\ C & \\ & \backslash\backslash \\ & O \end{array}$, and CH_3, reducing the load to three pieces, and so bring the task of memorizing and reproducing the formula well within his short-term memory capacity. An experienced organic chemist would see the structure as one unit (methyl propanoate) and would be able to store and reproduce probably five or six entire structures.

These assumptions were tested with various groups of people and found to be substantially true.[14,15] If a student could not arrange a given formula into its functional group (or groups) and the remainder, it is little wonder that he found difficulty in the areas of esterification and hydrolysis and confused carbonyl, carboxyl, and amide groupings. In other words, a student's perception of what is being taught will affect how he learns, stores, retrieves, and interlinks the new material with the old.

With this new insight we began to go back over the areas of reported difficulty to look for what amounted to an overload of the working memory—the part of the mind in which recalled and new material interact in the process of thinking, reasoning, and learning. If this working area is of finite size, what phenomena would we expect to find if we presented students with problems or learning situations of increasing load? Where the size of the load was small we could expect a good response to problems. As this load increased we might still expect

[14] N. C. Kellett, 'Studies on the Perception of Organic Chemical Structures', Ph.D. Thesis, University of Glasgow, 1978.

[15] J. I. Thomson, 'Perception of Organic Functional Groups at the School/University Interface', B.Sc. Thesis, University of Glasgow, 1980.

good performance provided the load was within the capacity of the working memory. However, as soon as the load exceeded this upper limit, performance would drop suddenly. Some questions would be tackled successfully by most students [the question is said to have a high facility value (F.V.)] while others would have a low F.V. There would be no questions performing between these two extremes (Figure 4).

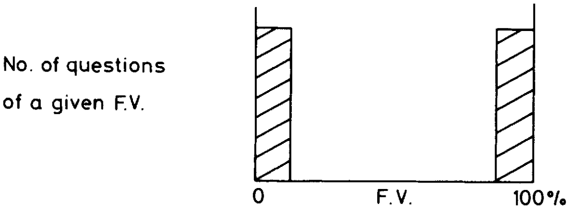


Figure 4

Going back to Duncan's work on the mole,[6] this is just what we found. Beyond a certain demand there was a sudden drop in performance. In practice, since the capacity of the working memory may be 7 ± 2 pieces of information the diagram would not be as sharply defined as above but rather as shown in Figure 5.

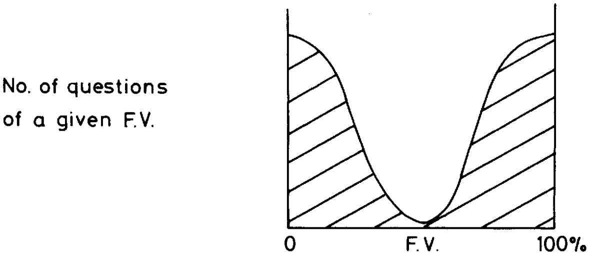


Figure 5

Combing through our earlier results has yielded curves of this kind which strengthens our belief that we are often dealing with problems of working memory overload.

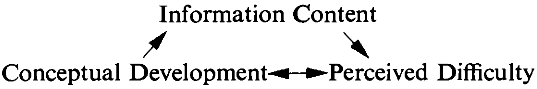
Looking back at the clues highlighted earlier in this article we have some evidence for the same phenomenon. The first clue indicated that, where specific theory had to be recalled (and selected from a mass of irrelevent theory) to be applied to an experimental situation, the process was inefficient. Where theory strictly relevant to the experimental situation was introduced the learning appeared to improve.

Where there was confusion about the meaning of words there was almost certainly an increase in the learning or problem-solving load. In some of Cassels' work, pupils were baffled by the word 'fused' when applied to sodium chloride. Questioning revealed that 'fused' meant 'extinguished' (when applied in common parlance to lights going out). The idea that something had 'melted' had not occurred.

The fourth clue showed that pupils would not choose a 'simplified' version of an equation if it meant going through a highly complex stage which could only be reduced by recall of further information.

The fifth clue leads to an extension of our ideas. The feelings of insecurity generated by repeated exposure to 'overload' situations have a long-term effect which may well colour any further learning in that area or even in that subject. It is not an uncommon observation among those who teach at tertiary level that students are still insecure in some areas of chemistry, such as elementary chemical calculations, well beyond the stage where they are showing quite sophisticated thought in other areas of the subject.

In a paper of this length only representative examples of findings can be quoted, but similar examples have occurred many times in our investigations which only serve to strengthen our belief that there is a fundamental connection between information content, the state of conceptual development, and a student's perceived difficulty.



If a pupil's concept is well developed he can group a situation of apparently high information content into a small number of chunks or units. Further, he can sequence these units or even declare some of them redundant to his present purpose, for example in a problem-solving situation. Under these circumstances he will not perceive the problem as a difficult one.

Let us look at the possible combinations of information content (high and low), conceptual development (high and low), and perceived difficulty (high and low) (Figure 6). Two of these combinations are not tenable. For example, a pupil placed in a *high*-information learning or problem-solving situation while his conceptual development is still *low* will *not* perceive the problem as *easy*. Two other combinations are possible but unlikely. A pupil in a low-information

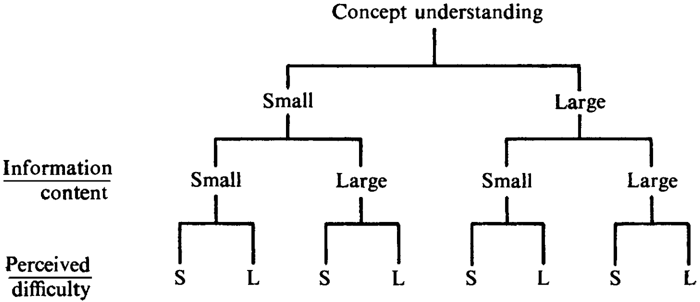


Figure 6

situation while his concept development is low will be more likely to perceive the task as easy rather than difficult. Figure 6 can therefore be redrawn as Figure 7.

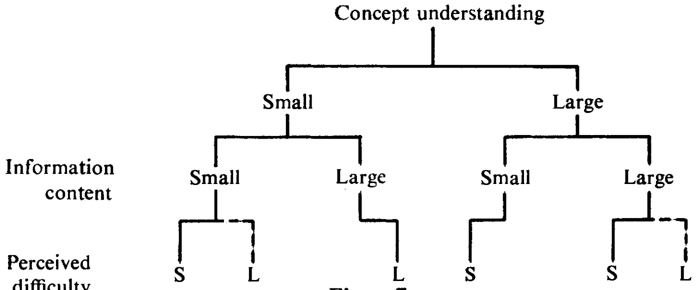


Figure 7

The dotted lines show the less likely combinations. Of the remaining four 'strong' routes through this diagram only *one* of them leads to high perceived difficulty—a pupil placed in a high-information situation while his concept development is still low. The reader may see this for what it is: plain common sense. Why then are so many teachers at all levels creating in so many students areas of chemistry which are perceived to be so difficult? Does the problem lie with the teaching methods, or is it a consequence of the nature of the science itself, or is it a function of the teacher's distance from the learning situation dulling his sensitivity? Earlier in this paper evidence was shown of teachers' lack of success in predicting their pupils' difficulties. Had this been an isolated measurement we should not have dared to mention it but it has occurred time and again in all areas of our research. Clearly there is no single answer and the problem lies in a combination of all three factors. This can be summed up in the 'Concorde' diagram in Figure 8.

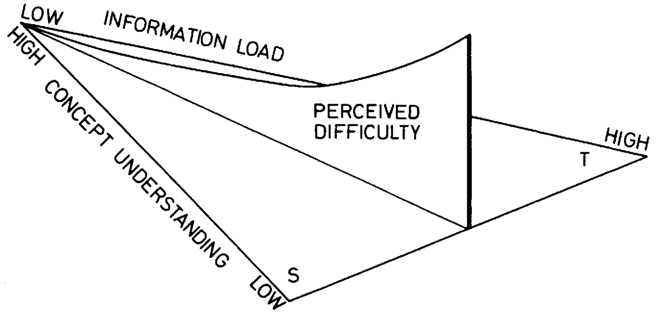


Figure 8

Where high concept development and low information content meet, perceived difficulty will be at a minimum. This will rise to a maximum as concept development decreases and information content increases.

A pupil beginning a new topic will be at position S in the diagram. If the teacher presents the material in such a way as to be at position T the pupil at S will be unable to 'see' what is going on and will regard the topic as difficult. If the teacher persists at position T the 'tail' barrier may rapidly become an attitudinal one converting the student view from 'I cannot understand' into 'I shall never understand', laying the basis for the hangover effect we observed so often.

If the teacher presents the topic at the low end of the information-content axis, the pupil at S will 'see' what is going on and will move along the concept-development axis to its higher end. As he does so, the teacher can increase the complexity of the information but the pupil from his new position will be able to keep it in sight. In fact, as the pupil's conceptual development increases, the information load can be broken into units so that the perceived load may be seen almost as a constant; that is a constant number of chunks. Thus the structure of glucose will be perceived by the student as little more complicated than ethanol did when he was a beginner.

Again the reader may dismiss this as common sense, but the inescapable question returns—why do students perceive so much difficulty in chemistry if teachers are following such common-sense procedures?

One only has to observe teachers in action to find the answer.

I am grateful to a colleague[16] for permission to use the script of his videotape which attempts to portray how a set of instructions for a chemistry practical lesson must sound to a pupil.

IIIC were still on their feet, sorting themselves out, when Mr. Dixon strode into the lab. As usual, he wasted no time in getting under way . . .

> "All right, get in your seats. Come on, settle down. Now I promised you last day we were going to carry out a practical today. Unfortunately, the headmaster has decided to call an early stop, so we are down to one period and we've got to get it all done inside this one period, so we can't afford to waste any time."

He cleared his throat.

> "As I promised last day we are going to try and follow a reaction using the calanthropic technique. Now, you've heard about this before, but you've never done it. What we are going to do is, we are going to study the reaction between solanol ditrate and digitis mitronide. We are going to measure the calanthropy and follow the reaction by the changes in calanthropy that accompany the reaction. Now, obviously we need a wee revise about how we measure calanthropy."

He moved round to the front of the demonstration bench, leaned back against it, and continued in the voice that his pupils recognized as the one he used when he expected them to pay particular attention.

> "We are going to take 10 winceyettes of solanol ditrate and put it in a

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[16] D. MacFarlane, 'Solanol Ditrate', Journal No. 16, Scottish Curriculum Development Service, Dundee, 1979, 48—51.

> calanthropy tube. Once it is in the calanthropy tube then you're simply going to measure the calanthropy, drop in the sphere—"

his hand flicked through the air and he made a clicking noise with his tongue—

> "that's you got your zero point. Once you know the calanthropy of the solanol ditrate then any changes in that figure from then on are going to reflect changes in the chemical reaction. Now, we'd better check that you know what's happened."

He moved himself off the bench, reached sideways, without looking, and picked up a piece of chalk. He was at the board and writing as he spoke again . . .

> "We're starting off with a solution, solanol ditrate. We're adding digitis mitronide. Now it is very clear, eh . . . George, you know what we get."

George had been paying attention:

> "Solulation!" he said.
>
> "Right!" said Dixon, "You get a solulate of solanol mitronide. *That* doesn't have any effect on the calanthropy, but you're left with a solution of digitis mitron. . . . Wait! Now I've got mixed up. George, what is it?—that's right, digitis ditrate. Now you are quite clear that the digitis ditrate has a lower calanthropy than the solanol ditrate?"

One or two nodded.

> "Now we are not interested in finding *that* out. We *know* that if you carry on measuring the calanthropy, it is going to get faster. We're not interested in that. We're interested in whether it continues to get faster, or if it stops and reaches a constant calanthropic value, or if it increases again, in other words gets slower. Now when you've carried out the reaction you're going to have a series of ordered pairs."

He constructed two columns on the blackboard and quickly inserted dashes as entries.

> "You're going to have figures for the number of winsters of the digitis mitronide you've added, and you're going to have a series of your measured values of calanthropy. Now we're sure about that? You're going to take the solution of solanol ditrate; you're going to measure its calanthropy, and you're going to take the berridenes, and you're going to add digitis mitronide, one winster at a time. Give it a good stir after each addition and measure the calanthropy."

He stirred something in the air in front of him.

> "There is only one problem you're going to have, and that is that the berridenes you're using with the digitis mitronide are going to react with the solanol ditrate. You've had that problem before, so you mustn't let them come into contact with the solanol ditrate, or you'll get a reaction that isn't this one. And obviously any change in the calanthropy if your berridenes are

> reacting with solanol ditrate won't reflect the changes caused by this reaction.
>
> Now, I think I've covered the whole thing."

He paused to glance round the class. He could usually tell when IIIC had understood his instructions. Reassured, he wound it up quickly . . .

> "What I want you to do now, before you start the practical, is write down exactly what I have told you to do, in sequence, every step you are going to carry out, written down, so that *I* know what you're going to do. All right? Get on with it."

How many thousands of times a day must such situations occur in schools, colleges, and universities? The teacher is not trying to be obtuse, but he is so familiar with the work that he forgets the first-time learner. The point of the experiment may be simple, but what is forgotten is that the welter of preliminaries, precautions, new skills, and new language can completely obscure the point of the experiment from the learner. He does not know what is vital and what is trivial because the experiment is being used to develop the very concept the pupil needs to unravel the experiment. This is a vicious circle which must be broken if the lesson of the experiment is to come across clearly to the pupil.

This overload phenomenon is not confined to practical work. Here is an excerpt from a new school book[17] in which the authors 'recommend that the bulk of the material presented here should be experienced, learnt and *remembered* before the Principles course is begun'. The following quotation is from page 2!

> 'The metallic properties of conductivity and reflectivity result from the freedom of movement of these valence electrons. Metals, in the solid state, are a regular arrangement of positive ions in a continuous volume of free valence electrons whose boundary is the crystal itself. There is little resistance to the movement of these electrons, since neighbouring atoms have low-energy unfilled valence orbitals through which the electrons can move. Hence metals have high electrical conductivity. Covalent solids (*e.g.* diamond) and molecular solids [*e.g.* ice, iodine (I_2) and organic solids] have their electrons fixed in covalent bonds and non-bonding electron pairs, while in ionic solids the electrons are fixed on the individual ions. In these solids, since their valence orbitals are filled, there are no low-energy orbitals into which conduction electrons can move. The forces which bind a metal are the forces of attraction between positive metal ions and the 'sea' of valence electrons. This type of bonding is known as 'metallic bonding'. These forces are not greatly changed by mechanical distortion of the metal, and hence most metals are both malleable and ductile.'

Not one term is defined and idea is piled upon idea relentlessly. This single paragraph more than overwhelms the working memory and almost certainly has the effect of making the learner switch off. This criticism is not confined to this

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[17] A. R. H. Cole, D. W. Watts, and R. B. Bucat, 'Chemical Properties and Reactions', School of Chemistry, University of Western Australia, Perth, 1978.

particular book. Few basic chemistry texts can stand close scrutiny of this kind.

Examination questions are often devious in their presentation while the ideas which they are testing are trivially simple. If the working memory is clogged with minutiae and the student answers incorrectly, how can the question test the real point? One example will suffice:

> 'Concentrated ammonia contains 34.0% ammonia by weight and has a density of 0.880 g ml^{-1}. How many gallons of this solution would be needed to neutralize 10.0 lbs of 95% sulphuric acid?'
>
> (1 lb = 453.6 g; 1 gallon = 4.545 litres)

6 Consequences

If the findings cited in this paper are not just isolated incidents, and if the working hypothesis which has been put forward has any validity, there must be consequences for teaching chemistry which should at least be considered.

1. The whole structure of laboratory work must be examined and some tacit assumptions about practical work questioned.

Laboratory manuals of the kind used in undergraduate teaching may positively militate against useful learning. The fact that students are accused of following them line by line with little understanding is more likely to be a condemnation of the form of the manual rather than of the student. Faced with a close-typed welter of information, recipe-following is all a student can reasonably do. In the middle of the verbal 'wood' the student is in no position to observe the beautiful symmetry of the 'forest'.

A number of workers[18-20] have attempted to measure how well the objectives of practical work are transmitted. Their sad findings have inevitably been that little head knowledge (as opposed to hand skills) has come across during practical sessions. It may be that the most efficient way to illustrate (or generate) theory is through practical demonstration during a lesson.

2. The structure of chemistry texts (often cubic close packed) requires careful examination. There is no merit in writing a text in the style of the old *Quarterly Reviews*, saving words and cutting corners. The level of language demand, particularly of language which in common parlance has a different meaning, must be carefully controlled. An unfamiliar or misunderstood word represents at least one chunk in the information load. Teachers at all levels would do well to consult the word lists in the recent RSC publication 'Understanding of Non-technical Words in Science'.[7]

3. Exam-question setters must also be clear about what they are testing and design questions to test that unambiguously and uncluttered by extraneous

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[18] A. H. Johnstone and M. McCallum, 'Objectives in Practical Work', Proceedings of the Education Division of the Chemical Society, Nottingham, 1972.

[19] A. H. Johnstone and C. A. Wood, 'Practical Work in its own Right', *Educ. Chem.*, 1977, **14**, 11.

[20] A. H. Johnstone and A. J. B. Wham, 'A Model for Undergraduate Practical Work', *Educ. Chem.*, 1979, **16**, 16.

material. This applies as much to multiple-choice questions as to longer ones. Tutorial problems can also come into the category of being too clever. Students who have tried to grapple with them become discouraged and resentful. Often the basic ideas are simple but wrapped in obscurity of language or format.

4. The sequence of a course may also be critical, because the new material which we try to learn is coloured by what we already know. Our ability to group and sequence new information is controlled by our present corpus of knowledge and experience.

Some analysts of chemistry courses[21] have declared some parts of them unteachable by using a Piagetian, developmental model. It is just as likely that material is unteachable because the correct pre-knowledge and experience, within which the pupil requires to group, sequence, and store the new information coming in, is missing.

Much fundamental work is needed here to provide chemistry teachers with some rationale for curriculum construction. The present 'controversy' between the 'Back to Basics' and the 'Principles' schools is likely to be a fruitless endeavour unless we recognize the structure of human thinking and teach accordingly.

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[21] M. Shayer, 'How to Assess Science Courses', *Educ. Chem.*, 1970, 7, 182.