The Higher Education Academy Physical Sciences Centre

ISBN 1-903815-16-9

Factors Influencing Curriculum Development in Chemistry

A Physical Sciences Practice Guide

Ngozi Mbajiorgu
and
Norman Reid
March 2006

RS•C ROYAL SOCIETY OF CHEMISTRY

Tertiary Education Group

Physical Sciences Centre
Department of Chemistry
University of Hull
Hull HU6 7RX
Phone: 01482 465418/465453 Fax: 01482 465418
Email: psc@hull.ac.uk Web: www.physsci.heacademy.ac.uk

Report of a Literature Review. Factors Influencing Curriculum Development in Chemistry

Ngozi Mbajiorgu and Norman Reid
Centre for Science Education
University of Glasgow

Published by the Higher Education Academy Physical Sciences Centre

Contents

Introduction

This report presents a summary of the main findings from the science education research literature. These findings are used to offer guidance in developing a curriculum in chemistry both at school and higher education levels. It is recognised that the purposes for chemistry education at school level are, in many ways, different from those for higher education.

The overall evidence from the research literature is brought together under four headings:

Chemistry for Whom?
What Chemistry?
How to be Taught?
How to be Assessed?

From this, an attempt is made to develop a set of specific guidelines. These are offered as a set of ***landmarks*** which will define the territory of curriculum design as applied to *school chemistry*. A separate, but overlapping, set of ***landmarks*** is then presented for chemistry in *higher education*.

Curricula constructed following these guidelines are likely to match the needs of learners, their aspirations and requirements. For school level, a very important aspect of this will be the aim to develop responsible citizenship and a population which can make informed decisions based on a sound understanding of the chemical issues involved. For undergraduates, an important aspect will be the need to develop the skills required for a very wide range of career opportunities.

The bibliography and the report do not cover all aspects of science education: thus, for example, culture and worldview and their different ramifications are not discussed. Nonetheless, research findings made in other countries are not neglected as we have consulted major international science education journals. We have concentrated on issues of curriculum development and design in Britain, addressing issues that have, over the years, been prominent and of influence in chemistry education. We have confined the search to the areas we think are necessary for curriculum design and development: the areas we considered can be used for guiding selection of goals of chemistry education, content selection and sequencing and assessment.

We have looked at the nature of and approach to the teaching of chemistry, problem solving in chemistry, laboratory work in chemistry, assessment in chemistry education, students' attitudes related to chemistry education, theories of science/chemistry learning and psychological theoretical underpinnings

The aim throughout has been to base all recommendations on the ***clear evidence offered in the research literature***.

Appendices offer an annotated bibliography and details of the journals consulted.

We are grateful to Stuart Bennett, Alex Johnstone and Tina Overton for helpful comments on earlier drafts.

Ngozi Mbajiorgu
Norman Reid
March 2006

Executive Summary

The aim has been to bring together the evidence from empirical research and to use this evidence to define a set of clear guidelines to inform future curriculum planning. Thus, the recommendations are ***not*** based on opinion or experience but attempt to reflect what is clearly demonstrated empirically.

The chemistry curriculum should:

1. *Meet needs of all learners*	Meet the needs of the majority of school pupils (who will never become chemists or even scientists), and most students who will undertake chemistry degrees but never become bench chemists. Thus, the curriculum must seek to educate *through* chemistry as well as *in* chemistry.
2. *Relate to life*	At school level, be strongly 'applications-led' in construction, while university courses should relate tightly to applications.
3. *Reveal chemistry's role in society*	Reflect attempts to answer questions like: what are the questions that chemistry asks? How does chemistry obtain its answers? How does this chemistry relate to life?
4. *Have a low content base*	Not be too 'content-laden', so that there is adequate time to pursue misconceptions, to aim at deep understanding of ideas rather than content coverage, and to develop the appreciation of chemistry as a major influence on lifestyle and social progress.
5. *Be within information processing capacity*	Not introduce sub-micro and symbolic ideas too soon or too rapidly; avoid developing topics with high information demand before the underpinning ideas are adequately established to avoid overload and confusion.
6. *Take account of language and communication*	Be set in language which is accessible (especially at school level) and offer learners opportunities to express chemical ideas verbally and in writing (especially at university).
7. *Aim at conceptual understanding*	Be couched in terms of aims which seek to develop conceptual understanding rather than recall of information, being aware of likely alternative conceptions and misconceptions.
8. *Offer genuine problem solving experience*	Offer experiences of more open-ended problems (along with algorithmic exercises), with emphasis on the use of groupwork to solve 'real-life' problems in chemistry.
9. *Use labwork appropriately*	Involve laboratory work with very clear aims: these should emphasise the role of labwork in making chemistry real as well as developing (or challenging) ideas rather than any focus on practical hands-on skills; labwork should offer opportunities for genuine problem solving.
10. *Involve appropriate assessment*	Involve assessment which is integrated into the curriculum and reflects curriculum purpose, is formative as well as summative and aims to give credit for understanding rather than recall, for thinking rather than memorisation.

Pages 18 and 19 expand this list of recommendations based on research evidence in terms, respectively, of school chemistry and university chemistry.

Main Conclusions from Research

The Nature of Chemistry

Chemistry, like the other science disciplines, operates at three thought levels: the macro, the micro and the symbolic (see Figure 1). The macro refers to the phenomenological: what can be perceived by the senses without the aid of instruments. This is usually concrete. The micro refers to that which can only be perceived with the aid of instruments or that which is abstracted by inference from chemical processes. This is often abstract. The symbolic refers to symbols, models and equations and these are often representational. The micro and the symbolic interpret the macro. These interact and have to be manipulated skilfully for understanding to take place. The novice learner has great difficulty in working at all three levels at the same time, almost certainly because of information overload.

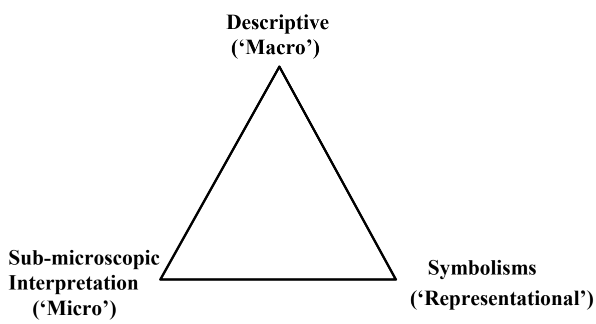

Figure 1: Three levels of science concept representation (Source: Johnstone, 1991)

Language and Structure of Chemistry

The language of chemistry is another important aspect of its nature. This can be considered from different perspectives. One perspective is its discursive characteristics. Whereas social discourses are characterised by being personal, theory constitutive, anthropomorphic, speculative and animistic, the language of chemistry is often impersonal, descriptive, transmissive, objective and labelling. Again, everyday language often assumes an operational meaning in chemistry. In order words, the technical language of chemistry is actually composed of words that have common sense conceptions. This interaction leads to confusion and influences performance of the students. It is important to build chemical language in line with social discourse.

Chemistry language has high information density. This implies that the language is often of the content type. It is claimed that, while every day discourses have about 2-3 content words per clause, chemistry often has between 10-13. We have also noted that the micro level, where chemistry is often focused, involves processes of abstraction. This has an effect on the language of chemistry. The process of abstraction is achieved by nominalisation of actions and events and this often obscures meaning and introduces ambiguities.

The fact that the process of abstraction is inherent in chemistry indicates that there is structure in its semantic representation. This implies there are basic levels of abstraction and therefore there are basic concepts. The presence of semantic categories is an issue of great importance in the chemistry curriculum. This hitherto has not been given adequate attention. For example, school students (and maybe some university students) do not understand phenomena from a particle view. The particulate view contradicts students' intuitive and everyday view of matter as continuous. The concepts of chemical reactions, chemical bonds, conservation and structure of matter should be understood by students before they go on to other concepts. There are specific problems associated with the use of normal English words in a specialised sense in chemistry

Finally, chemistry boasts numerous models for each concept. Again this should be considered in any curriculum planning. The models should be scrutinised with great care because most derive from the perception of single or few authors of textbooks and do not necessarily represent expert conceptions. Again, the presence of different models explaining one concept leads to confusion both on the part of the teachers and students.

Alternative Conceptions in Chemistry

Research is unequivocal about the presence of alternative conceptions in chemistry. Students have developed these conceptions as a result of their interaction with physical substances in nature. Many of the alternative conceptions are related to students' understanding of the chemical substance, particle kinetics and chemical change.

Research has revealed that these alternative conceptions are resistant to change but that they nonetheless can be changed over a long period of time. For chemistry, however, it has already been noted that misconceptions relating to chemistry knowledge and its explanation is rife. The best way to handle alternative conceptions or misconceptions is to create cognitive conflict or through the use of anomalous data.

Teachers need to check what conceptions students bring to their chemistry learning and to set up opportunities for these to be discussed and challenged as necessary. It has to be recognised that this is a time consuming process. It will depend on questioning, discussion, group work and time allowed for learners to 'play with ideas'. In the long run, this time will be well spent but it does demand a content reduction.

Problem Solving in Chemistry

Given the nature of scientific activities, that is its nature as a process, the place of the skill of problem solving in any scientific endeavour (at all levels) cannot be questioned. However, literature reveals that its conception as a generic skill that can be taught is in question. Research has unequivocally demonstrated that the difference between expert and novice problem solving ability is greatly dependent on the extent of domain knowledge they possess. Thus, experts are better problem solvers because they have acquired a great deal of domain specific knowledge. The presence of extensive domain specific knowledge enables an expert to chunk information into manageable units as well as pick out important information while ignoring redundant material. It also determines the criteriality of features, propositions and other relations. Thus, novices use sensorial or surface features in analysis whereas experts use other features or criteria such as causal relations, functional relations, internal consistency across objects or problems etc. This has led to the emphasis on formation of background knowledge and formation of schema rather than the teaching of problem solving skills.

Deriving directly from the above is the use of the different types of problem solving. These have been organised into a scheme of eight as shown in Table 1.

Type	Data	Method	Goals	Skills Bonus
1	Given	Familiar	Given	Recall of algorithms.
2	Given	Unfamiliar	Given	Looking for parallels to known methods.
3	Incomplete	Familiar	Given	Analysis of problem to decide what further data are required. Data seeking.
4	Incomplete	Unfamiliar	Given	Weighing up possible methods and then deciding on data required.
5	Given	Familiar	Open	Decision making about appropriate goals. Exploration of knowledge networks.
6	Given	Unfamiliar	Open	Decisions about goals and choices of appropriate methods. Exploration of knowledge and technique networks.
7	Incomplete	Familiar	Open	Once goals have been specified by the student the data are seen to be incomplete.
8	Incomplete	Unfamiliar	Open	Suggestion of goal and methods to get there; consequent need for additional data. All of the above skills.

Table 1: Eight Scheme Categorisation of Problem Types (Johnstone, 1993)

By deduction from the different theories of learning, especially the cognitive load theory, and from problem solving literature, it seems right to argue that the different problem types are important at different levels and stages in the learning process. Algorithmic problems (type 1) are important in schema formation. However, this has to be accompanied by self-explanations, elaboration and identification of problem states and rule operators (what is generally referred as the ‘worked example’ effect). Then, the other problem types have to be introduced gradually. Whereas algorithmic teaching is necessary for novices, students who have acquired some form of background knowledge in chemistry ought to be taught using the other problem types. Thus, more open-ended problems are better in determining expertise or domain specific knowledge held by students. This is contrary to the conception of many educationalists who perceive the use of more open-ended problems mainly as a better way of teaching problem solving skill because they are more akin to everyday problems. Nonetheless, more open-ended problems have their place at school level and may offer students insights into the way chemistry works and the nature of real problems which chemistry has to address and sets of such problems exist in the literature. At university level although the more algorithmic problems have an important place, there is a need to use many more extended open-ended problems to enable the students to develop the wider skills and insights relevant to their future careers. Many such problems exist in the literature.

Three descriptors can be used to predict success in problem solving: (i) the nature of the task, that is the structure and complexity; (ii) the cognitive ability of the problem solver; and (iii) learning characteristics (eg the motivational variables, prior knowledge, and level of field dependency). Curriculum planning should therefore pay particular attention to these.

Problem-based learning is a phrase which has appeared, especially in relation to higher education. It is important to recognise that the phrase is often used loosely. Problem-based learning is *not* simply the use of problems in laboratories and tutorials although this is, of course, desirable. Problem-based learning is a *total paradigm shift* in teaching and learning and there is evidence, from the field of medicine, that it does generate different learning outcomes.

Laboratory Work in Chemistry

The literature is clear on the importance of practical work in chemistry. A number of issues are of particular interest. These include questions of logistics, goals, procedures and assessment. Teachers often distinguish practical from theory: the practicals are seen as appendages to theory and goals set accordingly. These goals relate to the view that laboratory work is supposed to consolidate conceptual understanding taught in the theory lessons. This ought not to be so. Laboratory work should not be conceived as a handmaid of theory lessons but as a partner in the development of concepts and understanding. It has been demonstrated that part of the reason labwork is not successful is because of this conception. Conceived in this way, the teachers prepare elaborate laboratory manuals aimed at guiding the students from one step to another until the final result is obtained, concretising what is learnt in the theory class. On the other hand, the laboratory should be used for problem solving and development of concepts. This will lead to a revision in the way labwork is conducted. Manuals will be seen not as procedural guides but as guides to conceptual development. There is clear evidence of the power and effectiveness of laboratory experiences in offering opportunities for genuine problem solving.

In designing a labwork experience for any curriculum, it is essential to specify the purpose of that labwork. The organisation of labwork is therefore dependent on the goal set out for each session.

Thus four laboratory styles can be distinguished with three descriptors (Table 2).

Style	Description		
	Outcome	Approach	Procedure
Expository	Predetermined	Deductive	Given
Inquiry	Undetermined	Inductive	Student generated
Discovery	Predetermined	Inductive	Given
Problem-Based	Predetermined	Deductive	Student generated

Table 2: Laboratory Instructional Styles (Domin, 1999)

As can be seen from the description of the laboratory styles, the effectiveness and appropriateness of each style is dependent on the goal set out for the activity. Again the use of each style is also influenced by the stage of education. For the purposes of further emphasis, whatever the style, labwork should not be seen as a means of *concretising* conceptual learning but as a means of *developing* conceptual learning.

The other purposes of labwork will vary according to level. The purpose of school labwork cannot place high emphasis on practical skills of chemistry in that these are almost completely irrelevant to the majority of learners in terms of their future studies and careers. At university level, a significant proportion (although not a majority) will need experience is some specific skills. However, for most graduates employed as bench chemists after graduation, the specific skills are often very limited and can be developed as needed. It may well be thinking skills, confidence, the grasp of how experimentation can be used, an understanding of how data can be interpreted which are much more important in both the short run and the long run. There are excellent reviews of the purposes of labwork. There is clear evidence in the literature that labs can be modified easily to generate better outcomes.

Assessment

This report assumes that the current paradigmatic underpinning of science education (constructivism) is well accepted and understood. Thus, in the literature, assessment is tending toward a more constructivist approach. Before the 1980s, much of the literature had concentrated on objective testing, and variables influencing its use and the variants of it. Currently, where objective testing is emphasised, it is in relation to how its diagnostic features can be enhanced such as the alternatives yielding more information on students' prior knowledge and conceptual understanding.

The more recent techniques advocated in the literature are: concept mapping assessment techniques, use of structural communication grids, portfolios, V-diagrams, structured interviews, interactive protocols, image-based tests, observation, portfolios, and computer-based assessment. One of the most widely considered, however, is the concept mapping technique. Scoring procedures have been proffered and it has continued to develop with psychological developments and science education theoretical developments. However, serious questions have been raised about its use in summative assessment. Its main use may lie as an aid to understanding which is idiosyncratic to the individual learner. Another use may lie in formative assessment.

One important aspect of assessment is the need to define the purpose for the assessment. Very often assessment is used for multiple purposes and its design never reflects any adequately.

Although there are many different types of assessment in the literature, it is important to employ the right style of assessment for a particular purpose. In particular, it is important not to de-skill pupils by using objective testing like multiple choice which can frustrate the able as well as devalue open-mindedness and critical thought. The literature makes it clear that it is a very flawed way to assess. Structural communication grids offer a much more versatile form of objective testing, with greater emphasis on understanding although, again, overuse can de-skill.

Attitudes

Attitudes have been described as comprising cognitive, affective and behavioural components. Once an attitude has been established it tends to be stable over time. Technically, there is a difference between attitude and other affective concepts such as interest and motivation, but only attitudes are considered here. Attitudes have been demonstrated to influence and be influenced by achievement and by cognition respectively.

Researchers demonstrate that there is a link between the cognitive and the affective and that chemistry education goals should embrace the two and not treat them as mutually exclusive domains. The implication is that attitudes can be developed and much of the study in literature indicates that the approach to presentation and organisation of the curriculum goes a long way to determining the development of desired attitudes in students.

There are four areas where attitudes are important:

a. Attitudes towards chemistry;
b. Attitudes towards topics and themes in chemistry;
c. Attitudes towards the learning of chemistry;
d. Scientific attitudes.

Much research has shown clearly that a negative attitude towards chemistry is the dominant factor affecting student willingness to study further chemistry. Based on social psychological models, it has been shown that attitudes towards topics and themes in chemistry are developed by means of interactive teaching materials (teaching materials where the learners have cognitively to relate new input to previously held attitudes by means of specific teaching strategies of which the most common is role play). A huge range of such materials currently exists.

There is little evidence relating to the latter two attitude targets. However, scientific attitudes are better regarded as scientific ways of thinking. The evidence available suggests that success in this is very heavily dependent on cognitive development. It is likely that many aspects *cannot* be achieved before the age of 16.

Approach

It is very difficult to test hypotheses related to curriculum design in that curriculum design change is not usually possible for a researcher. However, a comparison of the effects of curriculum design is sometimes possible. In one such study, the applications-led curriculum design for Standard Grade Physics is compared to the traditional design for Standard Grade Chemistry (Scottish equivalent of GCSE). The results are very clear cut showing the effectiveness of the applications-led design to generate very positive attitudes as well as high academic standards. This work is confirmed by studies in the Netherlands, where the applications-led structure is also used in Physics, and is consistent with outcomes from many other studies.

'Applications-led' needs to be defined clearly. It is not the same as presenting chemistry in context. The latter takes the familiar chemistry and illustrates and applies it in contexts. In an applications-led syllabus, the actual topics to be studied are *determined by the applications*, the aim being to select applications which are real, and relevant to the lifestyles of the learners at their stage of development and which will enable them to live autonomous lives in the future.

Science Learning and Teaching Theories

Science education has come of age and a number of learning/teaching theories have been propounded as a guide to practice. We have distilled those relevant to this report and categorised them under the cognitive acceleration theory, cognitive load theory, the information processing theory, the conceptual change theory and the alternative conceptions agenda. The presentation is in no particular order of evolvement.

The cognitive acceleration theory, championed by Shayer and Adey of King's College, London, is based on the assumption that there is a mismatch between the cognitive capacity of students and curricula demands. It therefore seeks to handle the problem by proposing an acceleration of the cognitive development of the students through intermittent activities. Research results, however, show that the impact on performance is mediated by a number of other factors and that cognitive capacity does not have a deterministic effect on performance. Most of the suggestions from the literature are to integrate the intervention packages into the curriculum.

Cognitive load theory, pioneered by Sweller of the University of New South Wales, Sydney Australia, is interested in the problems that arise from the interaction between task complexity and cognitive architecture. It engineered a number of instructional strategies that address the issues of the worked example effect, the completion effect, the redundancy effect, the expertise reversal effect, the modality effect, the split attention effect, the imagination effect, the isolated interacting element effect, the element interactivity effect, the guidance fading effect, and the goal-free effect. This is an evolving area for research and holds promises of directing teaching in chemistry. However, this theory is limited in its focus when a consideration is given to all the variables involved in the teaching/learning process.

The information processing theory, championed by Johnstone of the University of Glasgow, is premised on the fact that manipulating the teaching/learning situation in the light of the way students process information will lead to a better performance. Research has shown unequivocal results that authenticate this claim. The major message is the need to organise learning to reduce the demand on the working memory, to prepare the learner by prelectures or prelabs and to reduce noise or redundant material while making the signal or important material explicit. A predictive model was developed for science learning taking into account other strategies in the learning process. However, much of the research under this agenda has focused on the working memory section of this process, that is, on actual processing, to the neglect of other aspects of the information processing system (eg perception, and representation). However, recent work is offering some insights into the way information is stored in, and accessed from, long term memory.

The conceptual change theory is the practical implementation of the alternative conception agenda. This was proposed and pioneered by Posner and Strike. It takes its cue from the accommodation and equilibration principles of Piaget's work. Its assumption is that learning is a rational process and that information can be made to be rational and therefore acceptable or understandable to the learner given the learners' prior conceptions. It therefore prescribes the conditions for conceptual change to include dissatisfaction with existing conceptions (presence of anomalous data), intelligibility, plausibility and fruitfulness of a new conception. Research reveals that these are not always positive in bringing about conceptual change as individuals process information in idiosyncratic ways; and that the socio/affective perspectives are important in bringing about conceptual change.

The alternative conception agenda has its roots in the work of Ausubel but was granted impetus by Rosalind Driver in science education. Its major tenet is that children develop alternative explanatory frameworks and conceptions prior to formal science education. The agenda tries therefore to explore and unravel these frameworks and to apply the knowledge to science education. Subsumed under this is the generative learning model that takes this further to examine how appropriate links can be fostered between prior conceptions and science conceptions. The latter has not received adequate attention from the science education community. Recently, however, a number of studies have tried to concentrate on the representation of science knowledge and to understand these representations and the reorganisation of semantic science categories. The alternative conception agenda holds promises for influencing the conceptual sequencing of the science curriculum; as research results have indicated a progression of students toward adequate conceptualisations and personalisation of science knowledge.

Bringing it Together

The suggestions we make here will guide the recommendations at the end of the report. It is obvious from the summary above, that a number of theories have been propounded for science teaching/learning. These theories taken in isolation cannot predict performance nor describe an overall positive effect on the learning process. Each has a *contributing* role in the understanding of chemistry learning. If we take chemistry learning to involve the presentation of chemistry knowledge in a learning environment, the perception of the presented knowledge, the processing of the knowledge and the representation of the knowledge, we will begin to appreciate the relationship and interaction of the different theories.

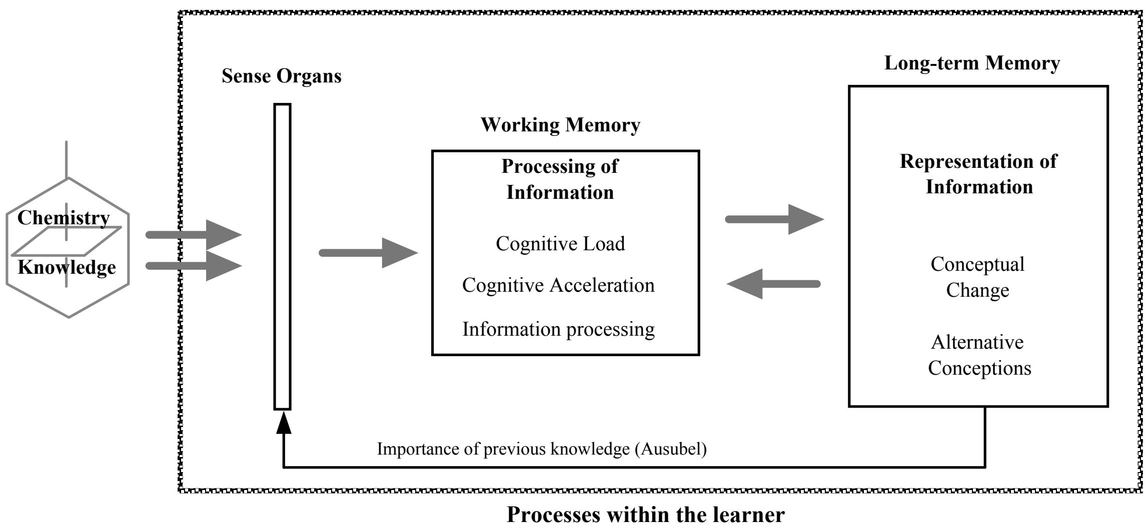

Figure 2: The relationship between the various theories of science/chemistry and learning and the learner's cognitive architecture

Figure 2 represents a systems approach in considering science teaching and curriculum design. The different theories and the stage at which they make their contributions are schematically represented. The nature and structure of chemistry should be addressed as well as the approach to be adopted in the sequencing and selection. Presentation should be concerned with the psychosocial environment (peer relationship, authority and institutional structures, etc.), physical environment, as well as chemistry knowledge and the learner. These two processes to a large extent determine the effectiveness of the processes within the learner. The explanations derived from each of the theories can therefore be applied in the two processes outside of the learner.

The above should not be taken to be as simplistic as it appears with a clear-cut line of demarcation between the different theories and their loci of operation. Rather, they interact and in actual fact traverse the boundaries, having some similarities and some differences. However, for clarity and the purpose at hand we make them as simple as possible.

Towards a New Approach at School Level

Aim: to summarise the evidence which can offer guidelines in the development of the curriculum in chemistry at school level.

The aim of any school chemistry curriculum is not only to educate *in* chemistry but also to educate *through* chemistry. The aim has to be to generate a population that is informed about chemistry and its importance in modern day society, a population who are positively disposed to chemistry and its impact on society. The longer term impact of this on social trends and attitudes cannot be underestimated while, from such an educated population, there will be those who choose to pursue the chemical sciences beyond school and who will become the leaders in the field for the future.

The outcomes from the research evidence are now interpreted against that background.

Chemistry for whom?

Too often, the school chemistry curriculum has been designed with the future stages of learning in chemistry in mind. Thus, honours chemistry requirements determine first year university courses which, in turn determine the senior school curriculum which then defines what should be taught at earlier stages. This means that the school chemistry curriculum is determined largely by the needs of the *minority* who might become chemists. The curriculum must be re-thought in terms of the whole group - who will become citizens. It has been demonstrated that those with more or less no chemistry from school can still do well in a first year university course.

The inevitable logical consequence of this new approach in curriculum design will be to seek to define the kind of chemistry which the wider population will need. Syllabuses then can be planned around these major themes, the themes being those of significance for the majority. Thus, it is important that the application areas relate to key areas of teenage lifestyle: themes like: music, cars and transport, cosmetics and beauty, health and consumer choice, food and drink, clothes, colour and decoration, pollution and resources, our society and other societies. Possible starting points might include: clothes, washing and dyeing; food and drink; cooking; cleaning; cosmetics and cleanliness; drugs and medicine; colour, decoration; consumer choice, analysis; resources. The above list is merely suggestive and not comprehensive in any way.

These are only examples but what is being advocated is a paradigm shift in our thinking as we seek to design syllabuses and to plan the individual learning experiences for students in chemistry. The same principles will apply at all levels but the choice of applications and the depth of treatment will vary widely. Essentially, the chemistry curriculum can be constructed by exploring three themes:

1. *What are the questions that chemistry asks*?
2. *How does chemistry obtain its answers*?
3. *How does this chemistry relate to life*?

Such an approach will meet the needs of the whole population but will provide the essential critical basis for those who will pursue the study of the chemical sciences beyond school.

What chemistry?

When faced with the question, *what chemistry*?, the temptation is to list the topics and themes to be included in a syllabus. These are usually defined by the logic of the subject as well as the needs of later stages of learning. This approach must be resisted. The majority of traditional chemistry taught at school is almost completely irrelevant to the population at large while large amounts are not required by those who wish to pursue chemistry. There needs to be a massive paradigm shift in thinking and the willingness to jettison much traditional chemistry. The main ideas involving the structure and nature of matter and its transformation can be illustrated with much less content. For each topic, key questions must be asked: is this essential for the informed citizen? Is this essential for the future potential scientist, or even chemist? Teachers need time to develop ideas. Pupils need time to sort out misconceptions, to discuss ideas and to think like a chemist. Content reduction would allow such time. There is clear evidence that adding more to a curriculum actually brings about *less* learning.

On grounds of information overload, it is essential not to introduce chemistry at all three levels (macro, micro, symbolic) at the same time. Indeed, there needs to be a sound experience in macro chemistry *before* the other two levels are introduced. The macro approach can be related to previous knowledge and experience, thus rooting chemistry in real life rather than allowing it to become a subject of abstraction and symbolic complexity. This means that early courses in chemistry should be rooted strongly in the macro and attempts at interpretation invoking the sub-micro and symbolic introduced carefully and gradually.

Although the outcomes from cognitive acceleration reveal that there are different cognitive effects for different pupils, it is nonetheless true that school pupils should not be faced with the highly abstract and symbolic at too early an age. In this way, the recommendations from cognitive acceleration are consistent with those from the three levels model and information processing. If the observed improved performance is due to the development of some chunking techniques, which reduce potential working memory overload, then this stresses the importance of working memory overload as a *rate-determining step* in all learning.

Information processing offers specific guidelines for curriculum development as well as teaching itself: themes with high working memory demand must ***not*** be offered before the learner's cognitive development is ready while the development of strategies and experience which enable chunking to take place need to be encouraged. It stresses the importance of previous knowledge and the way that knowledge was taught and stored. It stresses the limiting effect of negative attitudes.

Attitudes are often presented as important in curriculum specifications and then largely ignored in both curriculum construction and assessment. It is well established that a curriculum which is 'applications-led' rather than designed by the logic of the discipline generates *ver*y positive attitudes towards a subject. The nature of 'applications-led' needs careful exploration in that a curriculum where the chemistry is contextualised or illustrated is not necessarily the same in its impact. In an applications-led approach, students are introduced to the chemistry that is needed to make sense of the world around as they know it, giving insights in to the perspectives and methods of chemical enquiry as well as its outcomes. *The key point is that the actual chemistry to be taught is determined by the applications considered.*

Social attitudes relating to chemistry need emphasis. The approaches to develop these have been well established by means of mental interactivity. Teaching units need to be built into the curriculum with this aim in mind. The curriculum order can be inverted:

From:
Atoms, Molecules, Structures → Properties, Reactions → Explanations → Applications

To:
Applications → Explanation → Properties, Reactions → Atoms, Molecules, Structures

For early stages, the applications-led approach can be illustrated with a syllabus, which ran for several years with quite remarkable results. This syllabus was planned for 13-year old school pupils in a school drawing from a relatively deprived area. For the majority, it would be their first and last experience of chemistry. The idea of the elements was presented as ‘building blocks’, analogous to the letters in an alphabet that could form an apparently endless array of words. The periodic table was seen simply as a device to display these elements. Over the year, the pupils started to look at their world (the air, water, the sea, rocks and minerals, the atmosphere) with a simple agenda: what elements could be found (and where) and what is mankind doing with what was there? Many fundamental chemical ideas just arose naturally, eg the concept of bonding, reactivity, physical properties of matter, energy and bonds, states of matter. The course was descriptive, based on the world around, applications orientated, and it avoided quantitative aspects. The effect on the pupils was remarkable. At the end of the year, *every* pupil who was of sufficient ability, *without exception*, opted to take the chemistry course for the ensuing two years. This nearly doubled the chemistry uptake in that school, a most encouraging outcome!

The course offered an excellent background for the next two years of study although it had been specifically designed to meet the needs of the majority.

It is possible to suggest the kind of major themes which might underpin a school chemistry course for the next stages:

How Chemistry has Influenced Society	Chemistry and Today's Lifestyles	Chemistry and Wealth Creation	Chemistry and Industrial Production	Major issues Linked to Chemistry
Anaesthetics Drugs and medicine Batteries and energy Pollution Food Production	Cosmetics Colour and decoration Food and Drink Flavourings, sweeteners, additives Cleanliness Dipstick chemistry	The Music Industry Silicon Technology Chemicals for sale Organic Farming Recycling	Transport and Fuels Metals or Plastics Chemicals for Food Chemicals for Cleaning Chemicals and Water	Abuse of chemicals Biodegradability Pollution Testing of Chemicals Consumer Issues

How to be taught?

It is self-evident that language demands must be kept at an appropriate level. Language interpretation makes demands on working memory and the density of language must allow for this. Specific care must be taken in the use of non-technical language in chemistry in ways specific to chemistry. Thus words like ‘volatile’, ‘feasibility’, ‘density’, ‘equation’, ‘equilibrium’ have meanings in ordinary use which may be incompatible with their precise use in chemistry situations.

Pupils will come to the chemistry class with pre-conceived ideas. These may be derived from daily life, media or previous teaching. Many of these have been pinpointed. It is essential that curriculum construction takes these into account and allows time and appropriate opportunity for these to be explored so that, in a natural way as far as possible, such misconceptions and alternative conceptions are modified and altered.

Most of chemistry places too much emphasis on algorithmic problems. Nonetheless, these have their place in offering learner confidence in routine procedures and providing techniques and approaches which work. More open-ended problems (especially group based) have been shown to be highly effective in developing attitudes, generating enjoyment and addressing issues where chemistry can be applied in real-life situations. The curriculum must offer opportunities for such experiences. It has to be recognised that problem solving skills are highly context dependent. Therefore, problem solving cannot be essentially a generic skill and presented as a curriculum aim in this way.

The place of labwork is not really contested. However, its purpose is often unclear and poorly specified. The aims cannot be centred around the development of practical skills (for these are irrelevant for the majority at school level) nor should labwork be used to 'confirm theory'. Labwork in the curriculum should be devised to develop:

> *Outcomes relating to the Learning of Chemistry*: To make chemistry real, tangible, related to actual materials and their behaviour; to illustrate ideas and concepts, to expose theoretical ideas to empirical testing.
>
> *Practical Outcomes*: Most specific skills are irrelevant but more generic skills are important: careful observation, safe experimentation, being accurate where appropriate.
>
> *Scientific Outcomes*: Skills of deduction and interpretation; an opportunity to see the place of the empirical as a source of evidence in enquiry; opportunities to devise experimental approaches which can offer genuine insights into chemical phenomena.
>
> *General Outcomes*: team working, presenting data, discussing, time management, developing ways to solve problems.

Great care will have to be taken so that assessment does not skew these aims.

How to be assessed?

Too much assessment relies on knowledge recall or recognition. The curriculum should seek to develop higher order thinking skills and the assessment must reflect this. The aim of the proposed curriculum should be to educate *through* chemistry as well as *in* chemistry. Assessment must take into account skills like data handling, analysis of experimental data, drawing appropriate conclusions, understanding the implications of chemical situations, as well as the assessment of how well the pupils actually *understand* the ideas of chemistry. All of these are very different from recall and recognition which often underpin much assessment. Great emphasis should be placed on the *interpretation* of chemistry situations rather than on the *recall of the outcomes*.

Towards a New Approach at Higher Education Level

Aim: to summarise the evidence which can offer guidelines in the development of the curriculum in chemistry beyond school.

The aim of any higher education chemistry curriculum is not only to educate *in* chemistry but also to educate *through* chemistry. However, the emphasis on the development of a graduate group who can demonstrate *competency in their understanding* of chemistry and its applications is of great importance. The emphasis on understanding is important in terms of developing a genuine competency.

The outcomes from the research evidence are now interpreted against that background.

Chemistry for whom?

It is consistently found that only a minority of chemistry graduates actually become bench chemists. Thus, the aims of a degree in chemistry must be wider than simply the production of those who will work in laboratories. Chemistry is in a powerful position as a science with a strong quantitative edge which underpins so much understanding in the world of materials, medicine, biology and medicine. Those with a mature understanding of chemical phenomena have, therefore, much to contribute beyond the confines of chemistry itself.

The chemistry to be included in the curriculum must reflect this context. It is impossible to cover all areas of chemistry in a degree. The rate of growth of knowledge will make the selection process increasingly more and more critical. The degree must simply offer the student an insight into the key fundamental ideas which underpin the subject along with knowledge of how to use the information and where to find what they need when faced with unfamiliar chemistry situations.

This also involves a paradigm shift in our thinking as we seek to design syllabuses and to plan the individual learning experiences for students in chemistry. The key question to ask is what chemistry is the *essential* basis for *every* student?

As with school chemistry, the chemistry curriculum can be constructed by exploring three themes:

1. *What are the questions that chemistry asks*?
2. *How does chemistry obtain its answers*?
3. *How do these answers offer insights into chemistry problems*?

Such an approach will meet the needs of the whole student group but will provide the essential critical basis for those who will offer leadership in the development of chemistry by means of research.

What chemistry?

When faced with the question, *what chemistry*?, the temptation is to list the topics and themes to be included in a syllabus. These are usually defined by the logic of the subject as well as the needs of later stages of learning. There is also the temptation for the curriculum to include those lecture courses which reflect the specialist research interest of the staff members available. *All of this must be resisted*.

There needs to be a massive paradigm shift in thinking and the willingness to jettison much traditional chemistry. The criterion must simply be: what is *essential* for all so that they can make sense of relevant chemical phenomena? This will require a study of what former graduates actually have found essential in their future careers. There needs to be time to allow students to understand and not simply memorise. Students need time to consider how the evidence was gained and to sort out misconceptions, to discuss ideas and to think like a chemist. Content reduction would allow such time. There is clear evidence that adding more to a curriculum actually brings about *less* learning.

On grounds of information overload, it is essential not to introduce chemistry at all three levels (macro, micro, symbolic) at the same time when introducing a new topic. The macro approach can be related to previous knowledge and experience, thus rooting chemistry in real life rather than allowing it to become a subject of abstraction and symbolic complexity. This means that early courses in chemistry should be rooted strongly in the macro and interpretation introduced gradually.

Information processing offers specific guidelines for curriculum development as well as teaching itself. Chemistry is both abstract and highly representational, the use of models (mental and physical) being common. By its very nature, many themes in chemistry are high in information in the sense that the learner has to manipulate many pieces of information *at the same time* to gain understanding. Such themes may well be important but they need to be presented in such a way that information overload is minimised.

Attitudes are often presented as important in curriculum specifications and then largely ignored in both curriculum construction and assessment. At school level, it is well established that a curriculum which is ‘applications-led’ rather than designed by the logic of the discipline generates *very* positive attitudes towards a subject. In an applications-led approach, students are introduced to the chemistry that is needed to make sense of the world around as they know it, giving insights into the perspectives and methods of chemical enquiry as well as its outcomes. There is considerable evidence of how to develop such teaching approaches and the very powerful benefits it brings to an undergraduate population. Social attitudes relating to chemistry need emphasis. The approaches to develop these have been well established by means of mental interactivity. Teaching units need to be built into the curriculum with this aim in mind and numerous such units already exist.

How to be taught?

Inevitably, students will come to the degree courses with pre-conceived ideas. These may be derived from daily life, media or previous teaching. Many of these have been pinpointed. It is essential that time and appropriate opportunity is allowed for these to be explored so that, in as natural way as far as possible, such misconceptions and alternative conceptions are modified and altered.

Many chemistry courses place much emphasis on algorithmic problems. Although these have their place in offering learner confidence in routine procedures and providing techniques and approaches which work, more open-ended problems (especially group based) have been shown to be highly effective in developing attitudes, generating enjoyment and addressing issues where chemistry can be applied in real-life situations. They also offer opportunities for genuine understanding to develop. The curriculum must offer opportunities for such experiences. It has to be recognised that problem solving skills are highly context dependent. Therefore, problem solving cannot be essentially a generic skill and presented as a curriculum aim in this way.

Higher education tends to revolve around lecture courses. The tendency is for these to be used simply to impart information, the pace often being quite rapid. There is clear evidence of the value of pre-lecture experiences where underlying ideas are revised and there is an attempt to ensure that students approach new material with minds prepared so that they can make a serious attempt at understanding. The role of lectures needs to be reviewed. These can be offered merely to give students the essential landmarks of a topic, the students being expected to develop their ideas from that. However, usually, lectures transmit knowledge. Major studies have demonstrated that students record in their notes only about 10% of what is said and the basis by which they select what to record is quite idiosyncratic. Students need to be given a clear picture of the purpose of lectures and to be offered direction during the lecture so that they can see what are the key points.

The place of labwork is not really contested. However, its purpose is often unclear and poorly specified. The aims cannot simply be centred around the development of practical skills (for many of these are irrelevant to most students) nor should labwork be used to 'confirm theory'. Labwork in the curriculum should be devised to develop:

> *Outcomes relating to the Learning of Chemistry*: To make chemistry real, tangible, related to actual materials and their behaviour; to illustrate ideas and concepts, to expose theoretical ideas to empirical testing.
>
> *Practical Outcomes*: Most specific skills are irrelevant but more generic skills are important: careful observation, safe experimentation, being accurate where appropriate.
>
> *Scientific Outcomes*: Skills of deduction and interpretation; an opportunity to see the place of the empirical as a source of evidence in enquiry; opportunities to devise experimental approaches which can offer genuine insights into chemical phenomena.
>
> *General Outcomes*: team working, presenting data, discussing, time management, developing ways to solve problems.

Great care will have to be taken so that assessment does not skew these aims. The use of prelab experiences is well documented and their effectiveness is very clear. The RSC booklet "Enhancing Chemistry Laboratories" offers an overview of the lab situation.

How to be assessed?

Too much assessment relies on knowledge recall or recognition. The curriculum should seek to develop higher order thinking skills and the assessment must reflect this. The aim of the proposed curriculum should be to educate *through* chemistry as well as *in* chemistry. Assessment must take into account skills like data handling, analysis of experimental data, drawing appropriate conclusions, understanding the implications of chemical situations, as well as the assessment of how well the students actually *understand* the ideas of chemistry. All of these are very different from recall and recognition which often underpin much assessment. Great emphasis should be placed on the interpretation of chemistry situations rather than on the recall of the outcomes. There is a large literature on assessment in chemistry at higher education level, offering much useful research-based insight.

Landmarks for Curriculum Construction in Chemistry - School Level -

This attempts to bring together the outcomes from the research evidence to offer a set of specific guidelines for curriculum construction. The aim is to develop a chemistry curriculum which will meet the needs of learners and societal demands. The aim is to develop a curriculum which is a sound reflection of the nature and methods of chemistry as a discipline, with its important place in a modern society. The aim is also to develop not only an informed population but also one which has developed informed attitudes relating to the study of chemistry and its practical implications for society.

The chemistry curriculum at school level should:

1. Be designed to meet the needs of the majority of pupils who will never become chemists (or even scientists), seeking to educate *through* chemistry as well as *in* chemistry;
2. Be strongly ‘applications-led’ in its construction, the applications being related to the lifestyle of the pupils and being used to define the curriculum: fundamentally, the content is determined *not* by the logic of chemistry but by the needs of pupils;
3. Reflect attempts to answer questions like: what are the questions that chemistry asks? How does chemistry obtain its answers? How does this chemistry relate to life?
4. Not be too ‘content-laden’, so that there is adequate time to pursue misconceptions, to aim at deep understanding of ideas rather than content coverage, and to develop the appreciation of chemistry as a major influence on lifestyle and social progress; avoid using analogies or models (or multiple models) in a way which causes information overload;
5. Not introduce sub-micro and symbolic ideas too soon or too rapidly; avoid developing topics with high information demand before the underpinning ideas are adequately established to overload and confusion;
6. Be set in language which is accessible to the pupils, avoiding the use of unnecessary jargon and offering careful clarification of words where the normal contextual meaning can cause confusion;
7. Be couched in terms of aims which seek to develop conceptual understanding rather than recall of information, being aware of likely alternative conceptions and misconceptions;
8. Offer experiences of graded problem solving situations starting from the more algorithmic and moving on to the more open-ended;
9. Involve laboratory work with very clear aims: these should emphasise the role of labwork in making chemistry real as well as developing (or challenging) ideas rather than a focus on practical hands-on skills; labwork should offer opportunities for genuine problem solving;
10. Require assessment which is integrated into the curriculum and reflects curriculum purpose, is formative as well as summative and aims to give credit for understanding rather than recall, for thinking rather than memorisation.

As an extra, the curriculum should be taught by teachers who are qualified as chemists and are committed to the place of the discipline in its social context. This is an important factor in the developing of a soundly taught pupil population with positive attitudes towards chemistry. This has manpower and resource implications as well as implications for pre-service and in-service support.

Landmarks for Curriculum Construction in Chemistry - University Level -

This attempts to bring together the outcomes from the research evidence to offer a set of specific guidelines for curriculum construction. The aim is to develop a chemistry curriculum which will meet the needs of learners and societal demands. The aim is to develop a curriculum which is a sound reflection of the nature and methods of chemistry as a discipline, with its important place in a modern society. The aim is also to equip the students with those skills which will enable them to make a contribution to society within and beyond chemistry. These skills should be seen in cognitive terms (like conceptual understanding, logical and critical thought, creativity, objectivity) as well as generic terms (like team working, written and verbal communication of chemical ideas).

The chemistry curriculum at higher education level should:

1. Be designed to meet the needs of the majority of students who will never become bench chemists as well as those who will make careers specifically in chemistry: thus seeking to educate *through* chemistry as well as *in* chemistry;
2. Have a strong overt 'applications-led' orientation, with chemistry being presented in its social, economic and industrial context as well as in relation to disciplines like medicine;
3. Reflect attempts to answer questions like: what are the questions that chemistry asks? How does chemistry obtain its answers? How does this chemistry relate to life?
4. Not be too 'content-laden', so that there is adequate time to pursue misconceptions, to aim at deep understanding of ideas rather than content coverage, and to develop the appreciation of chemistry as a major influence on lifestyle and social progress;
5. Be careful in the use of sub-micro and symbolic ideas too rapidly; avoid developing topics with high information demand before the underpinning ideas are adequately established, to overload and confusion;
6. Allow the students opportunities to communicate chemical ideas in a logical form: brief verbal presentation of ideas in tutorials, groupwork discussions and problem-based groupwork; the writing of clear concise reports on chemical phenomena;
7. Be couched in terms of aims which seek to develop conceptual understanding rather than recall of information, being aware of likely alternative conceptions and misconceptions;
8. Offer experiences of graded problem solving situations starting with the more algorithmic and moving on to the more open-ended; the use of small group problem based activities;
9. Involve laboratory work with very clear aims: these should emphasise the role of labwork in making chemistry real as well as developing (or challenging) ideas rather than a focus on practical hands-on skills; labwork should offer opportunities for genuine problem solving;
10. Require assessment which is integrated into the curriculum and reflects curriculum purpose, is formative as well as summative and aims to give credit for understanding rather than recall, for high level thinking rather than memorisation.

Lecturers in chemistry departments should have opportunities to develop new insights and skills through participation in activities organised within individual institutions as well as externally, such as those organised by the Higher Education Academy. Participation in such activities should have appropriate credit for career development.

Appendix 1: Annotated Bibliography of Citations in Alphabetical Order

Adey, P. (1987). Science develops logical thinking – doesn't it? Part I. Abstract thinking and school science. ***School Science Review, 68(245),*** **622-630.**
This article is one of the first articles emanating from the CASE works at King's College, London. The author, as in works at the beginning of any scientific invention, mused on the truism of the fact that science develops abstract thinking. He discussed nine major areas of abstract thought related to science. These included control and exclusion of variables, ratio and proportion, compound variables, conservation involving models, compensation and equilibrium, correlation, and probability. He also addressed sketchily, three subsidiary areas including, combinatorial thinking, coordination of frames of reference and classification.

Adey, P. (1988). Cognitive Acceleration: Review and Prospects. ***International Journal of Science Education, 10(2),*** **121-134.**
The author assumes there is a mismatch between the cognitive demands of many science curricula and the cognitive abilities of the students, and that cognitive development can be accelerated. Based on these two assumptions of overcoming the mismatch is proposed, by designing appropriate curricula and by accelerating the cognitive development of the students. The paper enumerated several disadvantages of taking the first approach and advocated the second approach. In the context of secondary school science (the level at which the paper is situated) and Piagetian model, that means speeding up the onset of the formal operations. The intervention lessons produced and used in a study reported had the following features, they are based on the schemata of formal operational thinking, introduction of use of technical vocabulary, use of concrete contexts, metacognition and bridging. These were used in a pilot study. The results of the pilot study, although inconclusive gave the cognitive acceleration model an impetus for further development.

Adey, P. (1996). Does motivation style explain the CASE differences? A reply to Leo and Galloway. ***International Journal of Science Education, 18(1),*** **51-53.**
In this paper, Adey responds to the criticisms of Leo and Galloway arguing that motivation factors may not fully account for the differences giving his reasons for the stand. He however accepts the fact that aspects of personal interaction may be responsible for the differential effects of CASE intervention packages.

Adey, P. & Shayer, M. (1993). An exploration of Long-term far-transfer effects following an extended intervention programme in the high school science curriculum. ***Cognition and Instruction, 11(1),*** **1-29.**
Reasoning that the general thinking skills can be taught, the authors designed a set of activities, set in the context of science and at the formal operations level. Four features were identified from literature to be characteristics of the activities to effect long-term transfer. These were elaborated on in this paper. Nine schools (of different demographic characteristics) and twenty-four classes were assigned to either the experimental or control group. The experimental groups were taught once every two weeks with the materials in place of the normal science classes for a period of two years. They employed the Science Reasoning Tasks to obtain data relating to the cognitive development of the students, common achievement tests for achievement and the GCSE results as measure of far-transfer. They found that the intervention accelerated cognitive development immediately after the programme and this dissipated one-year after the programme. The delayed achievement test a year later revealed a difference in favour of the experimental subjects although not statistically significant. The older boys had a higher effect size in the GCSE, there was no difference for the younger boys and older girls. The younger girls had higher gains than the control although not as large as those of the boys. They explain the results in terms of confidence, language training, and general cognitive development. Generalisations were made from the results and interpretations.

Adey, P & Shayer, M. (2002). Cognitive acceleration comes of age. In M. Shayer & P. Adey (Eds.) ***Learning intelligence: Cognitive acceleration across the curriculum, from 5 to 15 years*** **(pp1-16). Buckingham: Open University Press.**
Describes the proposed paradigm of cognitive acceleration (CA) based on the works of Piaget and Vygosky. The formulation is that there are some general intellectual functions in children, which develops with age and is influenced by environment. The major tenet is to refocus the aim of education toward intellectual development. The CA instructional design has six principles- (i) abstracting underlying concepts from schema theory of Piaget (ii) concrete preparation (introduction to the would-be problem context and vocabulary) (iii) cognitive conflict (creation of dissonance in the students' cognition) (iv) social construction (negotiation of knowledge in a social environment) (v) metacognition (an awareness of the individual learner's thinking processes) and (vi) bridging (transfer to other contexts). Finally, the paper gave an overview of the different projects where this has been applied in science mathematics and arts education.

Adey, P., Shayer, M. & Yates, C. (1989). ***Thinking Science: The Curriculum Materials of the Cognitive Acceleration through Science Education (CASE) Project.*** **Surrey: Thomas Nelson and Sons Ltd.**.
This pack contains 30 activities, which are aimed at helping the students develop thinking skills. It consists of a guide for teachers, a guide for technicians and the activities as well as worksheets for the students. It explicitly specifies and emphasised the teaching style to be adopted in using the pack. It is not meant to replace the curriculum but it is advised that it be used as a supplement. It was not recommended for any level of students but the teacher is to assess his/her particular student and use it as appropriate.

Ahtee, M. & Varjola, I. (1998). Students' understanding of chemical reaction. ***International Journal of Science Education, 20(3),*** **305-316.**
An instrument consisting of three questions relating to chemical reaction was administered to 442 students at different stages of chemistry education. The aim was to determine the students' understanding of the concept of chemical reaction. They found that very few students were able to use chemical terms and reasoning in the construction and explanation of the concept of chemical reaction. Implications for teaching were highlighted from this.

Aikenhead, G. S. (1986). The content of STS Education. ***STSRN Missive, 2(4),*** **17-23.**
The author addresses what STS science teaching entails in terms of the function of science teaching, the content, the structure and the sequence. In summary, it portrays STS teaching as being student oriented and presenting science in context and enumerates the goals. It also presents STS as having both science content and STS content (social aspects internal and external to the scientific community). These were elaborated on and the teaching methods compatible with STS teaching discussed. It also proposed an eight-category scheme for integration of the content.

Aikenhead, G. S. & Ryan, A. G. (1992). The development of a new instrument: "Views on Science-Technology-Society" (VOSTS). ***Science Education, 76(5),*** **477-491.**
Reports the steps taken to develop an instrument that assesses students' views on science, technology and society. It addresses the rationale for the instrument, the general characteristics of the instrument, and the five-step development procedure. It makes clear the benefits that may be derived from the use of the instrument and the ways in which it can be used. Areas covered by the instrument includes: the meaning of science and technology, influence of society on science/technology, influence of science/technology on society, influence of school science on society, characteristics of scientists, social construction of scientific knowledge, social construction of technology and nature of scientific knowledge.

Aikenhead, G. S., Ryan, A. G. & Fleming, R. W. (1992). Views on Science-Technology-Society (VOSTS). College of Education, University of Saskatchewan, Saskatoon, Canada.
This instrument has a pool of 114 empirically derived items on some science, technology and society issues. The areas covered include, the meaning of science and technology, influence of society on science/technology, influence of science/technology on society, influence of school science on society, characteristics of scientists, social construction of scientific knowledge, social construction of technology and nature of scientific knowledge. Each area has a number of items, with an item stem and varying number of alternatives. The last three alternatives give an individual opportunity to reject all of the alternatives provided, at the same time yielding a diagnostic response. However, no scoring procedure was suggested.

Andersson, B, (1990). Pupils' conceptions of matter and its transformations (age 12-16). ***Studies in Science Education, 18,*** **53-85.**
The paper is a review of works done in the understanding of children's conception of matter, with particular reference to their everyday understanding of matter and its transformation, their conceptions of atoms, molecules and systems of particles. It categorises the findings from research and draws the implications of this to teaching by considering the underpinning explanatory frameworks to the notions expressed by the students. It also considers science textbooks in relation to these and the correct scientific conceptions. The paper contended commonly used intervention seeking to achieve conceptual change in students and argued for detailed planning, testing and assessment of teaching, lesson by lesson. It ended by examining some programmes of the later sort and issues for further investigation.

Arnold, J. C. & Arnold, P. L. (1970). On scoring multiple-choice exams allowing for partial knowledge. ***The Journal of Experimental Education, 29(1),*** **8-13.**
The authors in this paper developed a scoring procedure for multiple-choice tests that allows for partial knowledge and examiners control of gain due to guessing. This adopted the games theory approach. The scores obtained through this method for twenty-five students were compared with scores from four other methods. The different procedures yielded similar scores for the high and low scoring students, but the relative positions for the middle grades varied widely from one scoring technique to the other. The authors suggested reasons for this.

Ausubel, D. P., Novak, J. D. & Hanesian, H. (1978). *Educational Psychology: a cognitive view.* New York: Holt, Rinehart and Winston.
This book is primarily concerned with meaningful learning. Although it emphasises reception learning, it recognises other forms of learning. Interestingly, the popular statement set out before the preface fits tightly to the notion of conceptual change and has been used by conceptual change advocates as the pillar of the theory, the book dealt with concept formation as an appendage to meaningful verbal learning. The fabrics of the book are woven around its major tenet that existing cognitive structure plays a great role in the process of new learning. The authors treated different issues (for example meaningful problem solving, discovery learning cognitive factors in learning intellectual ability practice). Ways of providing for individual differences. Psychosocial factors especially authority structures in the classroom and principles of measurement and evaluation were also addressed.

Baddeley, A. (1997). *Human memory: theory and practice.* Hove: Psychology Press Ltd.
In this book Baddeley considers the human memory in its historical, ecological and relational perspectives. It also concerned itself with clinical evidence, clearly showing present status of understanding about the human memory in all its ramifications. It justifies the study of the human memory, considers perception and remembering and the types of memory. It addresses the role of memory in cognition and dealt in details with the working memory and long-term memory and their roles in cognition. It considers the processes involved in learning and habit formation and how the memory architecture interacts with other cognitive factors in determining outcomes of memory functions. Finally, it looks at implicit and recollective memory. The first edition being one of the first of its kind, used a lot of persuasive language and empirical evidence.

Bennett, J., Rollnick, M., Green, G. & White, M. (2001) The development and use of an instrument to assess students' attitude to the study of chemistry. *International Journal of Science Education, 23(8),* 833-845.
This study drew on the methodology used in the development of Views-on-Science-Technology-Society to develop and validate an instrument for the measurement of students' attitudes in chemistry. This paper focused on the methodological issues and not on the result of the measurement using the instrument. The stages of the development were discussed and issues of analysis were addressed. The results were used to develop students' profiles on attitude in chemistry.

Berg, C. A., Bergendahl, V. C. B. & Lundberg, B. K. S. (2003). Benefiting from an open-ended experiment? A comparison of attitudes to, and outcomes of an expository versus an open-ended version of the same experiment. *International Journal of Science Education, 25(3),* 351-372.
The investigator determined the outcomes of exposure to two types of laboratory exercises. One adopted the expository method and the second adopted an open-ended method. The students were also classified into high and low attitude positions. Data was collected using an attitude questionnaire at the onset of the experiment, and thereafter with students' self evaluation sheets, and by interviews. It was found that students with low attitude positions preferred the expository method to the open-ended form and conversely, those with high attitude positions preferred the open-ended form. It was also found that the open-ended form showed a more positive outcome in terms of logistics. However, the investigation reveals that in an open-ended form students investigate a wide range of phenomena and come up with different results. This raises a number of questions for example how can laboratory work be assessed and what goals should a given experiment seek to pursue?

Bieron, J. F., McCarthy, P. J. & Kermis, T. W. (1996). A new approach to general chemistry laboratory. *Journal of Chemical Education, 73(11),* 1021-1023.
This article is a documentation of an innovation introduced into a general chemistry laboratory at a college in New York. The programme was designed in such a way that experiments are grouped in units. Each unit has a unifying theme and incorporated socio-scientific issues. They also incorporated the use of computers in the innovation. Prelabs were given and one prelab was sufficient for the experiments in a unit. The evaluation of the programme by the students indicated that they had a positive attitude toward the new programme and agreed that the number of experiments were adequate for the course. However, they found unappealing the fact that the experiments did not synchronise with the matter covered in the lectures, which was one of the rationale of the innovation.

Bliss, J. (1995). Piaget and after: the case of learning science. *Studies in Science Education, 25,* 139-172.
Critiqued Piaget's work in the light of the different variables involved, that is, stage theory and genetic epistemology. Examined science educational programmes, theories and interventions that have arisen as a result of Piaget's work. These include the cognitive acceleration programme, constructivism and mental model theories. Endorsed the use of mental models on the grounds of its incorporation of institutional variables encountered in actual classroom situations or situated learning.

Blosser, P. E. (1988). Teaching problem solving – secondary school science. . *ERIC/SMEAC Science Education Digest, 2* (ERIC Identifier: ED309040).
Reviews research and literature dealing with problem solving in the areas of biology, chemistry and physics. The meaning and importance of problem solving in science education were analysed. The author claims that problem solving in chemistry was characterised by the use of algorithms in solving quantitative problems. The implications of this and the trend in the other sciences were drawn.

Botton, C. (1995). Collaborative concept mapping and formative assessment key stage 3: understanding of acids and bases. *School Science Review, 77(279),* 124-130.
The investigator involved some Year 9 students in a collaborative concept mapping using a unit on acids. There was a briefing at the onset of the laboratory work and students were allowed to construct their concept maps. The investigator found collaboration in meaning making, and that the process led to quick diagnosis and identification of misconceptions. The students also found this form of assessment non-threatening leading to attitude change and confidence in them and enhance metacognitive processes.

Botton, C. & Brown, C. (1998). The reliability of some VOSTS items when used with preservice secondary science teachers in England. *Journal of Research in Science Teaching, 35(1),* 53-71.
To assess the reliability of VOSTS as an assessment instrument, the authors selected two sections of the instrument, defining science and epistemology. These were administered to 29 postgraduate preservice science teachers. A retest was made after one month. A cross tabulation procedure and a Pearson chi-square were applied to the data to determine consistency and independence of choices. A cluster analysis of the responses was also undertaken to identify any differences between clusters and dendograms were obtained from the SPSS cluster procedure. From the results obtained, they conclude that the selected items were generally reliability but for three. More interestingly, the authors suggest that the responses from VOSTS can be used to obtain a profile of students' views and indeed can serve as a form of diagnostic tool to give direction on efforts at appropriate science education.

Boyer, R & Tiberghien, A. (1989). Goals in physics and chemistry education as seen by teachers and high school students. *International Journal of `Science Education, 11(3),* 297-308.
The authors used two questionnaires to elicit responses from 1249 sixteen-year old students and 284 teachers on their perceptions about goals in physics and chemistry. They found that gaps existed between the views of teachers and their students. Whereas teachers preferred goals related to the logic of the subjects, students preferred goals of a social kind, that is, an instrumentalist perspective.

Brünken, R., Plass, J. L. & Leutner, D. (2004). Assessment of cognitive load in multimedia learning with dual-task methodology: auditory load and modality effects. *Instructional Science, 32,* 115-132.
Employing the dual task methodology the investigators used 10 female students to test (a) the comparative demand of presenting verbal and pictorial materials as audiovisual or visual-only form on the phonological loop and (b) if the inclusion of music to an audiovisual presentation would increase the phonological cognitive load. The major aim of the work is to validate the limited capacity assumption of the cognitive load theory using direct measures of resource demands. They found a strong evidence to support the assumption of a limitation in auditory capacity.

Bryce, T. G. K. & Robertson, I. J. (1985). What can they do? A review of practical assessment in science. *Studies in Science Education, 12,* 1-24.
The authors contend that this is a neglected area in assessment, although science is taken to be a practical oriented subject. They argue that in view of the emphasis given to it by different educational systems as their review revealed there should be a succinct definition of its purpose and assessments directly and not indirectly. They advocate the teaching of basic practical skills no matter the global goal of any laboratory activity. They identified methods used to assess practicals as evidenced in the literature as the external practical examination (a one-off examination); the internal practical examination (enquiry-oriented examination, stations technique, involving predetermined skills); and the continuous and quasi-continuous internal practical examinations (emphasis on grading written laboratory reports). The paper went further to identify methodological issues involved in these assessment approaches and the reasons for the failure of some of them. The authors offered the way ahead as involving the prescription of detailed checklists of practical skills, product checks, and being cautious with assessment of experiments and practical investigations. They recommend that assessment of practicals be 'practical and integral to laboratory work and given the statistically different outcomes of practical work between schools and teachers that teachers be appropriately equipped for practical assessment and guidance of students.

Carnduff, J.C. and Reid, N. (2003) *Enhancing Undergraduate Chemistry Laboratories*, London: The Royal Society of Chemistry, ISBN 0-85404-378-0.
This text represents the outcomes of an RSC Cutter Award and focuses particularly on the use and development of pre-lab exercises in university chemistry. It offers the educational research underpinning the use of such exercises, exemplars of good practice and guidelines about the development of such material. In addition, it offers an overview of the purpose of labwork in higher education, to be seen as an integrated learning experience. Although brief, it can give the essential guidance for the development and organisation of labwork at higher education level.

Cassels, J. R. T. & Johnstone, A. H. (1984). The effect of language on student performance on multiple choice tests in chemistry. *Journal of Chemical Education, 61(7),* 613-615.
As a follow up to an earlier study (see Johnstone and Cassels, 1978), the investigators prepared two sets of equivalent multiple choice objective questions and administered these to two groups of students totalling 3600 (16 year old) chemistry students. They controlled for the equivalence of the students in the two groups and manipulated the following: key words, terms of quantity, negative forms, large numbers of words and arrangement of clauses, and minor changes in parts of speech. They demonstrated that the language of the test items influenced the performance on such items. They related this to the information processing requirements of the students and concluded that the real need of understanding and performance is in the understanding of the interaction between language and the working memory capacity and background knowledge of the students.

Cassels, J. R. T. & Johnstone, A. H. (1985). *Words that matter in science.* London: Royal Society of Chemistry.
Using a sample of 30,000 pupils from 200 secondary schools, the investigators explored students' understanding of a selection of ninety common words. The tests were administered to the different years from first to sixth form. Each word was cast in four formats. The items were compared for inter group stability and the performance of words in different formats. The results showed a strong stability indicating that the sampling has been substantially random. They found that performance improved with age, and very few words were satisfactory in all their formats. It was also found that many words are not readily accessible to students, the context in which a word appears influences the understanding by students. Implications of these to concept formation and problem solving were drawn. They recommend that science teachers take time to explain the words used in science lessons.

Cokelez, A. & Dumon, A. (2005). Atom and molecule: upper secondary school French students' representations in long-term memory. *Chemical Education Research and practice, 6(3),* 119-135.
The authors explored the representation of the atom and molecule of upper secondary school chemistry students and how their conceptualisation was developed over the three years period. The sample was 930 students who responded to various questions posed by the researchers. The conceptions of the students were matched against the intended conceptualisation of the two concepts as specified by the curriculum and presented in textbooks. The major finding was that the majority of students cannot produce the minimum level of description of the concept of the atom and molecule required by the end of each grade and whatever knowledge they acquire seem to be quickly forgotten without further instruction. And that students' major misconception in this area corresponds to their internalisation of the octet rule as a mental model used to interpret the concept of the atom and considerable confusion exists between the concepts of atom and molecule.

Collins, A. M. & Quillian, M. R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behaviour, 8(2),* 240-247.
This work was the pioneer of organisation of memory as it is known presently. The authors in three experiments involving 24 subjects, with the reaction time methodology postulated that memory structure is in the form of hierarchies. The hierarchy has the superordinate, the category and the instance, with each represented at a node. Links are formed between the nodes and between the nodes and their properties. Their model could account for decisions when statements were true but could not account for judgments when the statements were false.

Cowan, N. (2000). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *Behavioural and Brain Sciences, 24,* 87-185.
Using data from studies in the literature the author supports the notion of a smaller number of 'chunks' held in the short-term memory (STM) at a time. Analysing these, he shows how the assumption of four chunks accounts for the variety of data. He however, warns that capacity limits can only be true within specified boundary conditions and that the claim of four assumes that rehearsal and the long-term memory will not combine the information into larger chunks; and that displacement of memory trace in the STM will not take place. He distinguishes two types of capacity limitations (*pure* and *compound*) and explains why *pure* capacity limit is narrow. Finally, the author proposes capacity limit of attentional processes. This article was followed by thirty-nine commentaries and a response from the author.

Craik, F. I. M. & Lockhart, R. S. (1972). Levels of processing: a framework for memory research. *Journal of Verbal Learning and Verbal Behaviour, 11,* 671-684.
In this paper, the authors reviewed literature and evidence for and against the multistore model of human memory. They propose an alternative model based entirely on the level or depth of processing of information tied closely to perception. The paper re-examined existing data on incidental learning, selective attention and sensory storage, the short term and long-term memory distinctions, the serial position curve and repetition and rehearsal effects. Implications were considered for memory research.

Danili, E. & Reid, N. (2004). Some strategies to improve performance in school chemistry, based on two cognitive factors. *Research in Science and Technological Education, 22(2),* 203-226.
The authors considered how performance of secondary school chemistry pupils might be improved in Greece given the difficulties faced by these students in the subject. The nature of chemistry, which is contributing to these difficulties, was considered and the cognitive structure and field dependency of students discussed from a psychological point of view. The work was in two phases. The first phase involved establishing that working memory capacity and degree of embeddedness are factors influencing performance using a sample of 105 first year upper secondary school pupils. In the second phase, the authors developed teaching materials designed specifically to reduce working memory load. A sample of 211 first year upper secondary school chemistry pupils was assigned to either a control or an experimental group. The experimental used the new teaching materials whereas the control followed the regular chemistry curriculum. They found a significant difference in the performance of the experimental group over the control and that the available working memory space (determined by the level of field dependency) influenced the performance of students.

Danili, E. & Reid, N. (2005). Assessment formats: do they make a difference? *Chemical Education: Research and Practice, 6(4),* 204-212
This paper compared the scores of first year upper secondary school pupils (age 15-16year old) obtained from different paper and pencil formats of classroom assessment. The aim was to test the validity of results from such assessments. The formats involved include multiple-choice, short answer, and structural communication grid. The tests were assumed equivalent because they assessed the same knowledge and understanding from the same topics. They obtained correlation coefficients of between 0.3 and 0.71. This suggests that the performance of the students were not perfectly matched. The authors raised a number of questions relating to the validity and use of different assessment techniques as a result of this study.

Danili, E and Reid, N. (2006). Some factors potentially affecting pupils' performance, *Chemistry Education Research and Practice,*7(1), in press (March, 2006).
This describes a major study where pupils were assessed in five different topic areas over much of a year's work at school level. The test employed several formats and measurements were also made of extent of field dependency and extent of divergency. The importance of these two cognitive characteristics on success in chemistry assessment is apparent but not equally in all test formats. It has already been established that working memory is an important variable as well. Taken together, the paper raises numerous important questions about assessment, what we are actually assessing (ability in chemistry or cognitive characteristics?).

De Jong, O. (2005). Research and Teaching practice in chemical education: living apart or together? *Chemical Education International, 6(1),* www.iupac.org/publications/cei. Retrieved on 29th October, 2005.
The article traces the history of chemistry education research and claims that there is a gap between chemistry education research and practice. It then identifies the reasons for the persistence of the gap and ways of bridging the gap from responses of an audience at a conference.

DeMeo, S. (2001). Teaching chemical technique. *Journal of Chemical Education, 78(3),* 373-379.
Asserting that developing appropriate techniques is one of the most important aspects of chemistry teaching the author reviewed literature on some of the most effective ways of teaching manipulative skills. Starting from Faraday, the different ways in which manipulative skills can be taught were identified and the use of prelabs were particularly detailed. Finally, he explained how the use of mental practice can be used to enhance the acquisition of manipulative skills.

Demircioglu, G., Ayas, A. & Demicioglu, H. (2005). Conceptual change achieved through a new teaching program on acids and bases. *Chemistry Education Research and Practice, 6(1),* 36-51.
This paper is a report of an investigation to determine the effect of a new teaching material on students' achievement, attitude and conceptual change on acids and bases. The authors through the review of literature identified misconceptions and alternative conceptions in this area of chemistry. The sample consisted of 88 tenth grade chemistry students (age 16-17years). The students were assigned to either the experimental or control group. The treatment involved the use of worksheets for activities that began with the challenge of students' misconceptions. This clearly involved cognitive conflict. Data were collected by the use of questionnaire, attitude scale and interviews. The results showed that although the new materials were more

successful in achieving conceptual change in students than the traditional teaching method, the level of conceptual change was still below expectation confirming the fact that students misconceptions are resistant to change. They also found a more positive attitude for the experimental group over the control group at the end of the treatment period. They called for a revision of the preservice science curricula to include elements of conceptual change.

Domin, D. S. (1999). A review of laboratory instruction styles. *Journal of Chemical Education, 76(4),* 543-547.
Presents a review of the different styles of laboratory instructions and identified four such styles, the expository, inquiry, discovery and problem-based. Each was analysed using three descriptors, outcome, approach and procedure. The author reflected on the constructivist paradigm and contended that the styles affect the environment in distinct ways, which in turn lead to different learning outcomes. He asserts that the comparative effectiveness of the styles was not certain since more research was needed. He therefore concluded by calling for more research in this area.

Donnelly, J. F. (1998). The place of the laboratory in secondary science teaching. *International Journal of Science Education, 20(5),* 585-596.
The author employed the observational technique and interview to determine the place of the laboratory in science teaching. Of particular interest to the author were the language of practice, the characteristics of the science lessons and the institutional and material aspects of laboratory work. The teachers were found to make a distinction between practical work and theory and this influenced their judgment and planning of a lesson as well as the relationship of the pupil to the lessons (e.g. interest and attention span). The science laboratory is viewed as a very important aspect of the science lessons and to this extent it influences the institutional and material situation of teachers. The paper analyses how this structures teachers work and relates to the teachers' own agency in undertaking this work.

Dori, Y. J. & Hameiri, M. (1998). The 'Mole Environment' studyware: applying multidimensional analysis to the quantitative chemistry problems.
In view of the difficulty in understanding posed by the mole concept in chemistry, the authors developed a package, Studyware. This is premised on the fact that such difficulties translate to inability to solve quantitative problems. Studyware contains problems classified into 63 different types based on a multidimensional problem analysis. The paper reports the initial validation of the package and its effect on students' learning strategies and pre-service chemistry teachers' understanding of the mole concept and its relationship to environmental literacy.

Dori, Y. J. & Hameiri, M. (2003). Multidimensional analysis system for quantitative chemistry problems: symbol, macro, micro, and process aspects. *Journal of Research in Science Teaching, 40(3),* 278-302.
Based on the importance of problem solving the investigators employed a multidimensional analysis system to classify, construct and analyse quantitative chemistry problems. They detailed the nature and use of this system and applied it in the study. They explored the effect of using this system in improving students' achievement and the difference between a control group and those involved in the experimental treatment. They also sought to establish the relationship between the problem complexity and transformation level according to this system and success in problem solving. 241 students from six high schools participated in the study. They found that the achievements of the two groups differed in favour of the experimental group and that and that the success rate in problem solving decreased as the complexity increased. Finally, hey found that improvement was dependent on the pretest score, mathematics level, but independent of gender. Recommendations were made based on the results.

Driver, R. (1983). *Pupil as Scientists?* Milton Keynes: Open University Press.
The book faulted the curriculum of its time that based its approach on induction, the heuristic method and presentation of scientific inventions as a catalogue of objective facts. It argues that children come to the science classroom with already formed ideas about the world and natural phenomena. It posits that these preconceptions influence how each student conceives a scientific facts even in the face of 'objective knowledge. With many examples this is driven home and claims that some of these ideas are resistant to change. The book expounds Piaget's theory, not so much the stage theory as his idea of the process of learning, and esteemed teaching for conceptual change over teaching for cognitive skill development. Finally, it raises the question of classroom practice and curriculum inclusions and organisation.

Driver, R. (1989). Students' conceptions and the learning of science. *International Journal of Science Education, 11(Special Issue),* 481-490.
Driver writes an introduction to this special issue by reviewing work done in the area of children's ideas in science and the conceptual change literature. She ends by raising an agenda for future research in the area.

Driver, R. & Easley, J. (1978). Pupils and paradigms: a review of literature related to concept development in adolescent science students. ***Studies in Science Education, 5,*** **61-84.**
The authors made a distinction between misconceptions and alternative frameworks and show how these are related to two kinds of studies, nomothetic studies, with four particular questions; and the ideographic studies. The authors then review nomothetic studies under grade placement studies, studies of psychological ordering of sub-concepts within a conceptual area, studies relating concept development to Piagetian stages and studies of misconceptions. Ideographic studies were reviewed under, Piagetian early studies on children's interpretations of natural phenomena, Piaget's epistemological perspectives, Piagetian studies on causality, naturalistic studies of pupils' alternative frameworks and conceptual frameworks (the effect of experience and instructions). They called for Piaget's work to be placed in the correct perspectives and for curricula to be versatile taking into consideration the individuality of learning while taking cognisance of patterns and trends in pupils' conceptual development.

Driver, R., Guesne, E. & Tiberghien, A. (1985a). Children's ideas and the learning of science. In R. Driver, E. Guesne, & A. Tiberghien, (Eds.) ***Children's ideas in Science*** **(pp. 1-9). Milton Keynes: Open University Press.**
The article introduces the idea of alternative frameworks by considering an episode involving two students doing an experiment and the process and discursive activities of their coming to know. The authors assert that children have built up explanatory frameworks before formal science lessons. These ideas are characterised as personal, incoherent and stable. They proffered a model of the interaction between these prior ideas and science learning by making reference to the psychological theories of Ausubel, Piaget and Wallon. The model incorporates the ideas of schemes and knowledge structures in the memory. Knowledge structures imply organisation of some form, which may need reorganisation for assimilation to take place. The authors give three purposes of this understanding.

Driver, R., Guesne, E. & Tiberghien, A. (1985b). Some features of children's ideas and their implications for teaching. In R. Driver, E. Guesne, & A. Tiberghien, (Eds.) ***Children's ideas in Science*** **(pp. 193-201). Milton Keynes: Open University Press.**
The article discussed the characteristics of children's ideas under the following headings: perceptually dominated thinking, limited focus, focus on change rather than steady-state situations, linear causal reasoning, undifferentiated concepts, context dependency, and predominant conceptions. The authors contend that in some areas the history of the development of conceptions parallel those in science itself and draw the conclusion that conceptual change is a long term process. Curriculum planning according to this article must therefore take into consideration the learners' prior knowledge, provide opportunities for pupils to make their own ideas explicit, introduce discrepant events, encourage the generation of a range of conceptual schemes, provide a range of situations for practice in using ideas.

Driver, R and Oldham, V. (1986). A constructivist approach to curriculum development. ***Studies in Science Education, 13,*** **105-122.**
Driver and Oldham documented a practical attempt at curriculum development using the knowledge from research in cognitive psychology and science education. The paper briefly presented the status of understanding reached in research about children's ideas, the constructivist view of learning, and the process of learning as conceptual change. They present five assumptions underlying their work, and a pictorial presentation of their model for curriculum development. They proceeded to record in an outline form the processes they went through for the curriculum development programme and the general features of a constructivist pedagogy.

Duncan, I. M. & Johnstone, A. H. (1973). The mole concept. ***Education in Chemistry, 10,*** **213-214.**
Pupils at the first year of a two-year O-grade course from nine Scottish secondary schools were used in this study. The aim was to determine the classification of the mole concept as concept for students who have attained Piaget's formal operations level by Ingle and Shayer in 1971. They gave a number of questions to the students with different logical structures. An analysis of the difficulties revealed that the difficulties in teaching the mole concept seems to be (i) overcoming the misapprehension that 1 mole of a compound will always react with 1 mole of another regardless of the stoichiometry of the reaction; (ii) balancing equations; and (iii) manipulation of the molarity of solutions. This paper represented an initial analysis so judgement about the classification was not made.

Duschl, R. A. & Gitomer, D H. (1997). Strategies and challenges to changing the focus of assessment and instruction in science classrooms. ***Educational Assessment, 4(1),*** **37-73.**
The authors make a proposal for assessing students for understanding in the science classroom. Its premise is that present agenda for science education is to develop thinking reasoning and problem solving skills. They describe a form of assessment, the assessment conversation that is enmeshed in classroom activities. A curriculum unit developed along the line of a portfolio instruction and assessment (SEPIA) and the actual implementation of the curricula unit by two teachers were documented. SEPIA was described in details with the

criteria that will guide the formation and assessment of students' explanations. The challenges faced by the teachers as well as those facing portfolio assessment with special reference to assessment conversation were discussed.

Fang, Z. (2005). Scientific literacy: a systemic functional linguistics perspectives. *Science Education, 89,* 335-347.
This paper analyses the language of scientific discourses and argues that they contain unique linguistic features. It contends that an understanding of these features is critical to the construction of scientific knowledge by students. It discusses these special features including the informational density, abstractness, technicality, and authoritativeness. It draws the educational implications.

Friel, S. & Johnstone A. H. (1978). A review of the theory of objective testing. *School Science Review, 59(209),* 733-738.
In this review, the authors assert that multiple-choice objective testing is by the far the most widely used at the time. They however acknowledge that there are many criticisms regarding its use. They therefore reviewed research findings on multiple-choice objective tests under the following the headings: effect of guessing, effect of changing the initial response, effect of item order alteration, optimum number of choices, position response set, and assessment of partial knowledge. The authors did not express any opinions at the end.

Friel, S. & Johnstone, A. H. (1988). Making test scores yield more information. *Education in Chemistry, 25(2),* 46-49.
The investigators applied the 'modified caution index' of Harnish to 100 year three students (age 16) scores on a 40-item four –choice multiple-choice test. They found that using this method yields diagnostic information of students' response patterns and better criteria for item selection on a test. The paper offered details of how this can be used.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: a look to the future. *Journal of Chemical Education, 76(4),* 548-554.
The paper identifies barriers to the understanding of chemistry and contends that chemistry is a complex subject. She argues that chemistry instruction is to take account of the nature of chemistry, structure of the discipline, the language, unfamiliar materials and the laboratory techniques. These barriers were then explained in terms of the information processing theory of learning and social constructivism. It contends that chemistry research has had very minimal influence to curriculum practices in the 20th century and advocates a more aggressive influence for the 21st century.

Gardner, P. L. (1996). The dimensionality of attitude scales: a widely misunderstood idea. *International Journal of Science Education, 18(8),* 913-919.
The author points out that there is lack of understanding or complete neglect of the dimensionality of attitude scales and that this results from not conceptualising the constructs in the instruments. He considers the issues related to the principle of psychometrics under complete neglect, conceptualising without considering dimensionality, available evidence about dimensionality ignored and exemplified them with works in the attitude literature. The paper asserts that part of this confusion stems from the confusion of internal consistency and uni-dimensionality and then offered a model for good practice.

Garforth, F. M., Johnstone, A. H. & Lazonby, J. N. (1976a). Ionic equations and examinations at 16+. *Education in Chemistry, 13(2),* 41-43.
The investigators surveyed the level of understanding of ionic equations by O-level students (age 15-17 years) using a sample of 534 chemistry students. They found that the students' performance was poor and that the nature of the difficulty shown by the results persisted across the different age groups. They explained that students of this age level are not capable of the level of abstract thinking required for the understanding. They advised that chemistry curriculum planners should take cognisance of this and that there are no justifications for the inclusion of this in the curriculum. Ironically, the authors acknowledge the importance of the understanding of ionic equations to the interpretation of a number of chemical reactions, stating that it provides a unifying explanation in chemistry..

Garforth, F. M., Johnstone, A. H. & Lazonby, J. N. (1976b). Ionic equations – difficulties in understanding and use. *Education in Chemistry, 13(2),* 72-73
In this follow-up paper, the investigators analysed the difficulties that students experienced in understanding and use of ionic equations. Using the same questions but a higher number of students (N = 900, 15-17 year old chemistry students) they identified concepts, which were necessary as prerequisites to the understanding and use of ionic equations. Each of the alternatives to the multiple-choice item stems were labelled in accordance with the prerequisite concept it addresses. The investigators found that in all groups of questions the distractors

involving the knowledge of 'spectator ions' incurred the highest proportion of incorrect responses. The paper analysed other areas of difficulty and recommendations were made as a result of the findings.

Garnett, P. J., Garnett, P. J. & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: a review of research and implications for teaching and learning. *Studies in Science Education, 25,* 69-95.
This paper detailed the commonly encountered alternative conceptions of students in the areas of acids and bases, particulate nature of matter, chemical equations, covalent bonding, chemical equilibrium, electrochemistry, molecules and intermolecular forces, and oxidation-reduction. It discusses some reasons for these alternative conceptions and some misconceptions and draws implications of these for science education.

Garrett, R. M. (1986). Problem solving in science education. *Studies in Science Education, 13,* 70-95.
Written in the mid-eighties, the author gives two frameworks that have influenced problem solving (gestalt and associationist traditions). The author reviews the literature along the lines of the methods or design used in problem solving including the control/experimental group design, individual interviews, protocols and case studies. Other issues addressed are the purpose of the problem solving investigations in literature, the type of tasks, the subject variables. The author tried to present the differences between problem solving literature in the USA and the UK and suggested research being concentrated on particular issues rather than being diffused.

Garrett, R. M. & Robberts, I. F. (1982). Demonstration versus small group practical work in science education. A critical review of studies since 1900. *Studies in Science Education, 9,* 109-146.
The authors define a number of terms and identified arguments in literature concerning demonstrations and small group work. He noted that the questions raised by earlier workers are still with us, questions of logistics, goals and procedure of laboratory work. A review of the works followed under the headings: the experimental design, the statistical techniques and conclusions produced, the investigational tools employed, and the purity and consistency of the strategies and tactics employed. They concluded that the way forward is to determine the function of the school laboratory and the development of instruments for measuring the outcomes of practical work as well as the laboratory environment. Demonstration and small group work were seen to have their relative places in practical work.

Gerjets, P., Scheiter, K. & Catrambone, R. (2004). Designing instructional examples to reduce intrinsic cognitive load: molar versus modular presentation of solution procedures. *Instructional Science, 32,* 33-58.
Drawing on five earlier empirical works by the authors, they ague that intrinsic cognitive load during problem solving is best reduced by presenting example-based learning in modular rather than molar form. In this form, complex solutions are broken down into smaller portions conveyed separately. They contend that this is superior to the molar type where all the information relating to the problem-category membership, structural task features and category-specific solutions procedure are presented simultaneously thereby increasing cognitive load. They review literature on cognitive load theory and detail the three kinds of cognitive load, intrinsic, extraneous and germane.

Gil-Perez, D, Dumas-Carre, A, Cailot, M. and Martinez-Torregrosa, J. (1990). Paper and pencil problem solving in the physical sciences as a research activity. *Studies in Science Education, 18,* 137-151.
The review began by asserting the results of many studies that show that students have serious difficulties in doing paper and pencil problem solving, often not knowing where to begin or how to go. It presents the two theoretical foundations (expert and novice tradition versus the algorithmic tradition) underpinning most problem solving literature, and the meaning of the term problem from literature. The paper addresses problem solving as a research activity and proffered several ways in which problem solving can be approached in the classroom. Finally, problem solving is related to the constructivist paradigm where students can apply their preconceptions and experience cognitive conflicts.

Hadden, R. A., Handy, J. and Johnstone, A. H. (1974). Education through chemistry? *Education in Chemistry, 11,* 206-207.
The investigators explored the affective contributions of the chemistry curriculum by administering a questionnaire testing students' use of science knowledge in socioscientific issues. A sample of 1300 sixteen year old pupils assigned to two groups, science pupils and non-science pupils responded to the questionnaire items. It was found that the science students had a higher attainment level of the affective objectives of the chemistry curriculum. They suggested a shift in the role that science teaching should play particularly in the education of non-science career aspirants. They however acknowledged that attitude development is a multidimensional issue.

Hall, R. H., Dansereau, D. F. & Skaggs, L. P. (1992). Knowledge maps and the presentation of related information domains. ***Journal of Experimental Education, 61(1),*** **5-18.**
A sample of 92 students was assigned to two groups. The experimental were taught by the use of concept maps whereas the control was taught by the traditional method of using text. The two groups were presented with knowledge in two different domains and in two different forms. It was found that students in the concept map group had higher immediate gains than students in the text only group in one of the knowledge domains but not in the other. The reasons for this domain sensitive differential were identified and discussed.

Han, J. & Roth, W-M. (2005). Chemical inscriptions in the Korean textbooks: semiotics of macro- and microworld ***Science Education,*** **online at www.interscience.wiley.com**
This paper did an in-depth analysis of grade-seven Korean science textbooks. To do this, they developed a framework for analysing chemical inscriptions. The paper questioned the inscriptions and illustrations used in chemistry textbooks in Korea, arguing that much of the problems encountered by students in relating the macro- to the microworld might be because of the illustrations and inscriptions used in textbooks. The paper proceeded to consider inscriptions in chemistry textbooks, and semiotics in science. They identified genres of chemical inscriptions and the weaknesses of the illustrations, the skill requirements for reading and understanding the inscriptions, ways of handling contradictions that may arise by the reading of the inscriptions. Questions were raised from the result of the study.

Handy, J. & Johnstone, A. H. (1973a). How students reason in objective tests. ***Education in Chemistry, 10(3),*** **99-100.** Using a sample of 120 students the investigators explored the reasoning behind students' choice from the alternatives given inn objective testing. Students were tested and afterwards asked for the reasons that advised their responses. They demonstrated that most correct answers in an objective test were selected validly, the number of students guessing blindly on any particular question was very small and that failure of students to answer comprehension questions was because of their being deficient in knowledge. However, they concluded from the result of the study that objective testing reveals the product of students thought patterns rather than the processes.

Handy, J. & Johnstone, A. H. (1973b). Reproducibility in objective testing. ***Education in Chemistry, 10(2),*** **47-48.**
The authors question the use of tests validated and trialled for reliability under a different condition such as time, environment and sample in another condition such as an examination condition. They tested the hypothesis that the outcome of such testing would differ and that questions form similar conditions, such as previously used examination items in another examination, would produce the same result. Using a sample of first year chemistry students they indeed found that the statistical results of the second condition were reproducible while the statistical result of the first was not. They however cautioned that if the internal standards of the tests performed differently, the students' scores should be corrected for guessing. They formulated a formula for the purposes of this.

Hill, R.A., Hassan, A.K. and Reid, N. (2004) Ideas Underpinning Success in an Introductory Course in Organic Chemistry, ***University Chemistry Education*****, 8, 40-51.**
Analysis of school syllabuses suggested four underlying ideas which would be important for students facing their first university-level organic chemistry course. Understanding of these ideas was tested before students embarked on the course and was related to their actual performance at the end of the course. Three of the four ideas were found to be important, with one being particularly important: understanding the concept of polarity. The study was based on information processing ideas and the work of Ausubel and supported the predictions from these models.

Hodson, D. (2005). Towards research-based practice in the teaching laboratory. ***Studies in Science Education, 41,*** **167-176.**
In reviewing the book *Teaching and Learning in the Science Laboratory* (edited by Psillos, D. and Nieggerer, H.), the author posits that in the past during the phase of inquiry learning the case for practical work was made in terms of cognitive, affective, skills-based and class management arguments. The change in the paradigmatic underpinning of science teaching notwithstanding, the author states the expectations of laboratory work, in terms of its goals, has not changed. Research findings indicate the effectiveness is questioned and reasons for this were proffered: (i) practical work is too gross a term, too large a category; (ii) teachers do not always (perhaps only rarely) do what they say they will do. In other words, there is significant mismatch between rhetoric and practice; (iii) students do not always do what the teacher intends or expects. They may misread instruction, fail to distinguish between what is significant and what is unimportant, lack the necessary skills to collect reliable data, or just get bored and fail to finish; and (iv) practical work frequently doesn't work, in the sense that it gives unexpected, inconsistent or inconclusive results, and sometimes no results at all. The review ended by analysing the different contributions to the book and extracting their strengths and weaknesses.

Hodson, D. & Bencze, L. (1999). Changing practice by changing practice: toward more authentic science and science curriculum development. *Journal of Research in Science Teaching, 36(5),* 521-539.
This paper documents the effort made by two science educators and an educationalist at changing the curriculum of a group of students by the introduction of the nature of science into their teaching. It discusses some of the variables involved in these processes. These include the teachers' change of view about the teaching of science, the psychological demands and the institutional constraints. The paper also considered some of the characteristics of inauthentic science education and makes a case for the changing of curriculum development practice. They called for the involvement of teachers in action researches in order to enable them transit to new curricula.

Holbrook, J. (2005). Making chemistry teaching relevant. *Chemical Education International, 6(1),* www.iupac.org/publications/cei. Retrieved on 29th October, 2005.
Posits that research has demonstrated chemistry teaching to be unpopular in the eyes of students; does not promote higher order thinking skills; leads to gaps between students' wishes and teachers' teaching; and is not changing because teachers are afraid of change and need guidance. He attributed these to the irrelevance of chemistry and argued that teaching for conceptual change and in context may be necessary but not sufficient to reverse the itemised shortcomings. He contended that education should be through chemistry and not chemistry through education, and went ahead to contrast the two modes of chemistry education. The article emphasises conceptual learning in the context of the society and not the student. Progression of chemistry teaching should therefore be from the societal (the familiar) to the concepts (the unknown). Using a concept map for the element chlorine, the author prescribes how it could be made relevant. The paper stresses a Science-Technology-Society Approach with a strong case made for strategies that make the experiences personal to the students and inculcating the skills of an STS approach. Finally, suggests background knowledge for the teacher to supplement the inadequacy of textbooks in such an approach.

Hollingworth, R. (2001). The role of computers in teaching chemistry problem solving. *Chemical Education Journal, 5(2),* www.juen.ac.ip/scien/cssi/cejrnlE.html Retrieved on the 29th of October, 2005.
Maintained that algorithmic problem solving approach yields moderate success and does not progress to conceptual understanding. The paper x-rayed the meaning and types of problem solving in chemistry; captures beautifully the place of expertise in problem solving as against novice problem solving. Unfortunately, it fails to relate the type of problem to the level of expertise while stressing the role metacognition plays. The author reviewed some materials on the ways of teaching problem solving skills and zeroed in on metacognitive strategies; and the use of the computer in this. This paper is very useful because it gives an annotated listing of some websites dealing with problem solving in chemistry. The website of the metHEAD tutorial on problem solving in chemistry of the University of New England was detailed because the author is part of the project. It concluded by making suggestions for future use of computers in problem solving.

Hodson, D. (2005). Towards research-based practice in the teaching laboratory. *Studies in Science Education, 41,* 167-176.
In reviewing the book *Teaching and Learning in the Science Laboratory* (edited by Psillos, D. and Nieggerer, H.), the author posits that in the past during the phase of inquiry learning the case for practical work was made in terms of cognitive, affective, skills-based and class management arguments. The change in the paradigmatic underpinning of science teaching notwithstanding, the author states the expectations of laboratory work, in terms of its goals, has not changed. Research findings indicate the effectiveness is questioned and reasons for this were proffered: (i) practical work is too gross a term, too large a category; (ii) teachers do not always (perhaps only rarely) do what they say they will do. In other words, there is significant mismatch between rhetoric and practice; (iii) students do not always do what the teacher intends or expects. They may misread instruction, fail to distinguish between what is significant and what is unimportant, lack the necessary skills to collect reliable data, or just get bored and fail to finish; and (iv) practical work frequently doesn't work, in the sense that it gives unexpected, inconsistent or inconclusive results, and sometimes no results at all. The review ended by analysing the different contributions to the book and extracting their strengths and weaknesses.

Inhelder, B. & Piaget, J. (1958). *The growth of logical thinking: from childhood to adolescent.* London: Routledge and Kegan Paul Ltd. (Translated by Parsons, A. and Milgram, S.)
In this work, the adolescent thought processes were explored. The authors considered how children transit from childhood thought to adolescent thought. They argue that the adolescent is capable of propositional logic whereas the child is only capable of operations on classes and relations alone. Using certain natural phenomena, they examined the development of propositional logic, the operational schemata of formal logic and the structural integration of formal thought. They arrived at the conclusion that the thinking of the adolescent is radically different from that of the child and that adolescent thinking is a result, albeit indirectly, of the transformations of thought and assumption of adult roles. Formal structures are seen as laws of equilibrium.

Johnson, P. (1998). Progression of children's understanding of a 'basic' particle theory: a longitudinal study. *International Journal of Science Education, 20(4),* 393-412.
In a three-year longitudinal study, the author investigates the progress made by a cohort of students as they move from year 7 to year 9 in an English comprehensive secondary school on the concept of a substance. The paper describes the six hierarchical conceptions of matter from literature. Data was collected by means of interview. It was found that the particle ideas were introduced by the teaching units; students progressed from one model of the concept to another over time; the development was along two dimensions, a continuous-particulate dimension and a macroscopic-collective dimension; and pupils seem to progress in one dimension at a time. The implications for teaching and research were highlighted.

Johnstone, A. H. (1978). Review of chemical education research and development in the UK, 1972-1976. *Chemical Society Reviews, 7(2),* 317-327.
In this paper, the author reviewed chemical research and development in the UK under the following headings, the general picture (higher degrees, width of interest, publication of findings); research on the curriculum (objectives, concepts, attitudes, practical work, and project work); and research and development in educational technology, evaluation of innovations, assessment techniques, and general research/research methods. He identified trends, strengths and weaknesses in these areas. He made some recommendations from the observed trends.

Johnstone, A. H. (1980). Chemical education research: facts, finding and consequences (Nyholm lecture). *Chemical Society Reviews, 9(3),* 365-380.
In this lecture, the author described the stages undergone by a group of researchers in identifying the reasons for the difficulty of chemistry as embodied in the Scottish Alternative Syllabus to students. The first phase was finding out the areas students considered difficult. The second phase was allocation of different areas to different investigators for further probing. At this stage the common problem was identified as information overload. The paper explained the sources of this overload, the presentation of the materials and the nature of chemistry. The paper discussed the topics of the curriculum in the light of the finding. Much work has been done since then on the two areas proving to be the source of the overload and a lot of insight and pedagogical techniques suggested.

Johnstone, A. H. (1981). Is knowledge enough? *Studies in Higher Education, 6(1),* 77-84.
The authors acknowledge that conceptual knowledge is not enough for a successful completion of a course in chemistry. They therefore developed and introduced some special exercises aimed at skill training for chemistry students. The paper documented the assessment of this project in terms of workability of the units, and the effect on achievement, skill acquisition and attitude of the students.

Johnstone, A. H. (1984). New stars for the teacher to steer by. *Journal of Chemical Education, 61(10),* 847-849.
In this position paper, the author claims that heeding the principles for managing working memory overload will yield immediate benefit for chemistry laboratory practices. He showed how the practices of the laboratory (from the laboratory manuals to the curriculum content order and equipment/apparatus use) combine to overload the working memory of the learner, whose background knowledge is still at a rudimentary level. He offered possible ways of rectifying this.

Johnstone, A. H. (1987). Can the slipper fit? – Grade related criteria for school science. *School Science Review, 68(245),* 737-744.
The paper considered the transition of assessment from norm referenced testing to criterion referenced testing in Scotland. It raised questions of the appropriateness of the new trend toward criterion referencing as a summative rather than a formative and diagnostic tool. It addressed the philosophical, logical underpinnings and used the William Occam's idea of judgement between variables. He discusses the problems arising from the practice and possible solutions. The paper encouraged the use of criterion referenced testing but advised that it be used appropriately.

Johnstone, A. H. (1988). Methods of assessment using grids. *Lab Talk, October 1988*, 4-6.
The author proposed an alternative to the multiple choice test technique. The use of grids, which comprise a set of numbered boxes according to the author has a number of advantages over the use of multiple choice test, which the paper discussed. The author offers the basic structure of grids, the principles of use, significance of response patterns on a grid, and the technique for scoring. Also addressed are the uses including to test ability to categorise and dig into concepts, to test the ability to sequence ideas, to test descriptions or procedures, and to test deductions and inferences at various levels. Unfortunately despite the advantages offered by this testing technique, its popularity has been low.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 7,* 75-83.
The paper relates the difficulty students experience in the learning of science to the nature of science with particular reference to its multilevel thought requirement, its language and the disparity between expectations of the teachers in the laboratory and the actual perceptual field. Of particular emphasis was the way science is taught. The interaction of these and the learners' learning processes are discussed. The author proposes the information processing system to guide teaching and research in science learning processes.

Johnstone, A. H. (1993). Introduction. In C. Wood and R. Sleet *Creative Problem Solving in Chemistry* (pp.iv-vi). London: The Royal Society of Chemistry.
To close the gap between everyday life problem solving and school problem solving, which often is algorithmic in nature, the author proposed a scheme of eight problem types along a continuum. Three descriptors are used to differentiate these problems, the data given, the method to be used to solve the problem and the goal to be reached. For each of the problem type any or none of the descriptors could be withheld. Combining what is withheld and what is provided gives the eight problem types. For example, all descriptors are given and known in the first type whereas for the eight type, all the descriptors are withheld or unknown.

Johnstone, A. H. (1996). Chemistry teaching – science or alchemy? *Journal of Chemical Education, 74(3),* 262-268.
The author compared teaching and researching and suggested that the development and pursuit of these should have the same structure. Based on this, he proposes a model based on the human information processing system. The paper described and explained the different stages of this system and demonstrated its power using the data obtained from the Scottish Examination Board. This was the result of 22,000 sixteen-year-old chemistry students on the mole concept. He then enumerated a list of ten principles for teaching and learning and showed how this can be applied in lectures, laboratories and curriculum design. He concluded by urging that chemical education should be a discipline with a shape and structure, as well as shared theories on which testable hypotheses can be raised.

Johnstone, A. H. (1997). '…And some fell on good ground'. *University chemistry Education, 1(1),* 1-36.
Using an allegory from the bible, the author represents the mind of the learner as the ground into which the seed (input) is to be made by the teacher. Likening this to a 'black box' to be opened he explains that an understanding of the learner's memory is absolutely important to any teaching and learning activity. He addresses the different stages of the memory and advocates the use of prelectures, lectures and postlectures to enhance perception, processing and storage.

Johnstone, A.H. (2000). Teaching of Chemistry – Logical or Psychological? *Chemistry Education: Research and Practice in Europe (CERAPIE)*, 1(1), 9-15.
Following a lifetime of research experience in science education, the author draws much evidence together to argue that the curriculum in chemistry should be constructed in such a way that it takes into account the psychological development of the learners as well as the psychological evidence about how learning in conceptual areas can take place. For curriculum development, there are important principles enunciated here.

Johnstone, A. H. (2001). Can problem solving be taught? *University Chemistry Education, 5(2),* 69-73.
The author considers the nature of problems arguing that a problem must have an unknown in one of its descriptors (data, method and goal). Therefore algorithms the author maintains are not problems and so problem solving cannot be reduced to routine processes which are the requirement of algorithms. Using different illustrations the author demonstrates that problem solving depends on knowledge and experience as well as some strategies that may be adopted in different problem situations. The paper discusses the organisation of knowledge in the long-term memory and draws the conclusion that we can teach techniques to organise the problem solving process as well as help students store and organise knowledge but that we cannot teach insight, which is the real requirement of problem solving.

Johnstone, A. H. & Al-Naeme, F. F. (1991). Room for scientific thought. *International Journal of Science Education, 13(2),* 187-192.
Drawing on works done in the past, this paper makes a case for patterns of performance for novice students and more mature students based on their working memory capacities and level of embeddedness. It explores the idea of potential and usable working memory, suggesting that differentiating between 'noise' and 'signal' can make a great difference between the performance of students and that this in turn is determined by a combination of the students' working memory capacity and field dependency. Strategies for manipulating these and helping the student to filter 'noise' from' signal' were proposed.

Johnstone, A. H. & Al-Shuaili, A. (2001). Learning in the laboratory: some thoughts from the literature. ***University Chemistry Education, 5(2),*** **42-51.**
This review examined the purpose of laboratory work under skills and affective aims. It also reviewed literature on the types of laboratory work and came up with an abridged descriptor of the different types as well as the strategies employed in each type, relating these to the purposes identified. Finally, it addressed the assessment of laboratory outcomes.

Johnstone, A. H. & Ambusaidi, A. (2000). Fixed response: what are we testing? ***Chemistry Education: Research and Practice in Europe, 1(3),*** **323-328.**
The paper was introduced by briefly tracing the history of fixed response testing and its advantages. Some concerns were raised about this mode of testing and then literature was reviewed dealing with fixed response assessment. The aim of the paper was to stimulate thought and debate among examiners and to alert them to be cautious.

Johnstone, A. H. & Cassels, J. (1978). What's in a word? ***IEEE Transactions on Professional Communication, PC-21(4),*** **165-167.**
The investigators assessed the effect of language on performance of students in chemistry using 6000 students from Scotland and England. They selected questions from the Scottish Certificate of Education Examination Board Item Bank and rewrote the questions by altering one word, reducing the length of the sentence in some, turning others from negative to positive form and for others, simplification by removal of subordinate clauses. They found that changing the language of questions brought about marked improvements.

Johnstone, A. H. & Kellett, N. C. (1980). Learning difficulties in school science – towards a working hypothesis. ***European Journal of Science Education, 2(2),*** **175-181.**
Following earlier work done by Johnstone and various other colleagues on the difficulty students experience in the sciences, the authors came up with the hypothesis in this paper that difficulty is as a result of students being unable to 'chunk' materials in the working memory. This is in direct relationship to the capacity of the working memory which is placed at 7 ± 2. This paper discussed this relationship using the area of organic chemistry. Implications for the curricula were addressed and strategies offered for the science teacher to use in order to help students overcome this difficulty.

Johnstone, A. H. & Letton, K. M. (1982). Recognising functional groups. ***Education in Chemistry, 19,*** **16-19.**
Using the principle of cognitive load theory of teaching isolated materials and chunking, the authors implemented the idea of an electrical question and answer board originally proposed in the University of Caen and disseminated by ReCoDiC (http://www.unice.fr/cdiec/a_propos/historique.htm). The aim was to allow students practice recognition of the functional groups from their structural formulae, before becoming involved in an organic course. This paper is a report of the initial effort and logistics involving the development, practical aspects of the development and observation of the use of the program.

Johnstone, A. H. & Letton, K. M. (1989). Is practical work practicable? ***Journal of College Science Teaching, 18(3),*** **190-192.**
The authors assert that laboratory work in our age is not efficacious because it does not take into consideration the psychology of learning. They reflected on the processes of the information processing system and showed how the limitation in working memory interacts with the procedures and requirements of laboratory work to create an impossible learning situation for the students. They proposed that laboratory work should be seen as a freestanding teaching mode; where acquisition of manipulative skills will precede the use of the skills in problem solving situations, rather than tying it to any theoretical lecture course. Secondly the lab manuals can be written in a manner that will reduce redundant materials.

Johnstone, A. H. & Letton, K. M. (1990). Investigating undergraduate laboratory work. ***Education in Chemistry, 27(1),*** **9-11.**
This work is a documentation of the evaluation of a second year undergraduate chemistry laboratory programme. The evaluation was aimed at finding out the areas (physical, inorganic and organic chemistry) of the laboratory students were finding difficult. Using the diaries of a sample of 24 students as well as the interview responses, the investigators identified the physical chemistry area as the most problematic. By scrutinising the manuals they implicated overload, particularly, conceptual overload as a cause of difficulty. They suggested that the way in which experiments and manuals are traditionally designed did not take into cognisance the psychological load, which they impose on students.

Johnstone, A. H. & Letton, K. M. (1991). Practical measures for practical work. *Education in Chemistry, 28(3),* 81-83.
As a follow-up to the earlier work, the authors analysed six lines from three pages of a second year undergraduate experimental instructions of an inorganic chemistry manual. They describe five principles they were to take in the improvement of the manual. These include 'noise' reduction in the lab, 'noise' reduction in the instructional manual, the principle of practice, prelab, and post lab. These were explained in details in this article.

Johnstone, A. H., MacDonald, J. J. & Webb, G. (1977a). Chemical equilibrium and its conceptual difficulties. *Education in Chemistry, 14(6),* 169-171. The investigators administered a rates approach to chemical equilibrium test to 255 secondary school students in Scotland. The aim was to highlight areas of difficulties in students' understanding of chemical equilibrium. The areas included, left and right sidedness, interpretation of the revised arrow, effects of variables on equilibrium systems, catalysis and energy. They analysed the nature of the difficulties and implicated to a great degree students' prior knowledge and method of presentation. They offered strategies for avoiding these conceptual difficulties.

Johnstone, A. H., MacDonald, J. J. & Webb, G. (1977b). Misconceptions in school thermodynamics. *Physics Education, 12,* 248-251.
In this investigation, the main idea was to examine the development of the idea of dynamic equilibrium through thermodynamics and to seek misconceptions in the concepts of enthalpy, free energy, and entropy. They administered a test of thermodynamics approach to 98 sixth form secondary school chemistry students. Eight major areas of difficulty and where students' prior knowledge hinder correct conception were identified. Again, the investigators blamed the teachers and teaching approaches as well as students' prior knowledge. They made a number of suggestions to overcome the problems including, teachers consciously helping students to make correct connections to students' prior knowledge, and the use of early concrete and pictorial presentation.

Johnstone, A.H., Morrison, T.I., and Reid, N. (1981, reprinted 1982, 1986, 1988). *Chemistry About Us*. London: Heinemann: London, ISBN 0-435-64499-8.
This textbook (for approximately GCSE age) was written to be based deliberately on the chemistry research evidence available at that time. It illustrates numerous new approaches which were demonstrated to be successful, many of which, sadly, have not been taken up in subsequent texts. Although dated, it points to a better way forward in curriculum presentation. It has also contains novel features in the way it seeks to apply chemistry to life by means of groupwork interactive exercises

Johnstone, A. H., Morrison, T. I. & Sharp, D. W. A. (1971). Topic difficulties in chemistry. *Education in Chemistry, 8*, 212.
In three large scale surveys, the authors identified the topics that students perceived as difficult in their O grade, H-grade and Sixth Year chemistry course. Although different criteria were used in each case, the authors found an agreement to the responses of the students. Questions were raised about what the authors called the 'intuitive' chemistry syllabus in existence at the time.

Johnstone, A. H. & Reid, N. (1979). Bringing chemical industry into the classroom. *Chemistry and Industry, 4,* 122-123.
In this paper, the authors report the result of an assessment of aspects of an interactive package developed to foster awareness of the implications of the chemistry education students were receiving. This paper assessed the aspects dealing with the chemical industry using a sample of 1100 pupils. The assessment involved paper and pencil tests and interviews. Results indicated that students who had used these packages had a better industrial awareness than their counterparts who had not used these packages.

Johnstone, A. H. & Reid, N. (1981). Towards a model of attitude change. *European Journal of Science Education, 3(2),* 205-212.
The authors in this paper proposed a model for attitude change with the aim was to bring together studies done in this area by showing its power in rationalising a wide range of experimental data and generating problems for research. To do this, they reviewed earlier works and definitions of attitude, and types of attitudes. They also addressed the relationship between attitude and cognition. The model took into consideration the experimental development of attitude and the stability of attitudes.

Johnstone, A. H. & Reid, N. (1981). Interactive teaching materials in science. *South Australian Science Teachers Journal, 812,* 4-15. This article is a report of the rationale and assessment of a series of interactive teaching packages for chemistry teaching for students aged 15-16 years. The packages come in a variety of forms, booklets, sheets, tapes, overhead projector overlays and slides. Three major areas deemed often neglected by science classes were of particular interest, scientific attitudes, social attitudes, and interpersonal skills. The materials adopted an obvious STS approach.

Johnstone, A. H., Sleet, R. J. & Vianna, J. F. (1994). An information processing model of learning: its application to an undergraduate laboratory course in chemistry. *Studies in Higher Education, 19(1),* 77-87.
This paper (an implementation of Johnstone and Letton's (1990, 1991) work reports the use of the information processing model to improve a laboratory course in inorganic chemistry for a first year undergraduate chemistry programme. The development took place over a duration of three years and involved the improvement of the written instructions and organisation, and the introduction of an initial training on laboratory techniques, a prelab and a mini-project at the end. In the first year, the written instruction was improved and evaluated by comparison to the old one. In the second year, the new manual was used and the other improvements were introduced and evaluated and in the third year a final improvement took place. There was an indication from students' diaries, and instructors' checklists that the changes were effective in improving students' attitudes towards the laboratory course.

Johnstone, A.H., Watt, A and Uz-Zaman, T. (1998). The students' attitude and cognition change to a physics laboratory, *Physics Education*, 33(1), 22-29.
The authors describe a very elegant experiment where they tested the ideas derived from information processing in an attempt to improve learning and attitudes in relation to a first year physics lab course. The outcomes are quite dramatic not only in the markedly increased performance in tests of understanding but also in the remarkable attitude changes observed.

Johnstone, A.H. and Webb, G. (1977). *Energy Chaos and Chemical Change*. London: Heinemann.
This book illustrates a way forward for themes of difficulty. Based in science education research evidence, the authors have analysed the key skills which are essential for all chemists at this level (about end school through first year university) and have developed a text which brings thermodynamics alive in its application in real chemical situations. It lays an excellent foundation for future study. It avoids the use of unnecessary abstract ideas and the use of mathematical manipulations. Many learners can memorise the use of these but have little grasp of the underlying thermodynamic ideas which are much more important. The book also exists in Italian. The text is specially important in that it was based on research evidence on learning.

Johnstone, A. H. & Wham, A. J. B. (1982). The demands of practical work. *Education in Chemistry, 19(3),* 71-73.
The authors analysed laboratory work in the light of the working hypothesis that learning is severely hampered in a high information situation. The state of a learner's working memory is described as unstable in such a situation exemplified by the laboratory. This was graphically presented. The actions induced by such a situation by a student are presented and possible actions on the part of the teacher to improve practical work were also suggested. The authors called for the redesign of experiments in the light of these after discussing ways these unstable situations are introduced in the laboratory.

Jones, B. & Lynch, P. P. (1989). Children's understanding of the notions of solid and liquid in relations to some common substances. *International Journal of Science Education, 11(4),* 417-427.
With the aid of primary school teachers, the authors explored the conceptions about the classification of some common substances (wire, plasticine, wood, wax, glass, flour, chocolate, sugar, ice, jelly, cotton and copper) as solids or liquids by a sample of 137 children. These children were distributed along grades 2 to 6 of the Australian school system. Using a clinical interview and questionnaire mode, they found that children's responses varied but can be classified into three, relationship to strength, spatial arrangement and potential for change; and that a significant difference only existed among the grades in three of the substances (wood, copper and wax). They addressed the implications of these especially in the light that when their subjects made correct responses they sometimes based it on incorrect premises.

Jones, M. & Gott, R. (1998). Cognitive acceleration through science education: alternative perspectives. *International Journal of Science Education, 20(7),* 755-768.
The investigation was carried out to determine the usefulness of the CASE (cognitive acceleration through science education programme) intervention programme. The investigation was based on two issues, whether CASE can be judged empirically to have worked and its philosophical justification. They found a differential effect on different schools and groups of students. For the first issue the authors concluded that an unequivocal 'yes' cannot be given because an analysis of the characteristics of the different schools revealed the role played by organisation, support, and motivation. On the second issue, the authors differed with the CASE philosophy that the package should be an optional extra and suggested an amalgamation of the two.

Kellett, N. C. & Johnstone, A. H. (1974). Condensation and hydrolysis – an optical problem? *Education in Chemistry, 11,* 111-114.
The reasons for difficulty experienced by students in the areas of esterification and condensation were explored in this investigation. Questions were posed to isolate the nature of the difficulties whether they are visual or

conceptual. Four questions relating to the visual difficulty and three to the conceptual difficulties guided the study. Two tests designed to test the complexity of structure a given student can handle and the recognition of functional groups were administered to 33 fifth and sixth form students. The administration was undertaken tachistoscopically. The results indicated that the difficulties the students' experiences are not visual in origin and that the students do not recognise the functional groups as units nor their roles.

Kempa, R. (1986). *Assessment in science.* Cambridge: Cambridge University Press.
Kempa begins by considering the uses of examinations and assessment in science education. He identified and reviewed the three modes of assessment techniques, the multiple-choice tests, short answer and structured questions and free-response questions that were commonly used at the time. The nature and quality of measurements deriving from these were discussed, and the ways in which they can be manipulated to measure process kills and practical abilities were detailed. The author then considered attitudes and affective aspects of learning and identified three broad classes of assessment tools, interviews, written tests and inventories and direct observation. The shift away from norm referencing to criterion referencing was addressed and implications of the trend to future assessment of learning were suggested.

Kerber, R.C. & Akhtar, M. J. (1996). Getting real: a general chemistry laboratory programme focusing on 'real world' substances. *Journal of Chemical Education, 73(11),* 1023-1025.
The paper describes a general chemistry laboratory programme that was built around students' every day life. The experiments dealt with recognisable everyday substances, most of which were organic substances, sometimes brought by the students from home. The course was organised based on the nature of the materials. The exercises relied mainly on mass measurements, and titrations, however other techniques were introduced as the year went by. Students' records were encouraged but sometimes the students were asked to use fill-in-the-blank report forms. Students' evaluation of the course conducted by anonymous university questionnaire improved and they indicated they would recommend the course to friends and that they have learnt more than from other course of the same characteristics.

Kirschner, P. A. (2002). Cognitive load theory: implications of cognitive load theory on design of learning. *Learning and Instruction, 12,* 1-10.
This paper is an introduction to a special issue of the journal that dealt exclusively with cognitive load theory. It addresses the fundamental elements of the theory, which include the cognitive architecture of the learner, cognitive load, and germane cognitive load and instructional design. It introduces the six papers that make up the issue and raised some fundamental questions about cognitive load theory.

Kozma, J., Chin, E., Russell, J. & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *The Journal of the Learning Sciences, 9(2),* 105-143. The investigators employed the historical and observational methodology to examine the practices of scientists in the laboratory, that is the way scientists use language, representations and tools. Two laboratories were selected for observation, and collection of data was by field notes and audiotapes. They draw implications from the results of their analyses of the data from their historical study for students' understanding through the processes of inquiry, discourse and use of representations. The authors prescribe guidelines for designing learning environments and symbol systems. The aim is to evolve learning environments that can support students using representations in order to understand structures and processes that underlie chemistry, and to make links between the macroscopic and symbolic.

Krnel, D., Watson, R. & Glazar, S. A. (1998). Survey of research related to the development of the concept of 'matter'. *International Journal of Science Education, 20(3),* 257-289.
Using a model from Piaget's psychogenesis of basic science concepts a survey and analysis of works related to children's development of the concept of matter was made. It gives a clear idea about how this influences classification, composition and physical and chemical changes of matter. The authors suggest that the age of the children is important in determining how they can be introduced to the concept of matter. The models of matter that lead to common misconceptions were identified and discussed. This article gives an explanation of the variables involved in the conception of matter. It is recommended to be studied by curriculum planners. It cites 101 articles in this area.

Krueger, B. And Wallace, J. (1996). Portfolio assessment: possibilities and pointers for practice. *Australian Science Teachers' Journal, 42(1).* weblinks2.epnet.com. (Accessed on 4th November, 2005)**.**
The authors perceive portfolio assessment as one of the assessment procedures that assists learning and shows students' progress towards set goals. It identifies the differences between portfolios and other forms of collection of students' work and from traditional methods of assessment. It considers the different forms of evidence needed in portfolio assessment as well as the design and development of assessment portfolios. It briefly considers the use of portfolios in assessment and criteria for scoring visual presentations.

Lagowski, J. J. (2005). A chemical laboratory in a digital world. *Chemical Education International, 6(1),* www.iupac.org/publications/cei. Retrieved on 29th October, 2005.
The author elegantly introduces the importance of laboratory experience through narrating a historical event, the discovery of the action of nitric acid by Ramsen. He traces the beginning of the use of the laboratory in training. However, he noted that there are two opposing camps as to the usefulness of the laboratory in chemistry teaching. Whereas he enumerated the reasons why some favoured the laboratory, he failed to do the same for the opposing camp. He summarises Domin's work (see Domin, 1999) and advocated research-oriented laboratory experiences where independent investigation and original thoughts are esteemed over verification of already learned material. To bring about this, the Cognitive Apprenticeship Theory (CAT), with formulations modelling chemical research laboratories was favoured. He reckoned that the enormous activities involved in prelabs, labs and post labs using the CAT, will necessarily involve the use of digital technology. He described the demonstration of the advantages of this in the laboratory. He concluded that this is hinged on a constructivist theory of learning.

Lambiotte, J. G. & Dansereau, D. F. (1992). Effects of knowledge maps and prior knowledge on recall of science lecture content. *Journal of Experimental Education, 60(3),* 189-201.
In a 2 x 3 factorial design, the investigators compared the effects of presenting information (key concepts and details) as a concept map, outlines or lists. Students heard the lecture auditorily and after were presented the key concepts in the three forms. Students were classified into those that have high prior knowledge and those with low prior knowledge. The authors found that there was no significant difference in the overall performance of the students. However, when the interaction between prior knowledge and form of presentation, It was found that concept maps was more advantageous when students' prior knowledge was low and the reverse was the case for high prior knowledge students. This was explained in terms of influence of prior knowledge on organisation of incoming information.

Leat, D. & Higgins, S. (2002). The role of powerful pedagogical strategies in curriculum development. *The Curriculum Journal, 13(1),* 71-85.
Claims that much of the failure of curricula reforms can be explained from the teachers' perspectives. Thus it adopted the human-scale approach to curriculum development and describes a specific application of this at Newcastle University and its successes. The model is related to how teachers plan as well as their major concerns in the classroom.

Leo, E. L. & Galloway, D. (1996). Conceptual links between Cognitive Acceleration through Science Education and motivational style: a critique of Adey and Shayer. *International Journal of Science Education, 18(1),* 35-49.
This paper analysed the results obtained from CASE intervention programme in the light of theoretical model of motivational style. In view of the fact that the results demonstrated differential effects for different groups of students, the authors claim that the motivational style of the different groups can account for the differential effect of the intervention. This is after detailing three motivational style and relating them to the techniques of CASE.

Liu, X. (1996). The internal consistency of a concept mapping scoring scheme and its effect on prediction validity. *International Journal of Science education, 18(8),* 921-937.
Contending that results from research has not been conclusive on the prediction validity of concept mapping assessment technique and adducing this to a number of reasons such as scoring schemes, formats of concept mapping, students' experience with this technique; the author set out to investigate the internal consistency of Novak and Gowin's scoring scheme and its effect on the prediction validity. The investigation involved four grade seven science classes in a two-phase investigation. During the first phase, two classes in experienced with concept mapping, were administered concept mapping and conventional test. During the second phase, two fairly experienced classes were administered a conventional and a concept mapping test. It was found that there was no correlation between students' concept mapping scores and scores from the conventional tests. It was suggested that teachers should focus on the structure of a whole concept map rather than on the correctness of specific concept mapping attributes or else to develop new scoring procedures for concept mapping assessments.

Lynch, P. P. (1995). Students alternative frameworks: towards a linguistic and cultural interpretation. *International Journal of Science Education, 17(1),* 107-118.
Using students from three language groups, this paper demonstrated the explication of students' alternative frameworks in chemistry in terms of language and culture. It revealed the distinct influences of the two by two strategies, triangulation and comparison of science vocabularies of the three languages investigated. They made the case for different subcultures implying subcultures within the western world e.g. pop-culture, influencing science learning and conceptions differently. A number of questions for school science instructions were raised.

Markow, P. G. & Lonning, R. A. (1998). Usefulness of concept maps in college chemistry laboratories: students' perceptions and effects on achievement. *Journal of Research in Science Teaching, 35(9),* 1015-1029.
This study adopted the quasi-experimental non-equivalent group design to investigate students understanding of chemistry concepts. One hundred and seventy students were placed in two treatment groups employing different strategies. One group used concept maps to represent their knowledge whereas the other utilised essays in presenting their understanding in pre and post labs. They found no significant differences in achievement between the groups in learning conceptual chemistry although the perception of the group that constructed concept maps was found to be more positive than the other group. The investigators concluded by suggesting concept maps be used to increase motivation which will in turn increase achievement.

Maskill, R. & Cachapuz, A. F. C. (1989). Learning about chemistry topics of equilibrium: the word association tests to detect developing conceptualisations. *International Journal of Science Education, 11(1),* 57-69.
Using an improved Word Association Test (WAT) the authors explored the conceptions of thirty 15 year old students in an English comprehensive school on the concept of equilibrium. The WAT was administered three times, before, in the middle and after instructions. This was followed by introspective reports by the students. This revealed representations that corresponded to expected learning or misconceptions. Of particular interest is the finding that the learning of the concept equilibrium received interference from other concepts, chief among which are – 'static balance', 'reversing as physical movement' and 'equilibrium when everything is equal'. In accordance with the purpose of the study, which was to investigate the value of WAT as a diagnostic/formative assessment instrument, they concluded that the use of WAT was successful albeit after two improvements, the use of sentence stimuli and allowing sentence responses.

Mayer, R. E. & Moreno, R. (2002). Aids to computer based multimedia learning. *Learning and Instruction, 12,* 107-119.
This paper is a position paper addressing the aids provided by knowledge from research on cognitive load theory. The principles deriving from this research agenda that were addressed include: the multiple representation principle, the contiguity principle, the coherence principle, modality principle, and the redundancy principle.

Mbano, N. (2003). The effects of a cognitive acceleration intervention programme on performance of secondary school pupils in Malawi. *International Journal of Science Education, 25(1),* 71-87.
The paper reported that students perform poorly in the sciences in relation to other school subjects in Malawi. It then identified some of the reasons for this pattern of performance and elects to explore the area of the mismatch between cognitive ability and curriculum demands. Working with 425 pupils and employing the quasi experimental design of the pre-test post test non-equivalent control group model the investigator sought to compare the effect of the CASE intervention programme on performance over a three-year period. The Science reasoning Task and results from the final national examinations were used to collect data. In addition, an interview was carried out with 15 students and six teachers. They found that there was a positive attitude of students to the CASE programme; that the intervention accelerated the cognitive development of the students by comparison to the control. However, the finding is that the intervention achieved a differential effect in performance of the experimental group students in favour of younger boys to older boys and girls. They conclude that cognitive development levels account for a small percentage of performance and suggest that CASE works through different mechanisms to improve school achievement; and pointed to motivational factors as well as learning styles as mediators.

McClure, J. R., Sonak, B. & Suen, H. K. (1999). Concept map assessment of classroom learning: reliability, validity, and logistical practicality. *Journal of Research in Science Teaching, 36(4),* 475-492.
Sixty-three undergraduates and twelve graduate students took part in this study which was geared to assess the effect of scoring method on reliability of assessment by concept map; the validity of assessment by concept maps; and the applicability of assessments by concept maps in classroom situations. The sixty-three undergraduates were given 90 minutes of training and were then required to produce concept maps based on concepts from a course they were studying. The graduate students were paired, each pair scored the concept maps using one of six scoring modes. The highest reliability was demonstrated when the mode evaluated separate propositions represented (corroborating Safayeni et al. 2005) for a dynamic representation. Five out of the six modes of scoring were found to be valid whereas the logistics were found to be compatible with classroom practices.

Mintzes, J. J., Wandersee, J. H. & Novak, J. D. (Eds.) (1999). *Assessing Science Understanding: A human constructivist view.* San Diego: Academic Press.
This book edited by three academics has twenty contributors and fifteen chapters. It is meant to present assessment tools for teachers teaching for scientific literacy and conceptual change. This is necessary because,

as the editors claim, commonly used assessment practices have serious limitations and destructive effects and do not capture successes in creating, learning and using knowledge. The chapters are situated firmly in the constructivist paradigm. Each of twelve of the fifteen chapters is devoted to a mode of assessment, including concept maps, Vee diagrams, structured interviews, interactive protocols, image-based test, observation, portfolios, computer-based assessment, multiple-choice tests, and written tests. Other important issues on assessment were also discussed. This is a timely book given the present trend in science teaching that emphasises understanding and personalisation of knowledge, that is, meaningful learning. This book is highly recommended for science teachers and science curriculum planners of this twenty first century.

Monk, M. & Osborne, J. (1997). Placing the history and philosophy of science on the curriculum: a mode for the development of pedagogy. *Science Education, 81,* 405-424.
The reasons for the lack of success in the incorporation of the history and philosophy of science into science curricula as well as teachers' lack of adoption of this were discussed. The authors argue that these efforts have not come to terms with the teachers' perception of the major role of science education and the context in which they work. A proposal for a model of incorporating these into the curriculum was made.

Moreno, R. (2004). Decreasing cognitive load for novice students: effects of explanatory versus corrective feedback in discovery-based multimedia. *Instructional Science, 32,* 99-113.
The paper explored the use of discovery-based multimedia environments to foster selection, organisation, and integration of information for novice learners. This is premised on the principle of cognitive load theory that learning can only occur when the limited working memory is able to aid in the construction and representation of a coherent knowledge. The author therefore devised a technique for lowering cognitive load for the novice in a problem solving learning situation. Using 49 students, the author tested the comparative effectiveness of the Explanatory Feedback (EF) and Corrective Feedback (CA) strategies. It was found that the EF was superior to the CF in the learning effect, reduction of cognitive load, and that there was no difference in their effect on student motivation and interest. This paper is important given the role played by the multimedia and problem solving in present science education.

Myers, G. Boyes, E. & Stanisstreet, M. (2004). School students' ideas about air pollution: knowledge and attitudes. *Research in Science and Technological Education, 22(2),* 133-152.
The conceptions of 1082 11-16year old secondary school students were elicited using a closed-response questionnaire on air pollution. The aim was to determine their knowledge and the interaction between the cognitive aspect and attitude of the students. Data was analysed using percentages, scattergrams and chi square. It was found among other things that the knowledge of students' about unpolluted air increased with age, a number of students saw air pollution as natural but a high proportion believed air pollution can be perceived. Again, a large proportion is aware of the consequences of air pollution. There were three distinct groups from the result of the analysis and the authors conclude that the clustering suggest that there is a loose relationship between the cognitive and affective domains, although knowledge seemed to have a positive influence on the attitude of the students. They also suggest that the aims of science education, cognitive and affective should not be mutually exclusive. Implications were highlighted for science teaching.

Niaz, M. (1988). The information-processing demand of chemistry problems and its relation to Pascual-Leone's functional M-space. *International Journal of Science Education, 10(2),* 231-238.
The sample consisted of 100 freshmen students, enrolled in three sections of a chemistry class for science majors in a Venezuelan university. The investigator demonstrated, using four predictor variables, that the performance of students increased in solving problems of chemical solutions as the functional M-space increased and that the performance of the students decreased as the M-demand of the students increased. The correlations between two other predictor variables, disembedding ability and general intelligence were not significant. He concluded that information processing is important in problem solving and that teachers be aware of the informational dimensions of a problem to avoid working memory overload. The paper makes the claim that a problem can have the same logical structure but different M-demand (complexity).

Niaz, M. (1989). Relation between Pascual-Leone's structural and functional M-space and its effect on problem solving in chemistry. *International Journal of Science Education, 11(1),* 93-100.
The structural M-space, disembedding ability, developmental level and general level of intelligence of 55 freshmen at the Universidad de Oriente, Venezuela were determined using four appropriate instruments. These were related to task difficulty or M-demand of task in chemistry. A multiple regression analysis was used to predict the success of students in solving chemistry problems. It was found that for students with structural M-space of seven, developmental level was the least in accounting for differences in success followed by the disembedding ability and then general intelligence. Students with structural M-space of eight had the same result for developmental level, followed by general intelligence and then disembedding ability. The author concluded that M-space is affected by other variables such as interest and task complexity as well context specificity of the problem, and made a case for instructional demands that will manipulate task complexity.

Niaz, M. (1995). Relationship between student performance on conceptual and computational problems of chemical equilibrium. ***International Journal of Science Education, 17(3),*** **343-355.**
Working in the area of chemical equilibrium with 78 science major freshman chemistry students, the investigator sought to establish problem solving behaviours in chemistry. The work proceeded by the investigator identifying the misconceptions held by students in chemical equilibrium, and how this aided them in solving different forms of problems in related to chemical equilibrium. He found that students' success on items that demanded conceptual understanding formed a scaffold in solving computational problems and vice versa. The results also indicated that solving of computational problems alone does not translate to an understanding of chemical equilibrium and so does not lead to an acquisition of a conceptual framework in this domain. He concluded that key aspects of a concept should be presented ('enumerate particulars') to facilitate conceptual understanding before going on to problem solving.

Niaz, M. (2005). How to facilitate students' conceptual understanding of chemistry….A history and philosophy of science perspectives. ***Chemical Education International, 6(1),*** **www.iupac.org/publications/cei. Retrieved on 29th October, 2005.**
In this article the author stated his objective as reviewing recent literature on problem solving in chemistry as well as evaluating chemistry textbooks to show how it can facilitate conceptual understanding. This is in recognition that chemistry education research puts high premium on conceptual understanding. From his review, he enumerated the variables that play roles in conceptual understanding. He reported an experiment that demonstrated the importance of training students to solve conceptual problems and not algorithms only. The result was in favour of the experimental group and the difference in performance was statistically significant. He reviewed (not evaluated) evaluations of chemistry textbooks done mostly by himself except for one done by Brito et al. (2005). His conclusions revealed his purpose, to propose the inclusion of the history and nature of science in chemistry textbooks as a means of facilitating conceptual change.

Nicoll, G., Francisco, J. & Nakhleh, M. (2001). A three-tier system for assessing concept map links: a methodological study. ***International Journal of Science Education, 23(8),*** **863-875.**
The investigators developed a method of assessing non-hierarchical concept maps. The emphasis was on how links are formed and the use, stability and complexity of each link. This method is of particular importance because it affords the opportunity of understanding students' propositional representations in a particular domain. Concept maps from 56 students were analysed and graded by using this method to demonstrate its power in analysing students' understanding and knowledge representation. Each node and link was coded and the coding given point scores.

Novak, J. D. (1978). An alternative to Piagetian psychology for science and mathematics education. ***Studies in Science Education, 5,*** **1-30.**
Novak in this paper traced the historical rise of the Piagetian psychology to the lime light and events leading up to it. It introduces Kuhn's concept of scientific revolution and uses this to lay a foundation to the trend away from extrapolating Piagetian developmental psychology to science learning to the trend towards concept formation. The paper then pitches Piagetian ideas against Ausubel's ideas about meaningful learning and shows where and how they are similar as well as where they differ. With evidence from the review of empirical studies and from own studies, Novak arrives at the conclusion that it is better to aid a child in concept development which will eventually transfer to ability to solve problems and highly formal and abstract thinking. He therefore called for well designed educational experiences that will be a scaffold to well developed frameworks of concepts relevant for science learning

Novak, J. D. & Gowin, B. (1984). ***Learning to learn.*** **Cambridge: Cambridge University Press.**
The book is sewn together by two assumptions of the authors, that people think with concepts and that knowledge has structure. The aim of the book was therefore to explore how to help students and teachers understand the process of knowledge construction and the structure of knowledge. Two strategies were employed, the use of concept maps and Vee diagrams. The book addressed the use of concept mapping in meaningful learning by considering its nature and meaning and activities and ways of helping students construct concept maps and scoring criteria. The use and scoring of Vee diagrams were also detailed. Their uses as evaluation, research planning and interview instruments were discussed as well as their use as instructional design aids. The book is commended for its fine details on concept maps and Vee diagrams.

Nussbaum, J. (1985). The particulate nature of matter in the gaseous phase. In R. Driver, E. Guesne, & A. Tiberghien, (Eds.) ***Children's ideas in Science*** **(pp. 124-144). Milton Keynes: Open University Press.**
The paper briefly traced the history of the development of the atomistic view of nature and proceeded to review four selected studies investigating students' understanding of the particulate nature of matter. The major problems identified were with the vacuum concept, particle kinetics and chemical change. Interestingly, the author relates these alternative conceptions to those held in the past by philosophers and scholars suggesting the

universality of some of these alternative conceptions. A strategy to make teaching effective was suggested to include cognitive conflict and meta understanding and exposition of students' prior conceptions.

Osborne, J. Driver, R. & Simon, S. (1998). Attitudes to science: issues and concerns. *School Science Review, 79(288),* 27-33.
Considering data from the A-level examinations results in England and Wales and accounting for demographic variables, the authors showed clearly that the participation in the physical science of secondary school students are on the decline in these countries. They implicated the attitude towards the physical sciences as the factor accounting for this. They identify three key elements of attitude towards science and described these in details and the findings from research. Identification was made of certain factors as inhibiting uptake and achievement in the sciences e.g. lack of communication between teachers and students, the perceived difficulty of the sciences by students. Major factors dominating attitude to the sciences include gender, perceived difficulty, effective teaching and students' background. A suggestion was made, that reversing this trend will involve using specialist teachers in specialist areas (attitude of teachers – confidence, influence attitude of students); science should be taught in context; teach for scientific literacy; and use appropriate content. Finally, a proposal was made to education *about science* rather than *in science*.

Osborne, R. & Wittrock, M. (1985). The generative learning model and its implication for science education. *Studies in Science Education, 12,* 59-87.
The authors review was premised on the fact that the 1970s witnessed an upsurge in interest in children's ideas. They summarised the findings from researches up until the time of writing. They identify three traditions (the developmental tradition, the behaviourist tradition and the constructivist tradition) that had had major impact on science teaching. They trace the origin of the constructivist tradition and argue for the centrality of generative learning to this tradition. They give the key postulates of this model and make a schematic representation of it. The authors relate this to the constructivist tradition. They draw implications of this to teaching and learning, curriculum development and research.

Paas, F., Renkl, A. & Sweller, J. (2004). Cognitive load theory: instructional implications of the interaction between information structures and cognitive architecture. *Instructional Science, 32,* 1-8.
Contends that performance decreases with cognitive underload or overload, but that cognitive load theory is concerned with situations where a learner has to learn complex materials. The authors furnish the assumptions of the cognitive load theory. They provide the basics of the theory from evidence from empirical works in literature and explain the implications for instructional design. Finally, they introduce the papers in the special issue in which the paper was published.

Piaget, J. (1930). *The child's conception of physical causality.* London: Kegan Paul.
Piaget explored explanations of movement, predictions and explanations, explanations of machines and a child's conception of reality and causality using specific natural phenomena and events. He used three methods: a verbal method, a half verbal half practical method and an experimental method. He arrived at seventeen types of explanations, three processes characterising the evolution of causality and three stages of progression in this process.

Piaget, J. (1970). *The principles of genetic epistemology*. London: Routledge and Kegan Paul. (Translated by Mays, W.).
The book considers the stage-wise formation of knowledge. Piaget maintains that knowledge is gained by linking structuralism to constructivism and that the individual must perform continuous reorganisations in order to know. The genesis of knowledge was considered in details and problems associated with classical epistemology were addressed.

Piaget, J. (1972). *The child and reality: problems of genetic psychology.* London: Frederick Muller, Ltd. (Translated by Rosin, A.)
This book describes the development of the child as a temporal phenomenon. Piaget contends that time is necessary for duration and for order of succession and that mere learning of a particular operation will not lead to transfer except it coincides with maturation. He argues that the process of coming to know is unconscious, whereas the results of such processes are conscious and that cognitive processes are influenced by structures. He explains the concept of awareness and identified the stages of cognitive development as sensory-motor stage, pre-operational stage, concrete operational stage and the formal operational stage. He describes the child's praxis and considered perception and learning and their relationship to empiricism. Piaget contends that empiricism cannot account for the processes because an object is known only so far as the subject achieves action on it, which is incompatible with passivity implied by empiricism. The relationship of language and intellectual operations were analysed, as well as the stand of genetic epistemology in the light of gestalt theory. Finally, the importance of genetic epistemology was offered and its place in life and thought x-rayed.

Piaget, J. (1977). *The development of thought: equilibration of cognitive structures.* Oxford: Basil Blackwell. (Translated by Rosin, A.)
The book dealt in details with the processes of equilibration. The conclusion is that subjects try to reach equilibrium by avoiding incoherence. There are successive improvements of the forms of equilibration, which are essentially three, by active construction and increased coherence. The process of equilibration is thus dynamic rather than static.

Pollock, E., Chandler, P. and Sweller, J. (2002). Assimilating complex information. *Learning and Instruction, 12,* 61-86.
In four experiments using students at different levels of expertise, the investigators demonstrated the interaction between level of expertise and understanding of complex information. The students were divided into two groups. The experimental group treatment consisted of presenting isolated materials of the complex information in the first phase and all the elements and their interactivity at the second phase. For the control, all the information was presented at the same time at the two phases. Results showed that for novice students, the isolated-interacting elements proved superior to the 'interacting elements only' method of instruction whereas the reverse is the case where students already possessed rudimentary knowledge in the field. Implications for instructional design were drawn.

Posner, G. J., Strike, K. A., Hewson, P. W. & Gertzog, W. A. (1982). Accommodation of scientific conception: toward a theory of conceptual change. *Science Education, 66,* 211-227.
Conceptual change was first suggested in this article. The authors drew on Kuhn and Lakatos conceptions of the scientific revolution in propounding this theory. They assume that learning is a rational process involving the use of concepts to organise and interpret phenomena. The paper discusses two levels in the cognitive structure at which conceptual change can occur leading to reorganisation or discarding of a schema. Four conditions for conceptual change are prescribed and the notion of an appropriate cognitive ecology put forward. Strategies arising from the explanations were addressed.

Ramsden, J. M. (1998). Mission impossible: can anything be done about attitudes to science? *International Journal of Science Education, 20(2),* 125-137.
The paper is born out of the concern to the author of the disparity between the decline of interest in attitude research and teachers' increased concern about the attitude of students to science education. The paper thus clarified the meanings and definitions of key terms e.g. science, attitude, interest, motivation and the distinction between scientific attitudes and attitude to science. It raised the questions of the constructs of attitude and attitude development. Other issues discussed are those of research instrument design and methodology and nature and purpose of research into pupils' affective responses to science. The author addressed the implications for research.

Reid, N. (1999). Towards an application led curriculum. *Staff and Educational Development International, 3(1),* 71-84.
This is paper is a call to reconsider the basis of curriculum design. It analysed the basis for such designs in the past and the approaches that had been adopted. It suggests other criteria, particularly attitude, that should be considered in design of curriculum, and what the correct aim of studying chemistry should be. The author argues for an application led chemistry curriculum and defines what is meant by an applications led curriculum. Comparing the performance and participation of Scottish chemistry and physics students the author shows how an application led curriculum can enhance both performance and participation. The paper concludes by giving the principles required for such a task.

Reid, N. (2000). The presentation of chemistry: logically driven or application led? *Chemistry Education: Research and Practice in Europe, 1(3),* 381-392.
The paper presents an argument aimed at changing the direction of present chemistry curricula material selection and presentation. It contends that a large majority of students who study chemistry at the secondary school level end up not going onto careers needing chemistry. Therefore the aim of chemistry should be educating the students for citizenship. The author thus suggests that the chemistry curriculum should be application driven rather than from the logic of the discipline. He asserts that in order for chemistry education to achieve this purpose, three themes must be explored and that the application must be seen to be relevant to the child and not to the chemist otherwise it may remain as abstract as a logically driven curriculum. Examples where this has been done were presented. He makes a distinction between context led approaches and application-based approaches, and review some outcomes from some extant curricula. Finally, a suggestion was made on the application of this to the design of curricula.

Reid, N. (2003). *Getting Started in Pedagogical Research in Higher Education*, LTSN Physical Science, LTSN, Hull, ISBN 1-903815-07-X
Most books seeking to present methods to carry out educational research are very difficult for those who are starting. This short text seeks to fill that gap. It is designed to be jargon-free and is heavily illustrated from genuine research data derived from the areas of teaching and learning in astronomy, chemistry and physics. It offers entry points, summaries of key strategies and methods, and comments on how to handle the data obtained.

Reid, N. (2006). Thoughts on Attitude Measurement, *Research in Science and Technological Education,* 23(1), in press (May 2006).
Attitude measurement is reported in numerous papers relating mainly to attitudes towards chemistry and physics. There has been continual disquiet about the methods used. This papers seeks to offer an overview and history of attitude measurement, specifically orientated towards science education. It was noted that attitudes and behaviour are closely related and that although attitudes are fairly stable, they are open to change and development. The relationship between attitude and science education was explored and attitude targets in science education as well as scientific attitudes were identified and explained. Approaches to attitude measurement were detailed with particular reference to the types of questions asked, and the methods of questioning; issues of reliability and validity; and attitude scaling techniques. The author shows how many of the methods are fundamentally flawed and, while not giving totally wrong outcomes, will often not be able to paint a picture which is sufficiently clear to be helpful. There are clear recommendations on procedure and exemplars of good practice.

Reid, N and Palmer, D. (2003). *An Annotated Bibliography of Research into The Teaching and Learning of The Physical Sciences at The Higher Education Level*, LTSN Physical Sciences, LTSN Hull, ISBN 1-903815-0503. Also a web resource: http://dbweb.liv.ac.uk/ltsnpsc/AB/AB-html/AB-html.html
This offers a review of the key entry points in the literature of science education for astronomers, chemists and physicists, under a series of headings. It was designed as a resource for the academic who is starting to carry out research in science education, using literature which is widely accessible.

Reid, N. and Serumola, L. (2006). Scientific Enquiry: The Nature and Place of Experimentation: a review, *Journal of Science Education*, 7(1), 1-15.
Scientific thinking is often presented as a desirable outcome form science courses, often at very young ages. The authors have analysed the ideas implicit in the idea of scientific thinking. They review the literature and cast doubt on whether such outcomes are attainable at such ages (primary and early secondary school).

Reid, N. and Serumola, L. (2006). Scientific Enquiry: The Nature and Place of Experimentation: some recent evidence, *Journal of Science Education*, 7(2), in press.
This follows from the previous paper and describes some experimental work looking at some aspects of scientific thinking with early secondary stage pupils. The result revealed that there is little evidence that such thinking is occurring with such pupils at the moment. They outline an intervention strategy to encourage such thinking and then look again at the pupils after this experience. While there are a few developments, the overall impression is of a lack of progress. This is interpreted in terms of the cognitive development of such pupils and the suggestion is made that such outcomes may be impossible until the pupils are older.

Reid, N and Skryabina, E. (2002). Attitudes Towards Physics, *Research in Science and Technological Educatio*n, 20(1), 67-81.
The authors describe a major study where attitudes towards physics were measured at various ages from age 10 to age 20. Attitudes did not decline with age but moved up and down. The variations could be related to specific curriculum experiences and pointed to the importance of the teacher and the curricular experience. Other influences were negligible in comparison. This study suggested the importance of applications orientated curricula and offers some interesting insights into the factors which make physics attractive. It is highly likely that chemistry will show similar patterns.

Reid, N and Skryabina, E. (2002). Gender and Physics, *International Journal Science Education,* 25(4), 509-536.
This paper describes the gender aspects of the same study as above. It reveals that physics is no less attractive to girls but that their interests lie in different areas. Where both boys and girls interests are balanced in a curriculum, both genders will stay with physics, although social stereotyping may have a negative impact for girls.

Reid, N. & Yang, M-J. (2002a). Open-ended problem solving in school chemistry: a preliminary investigation. *International Journal of Science Education, 24(12),* 1313-1332.
The authors designed open-ended questions with which they explored ways that 14-17year old students solve open-ended questions. The aim was to build up patterns, from students' discussions, written materials, observations and audiotapes, of students' approaches to and reasons for difficulties in problem solving. The students worked in groups of three. They found that students' attitudes to group problem solving were positive. Background knowledge was also identified as one of the key prerequisites for successful problem solving. But more importantly the authors identified the formation of links between concepts to be of greater importance. The authors note that most of the problems used by both researchers and teachers are algorithmic in nature and by implication do not call into use the factors identified in this study. They therefore questioned the notion that problem solving skill is generic and can be taught.

Reid, N. & Yang, M-J. (2002b). The solving of problems in chemistry: the more open-ended problems. *Research in Science and Technological Education, 20(1),* 83-98.
In this position paper the authors examined the correlates of problem solving in chemistry. The paper discussed the various conceptions of problem solving as well as the different classifications by various scholars. The place of procedures and algorithms in problem solving were analysed and the role of the long term memory, working memory, and other factors in problem solving. The review concluded that open-ended problems are important for all learners and that group work should be used to foster the development of problem solving skills since problem solving in our daily experiences often takes place in a collaborative environment.

Renkl, A., Atkinson, R. K. & Große, C. S. (2004). How fading solution steps works – a cognitive load perspective. *Instructional Science, 32(1-2),* 59-82.
It has been demonstrated by cognitive load research that students should first be exposed to worked examples before being exposed to problem solving situations. When and how this should be done is the focus of this paper. Using 123 psychology students, the investigators explored the effect of the position and specificity of the steps in a problem that are faded on success in problem solving and learning in one experiment. In a second, the underlying mechanisms that render fading effective were explored. In the first experiment they found that neither the position nor the specificity has any significant effect on learning outcomes and in the second, they demonstrated that fading enhances fewer unproductive learning events, because it induces self-explanation activities leading to better learning outcomes.

Renkl, A., Stark, R., Gruber, H. & Mandl, H. (1998). Learning from worked-examples: the effects of examples variability and elicited self- explanations. *Contemporary Educational Psychology, 23,* 90-108.
The authors argue that learning with worked examples enhance schema formation more than by problem solving. In an experiment using 56 bank apprentices, in a 2 X 2 factorial design they explored the influence of worked examples and elicitation of self-examples on transfer. They found that transfer skills were greater when the subjects engaged in self-explanations of the stages of the example and not when the problems were multiple. Uniform examples generate low load even when not supported by self-explanation On the contrary, they found that multiple examples without self-explanations lead to very low outcomes. They also found that prior topic knowledge rather than domain knowledge influenced the quality of self-explanations.

Ribeiro, M. G. T. C., Pereira, D. J. V. C., & Maskill, R. (1990). Reaction and spontaneity: the influence of meaning from everyday language on fourth year undergraduates interpretations of some simple chemical phenomena. *International Journal of Science Education, 12(4),* 391-401.
14 fourth year chemistry students were interview to find out their concepts of reaction and spontaneity of four chemical phenomena. It was found that the students used mostly sensorial or perceptual features in their interpretations. When this was challenged by conflicting data, half of the students changed their conceptions to correct scientific conceptions. The paper demonstrated the interference posed by everyday familiar phenomena on the learning of scientific conceptions. The implications for teaching are addressed.

Rice, D. C., Ryan, J. M. & Samson, S. M. (1998). Using concept maps to assess student learning in the science classroom: must different methods compete? *Journal of Research in Science Teaching, 35(10),* 1103-1127.
One hundred and thirteen seventh-grade students participated in the study. These were trained in the construction of concept maps. Data was then collected from the students by means of concept maps. Using a test blueprint, the authors developed a scoring procedure for the concept maps. The students were also given a multiple choice test. The scoring of the concept maps was based on the propositions they contain and not just on hierarchy and branching. The investigators found a high correlation between the concept map scores and the scores from the objective tests administered to the students. They also found high correlations between the scores from the concept maps and state criterion-referenced and national norm-referenced standardised tests. They concluded that the method of scoring used in this investigation is a departure from former practices and

handles the questions of validity that had plagued the use of concept maps. They suggest that it should compliment other conventional test and not seen as an alternative.

Rikers, R. M. J. P., Van Gerven, P. W. M. & Schmidt, H. G. (2004). Cognitive load theory as a tool for expertise development. *Instructional Science, 32,* 173-182.
This is a commentary on the papers that appear in the special issue of *Instructional Science* dealing with the implications of the interaction between cognitive architecture and information structure. It concludes that the cognitive load theory recognises that students are at different levels of cognitive development and that this mediates between cognitive architecture and information structure to determine performance. It considers the role of cognitive load theory in expertise development.

Rips, L. J., Shoben, E. J. & smith, E. E. (1973). Semantic distance and the verification of semantic relations. *Journal of Verbal Learning and Verbal Behaviour, 12(1),* 1-20.
The authors propose an alternative model to explain some data, which the hierarchical model of long-term memory could not handle. In four experiments, they demonstrate that verification times for instance-category statements are predicted well by semantic distances between these rather than by the number of levels between the two. The results of the experiments led to the conclusion that memory structures are not logical structures but that semantic relations account for knowledge representations and learning. This implies that individuals may represent knowledge in purely idiosyncratic ways.

Roelofs, E. & Terwel J. (1999). Constructivism and authentic pedagogy: state of the art and recent developments in the Dutch national curriculum in secondary school. *Journal of Curriculum Studies, 31(2),* 201-227.
This article evaluates the implementation of the Dutch curricula in mathematics and English Language. Responses form 1000-1400 students and some teachers were used to judge the extent to which the aims of the new curricula were being achieved. Situation-specific questionnaires were used to elicit responses on four indicators of authentic learning, the type of learning advocated by the curricula. The theoretical bases of these innovations were constructivism and situated learning and the four indicators were, construction of knowledge, connectedness to students' personal worlds, value of learning activities beyond school and co-operation and communication. The results revealed very minimal achievements in the four indicators. Part of the reasons adduced for this trend were the textbooks in use and the teachers' lack of prowess in implementing such curricula. This study is interesting because it claims the Dutch curricula embraces the tenets advised by research and yet not much progress is made. It might be worthwhile to do an indepth study of the Dutch case.

Roth, W-M., McRobbie, C. J., Lucas, K. B. & Boutonne, S. (1997). The logical production of order in traditional science laboratories: a phenomenological analysis. *Learning and Instruction, 7(2),* 107-136.
Over a six-week period, the investigators collected data from the observation of some physics students in actual laboratory situation. The techniques for data collection included video tapes, observation, interview, tests and examinations. The results indicated that students constructed phenomena from interaction of existing practices such as language, actions, worldview and social relations. An action is judged adequate by the interpretation of the outcome rather than a judgement of the action in itself. It was also found that even with elaborate instructions, students constructed phenomena different form the one the instructor expected because they bring different interpretive frameworks to bear upon the result of their actions. The authors proposed strategies for dealing with students' non-scientific interpretations (phenomena) during laboratory work.

Rowntree, D. (1987). *Assessing students: how shall we know them?* London: Kogan Page.
Rowntree addresses various issues that concern assessment of students. He considered the meaning and purposes of assessment, the interpretation and side effects of assessment, what and how to assess and how to report the product of assessment. Rather than look at specific assessment techniques, the book considered enduring matters for selection, inclusion and use of assessment modes and techniques, that is a tool for evaluation of assessment practices for schools.

Rumelhart, D. E.; Lindsay, P. H. and Norman, D. A. (1972). A process model for long-term memory. In E. Tulving and W. Donaldson (Eds.), *Organisation of memory* (pp. 309-351). New York: Academic Press.
The authors described the long-term memory as a database. The structural organisation involves a set of nodes interconnected by semantic relations. The node represents a unit of information. This could be a proposition or an object. The paper categorised information to be either of three types, the concept, event or episode. The paper elaborated on these and made schematic representation of these claims.

Sadler, P. M. (1998). Psychometric models of student conceptions in science: reconciling qualitative studies and distractor-driven assessment instruments. ***Journal of Research in Science Teaching, 35(3),*** **265-296.**
Discusses the advantages of the multiple test assessment strategy in view of present knowledge about the process of science learning and the different stages its development has gone through. These include the classical test theory, and the item response theory, the use of the latter in assessment of alternative conceptions were identified. Using 2562 students, the author determined the impact of different instructional strategies on students' construction of astronomical concepts. With the aid of three items from the pool of 47, the author analysed the instrument, for ability to discriminate among different ability levels and susceptibility to alternative conceptions, progress toward understanding of correct scientific conceptions. Implications for the curricula and sequencing of concepts were drawn form the result of the study.

Safayeni, F., Derbentseva, N. & Cañas, A. J. (2005). A theoretical note on concepts and the need for cyclic concept maps. ***Journal of Research in Science Teaching, 42(7),*** **741-766.**
This paper reviewed literature on concept map as a mode of knowledge representation. It captures the need for concept maps and the debate on the structure of concept maps. The paper reflects on the relationship between categories, their relations and concept maps and makes a case for an improvement on present structures of concept maps, which are hierarchical and static in the representation of knowledge. Asserting that knowledge is dynamic, the authors proposed a cyclic concept map structure to capture the dynamic relationships among concepts. This was illustrated and discussed and the research implications were put forward.

Schmidt, H. (1990). Secondary school students' strategies in stoichiometry. ***International Journal of Science Education, 12(4),*** **457-471.**
The author analyses 6262 secondary school students' responses to test questions in order to determine the factors that influence their successes in chemistry problem solving. It was found that the type of problem (e.g. easy/hard and the number of withheld information) determined to a great extent the successes of the students. The implication of problem type and level of difficulty of a teaching unit was discussed, with considerable details for the area of stoichiometry.

Séré, M-G, (2002). Towards renewed research questions from the outcomes of the European project ***Labwork*** **in science education.** ***Science Education, 86,*** **624-644.**
This paper summarised and reported the outcomes of the Europe-wide research on labwork aimed at addressing the effectiveness of labwork in science education. The present article concentrated on articulating the objectives of labwork under the categories of conceptual, procedural and epistemological objectives. On the conceptual perspectives, they argue that the worlds of concepts and models are closely linked to the worlds of objects/events/observations. Therefore the laboratory should induce students to use theories and concepts through appropriate questions. That is the goal of laboratory work should not just be for practice to consolidate concepts but rather for theories to guide practice. On the epistemological front, they assert that what the students construe as what and how the scientist work influence what they do in the laboratory. On the other hand, what the students do also influence their understanding of the scientists' work. The laboratory is thus a good place to teach the epistemology of science. On the procedural front they posit that autonomy is enhanced by awareness of procedures, know-how and approaches.

Shayer, M & Adey, P. (1981). Towards a science of science teaching: cognitive development and curriculum demand. London: Heinemann Educational Books.
The book was written for science teachers and grew out of the need to reduce the mismatch between curriculum demands and expectations of students and their abilities. The aim was to formulate a model that would predict likely successes and failures in the school as well as address learning materials and students' cognitive processes. They restricted their modelling to the cognitive aspects of the learner, thus using the Piagetian stage-wise theory of cognitive development as an underpinning psychological theory. The book reports the development of two instruments, the Science Reasoning Tasks and the Curriculum Analysis Taxanomy. The former was to assess students' level of cognitive development and the latter to analyse the curriculum. This was then applied to the Nuffield curricula, showing it to be flawed by way of being not suitable to many students level of cognition. The book detailed the characteristics of the concrete and formal operational stages of Piaget's theory and how this can be used to develop class tasks. The book also reported a number of investigations carried out to the use of the model in selecting objectives and learning activities; determining the validity of the theory with regards to the UK population. The investigations revealed a mismatch between the abilities of the students and the cognitive demands of the curricula in use then (The Nuffield curricula). Strategies were proffered to rectify the mismatch. This marked the beginning of the Cognitive Acceleration Theory.

The amount of work undertaken by Shayer, Adey and colleagues as reported in this book is commendable. It also offers useful insights to the characteristics of students at the secondary school level as well as the demands placed on them. But their aspiration of developing a 'general model' of learning and one that would address learning material and pupils' thinking processes cannot be said to be realised. The model does not capture the influence of previous knowledge and alternative conceptions on learning as well as the very process of learning (for instance processes of concept formation). Matching a cognitive level with appropriate tasks does not necessarily translate to success. Neither does it consider the interaction between domain specific knowledge and task complexity. Present state of knowledge makes the model incomplete.

Shayer, M. & Adey, P. (Eds.) (2002). *Learning intelligence: Cognitive acceleration across the curriculum, from 5 to 15 years* . Buckingham: Open University Press.
This book has eleven chapters and eleven contributors. It describes the tenets and applications of cognitive acceleration in schools. The work so far done in this area is fully described in the book and the results of evaluation of some of the projects are specified.

Sirhan, G. & Reid, N. (2001). Preparing the mind of the learner. *University Chemistry Education, 5(2),* 52-58.
In this work, the authors adopted the pre-lecture strategy in a general chemistry course. The aim was three-fold: to enhance the preparation of the mind of the learner for new learning; to ease the load on the working memory; and to change attitudes towards learning. The pre lectures were organised in such a way that at the beginning of each topic or bloc the students used the 'chemorganisers' (as they were called) to prepare the learner for the lectures. This is premised on Ausubel's theory of advance organisers. They found that such a strategy removed the statistical difference in performance between groups of students with differences in entry qualification using the t test and Mann-Whitney test.

Sirhan, G. and Reid, N. (2002). An Approach in Supporting University Chemistry Teaching, *Chemistry Education: Research and Practice*, 3, 65-75.
This describes some new teaching materials called 'Chemorganisers'. These were developed to test ideas arising from information processing predictions. They were offered to first year undergraduates to ensure that underlying ideas from previous learning were refreshed so that the new material given in a series of lecture courses would be understood better. The evidence supports the predictions from information processing.

Snir, J., Smith, C. L. & Raz, G. (2003). Linking phenomena with competing underlying models: a software tool for introducing students to the particulate model of matter. *Science Education, 87,* 794-830.
Asserting the centrality of the particulate nature of matter to chemistry and indeed scientific endeavours, the authors designed software to teach this to middle school students. The aim was to handle the oddity that exists between the unseen conceptual level of phenomena and the macro or surface appearances of matter by constructing models and seeing their explanatory power. They proffered scientists' conception of an explanatory model. The challenges encountered in trying to teach the particulate nature of matter was examined, especially the challenge of changing students' alternative conceptions about matter. They did this by evaluating different curricula. Selecting three phenomena, the authors develop and simulate them to generate cognitive conflict. They carried out two experiments with some 6th and 7th grade students and found that in general, the software was able to induce cognitive conflict in the students as well as give students the opportunity of testing alternative models of the particulate nature of matter. Post interview also indicated that students made some progress toward a scientific explanation of the particulate model of matter. They also found that 30% of their students were able to do a far transfer task using their acquired knowledge.

Solomon, J. (1989). A study of behaviour in the teaching laboratory. *International Journal of Science Education, 11(3),* 317-326.
Practicing science teachers were used to make sense of normal laboratory behaviour of adolescent students. The teachers wrote case records immediately after each session with students from the case data. Three case studies of this sort were reported. The author drawing from the result of the study posited that there are realistic ways of dealing with difficult behaviour by recognising group space and group honour. Limitations of teachers in controlling adolescent behaviour were also made visible.

Solomonidou, C. & Stavridou, H. (2000). From inert object to chemical substance: students' initial conceptions and conceptual development during an introductory experimental chemistry sequence. *Science Education, 84,* 382-400.
Using 168 Greek students (aged 13-14years) the authors examined novice students' conceptions of eleven substances during an introductory chemistry experimental sequence. This examination involved their initial conceptions and subsequent progression in the construction of correct conception of the chemical substance. The work was situated in the constructivist paradigm and alternative conception theory. Literature relating to students' conception of the chemical substance in everyday life was critically reviewed. Their theoretical basis of the feature centrality of these substances were made explicit making way for the exploration of the change in feature centrality. The initial conception of the students was found to be as concrete inert objects. At the end of

the sequence, which made use of explicit conceptual development strategies, the students progressed from the concrete inert object conception to that of unknown substance with semantic relations. The article made suggestions regarding a chemical substance strategy to conceptual development in chemistry.

Stamovlasis, D., Tsaparlis, G., Kamilatos, C., Papaoikonomou, D. & Zarotiadou, E. (2005). Conceptual understanding versus algorithmic problem solving: further evidence from a national chemistry examination. *Chemistry Education Research and Practice, 6(2),* 104-118.
The authors analysed the final examination questions in organic chemistry for 17year olds from Greece. The aim was to determine if their postulated categorisation of questions was supported by their data, the distribution of students assigned as conceptual thinkers, if competence in algorithmic problem solving was connected with competence in conceptual problem solving and vice versa and finally, if Nakhleh's scheme was operating in the case at hand. Using a group of 499 students they found that the statistical treatment with principal component analysis gave a marginal structure, the three branches of chemistry had nearly equal distribution of students assigned as conceptual thinkers, Nakhleh's scheme was found to be operational in this case and that the level of performance in algorithmic questions was independent of the level of performance in conceptual questions and vice versa. Implications were drawn from the result of the study.

Stavridou, H. and Solomonidou, C. (1989). Physical phenomena – chemical phenomena: do pupils make the distinction? *International Journal of Science Education, 11(1),* 83-92.
In this investigation, the authors aimed to answer four questions subsumed under the following, the categorisation processes of students, feature centrality of the categories and interaction of these with students' personal representations in this area. A sample of 15 Greek students (ages, from 8-17 years) were asked to freely categorise eighteen everyday physical and chemical phenomena, after which they answer questions regarding their reasoning in the task. They found that the students had no concrete referents as possessed by scientists, and so categorised phenomena based on (i) static representations of everyday life, (ii) phenomenology of changes. On the physical/chemical dimension, students based their classification on the reversibility of a reaction. That is physical if reversible and chemical if irreversible. Finally they found all property references to be at the macro level and none at the microscopic level.

Stavridou, H., & Solomonidou, C. (1998). Conceptual reorganisation and the construction of the chemical reaction concept during secondary education. *International Journal of Science Education, 20(2),* 205-221.
The major problem of this article is how the impact of a formal study of chemistry impacts the conceptual organisation of everyday phenomena. In investigating this, they explored the step-wise conceptual development of four groups of French students at different stages of science education of the concept of chemical reaction. Employing the Free Categorisation Task and a clinical interview about instances of the concept, they found that students' formal study of chemistry aided them in the reorganisation of semantic categories. Their construction of the chemical reaction concept was found to be quite personal and different from the expectations of the curriculum, although there was progression from phenomenology to the concept of chemical change. They also found that only five students could construct the concept of the structure of matter but all failed to construct the concept of the chemical substance. They concluded that the construction of the concept of chemical substance is necessary for an adequate construction of the concept of chemical reaction.

Strike, K. A. & Posner, G. J. (1985). A conceptual change view of learning and understanding. In L. H. T. West & A. L. Pines (Eds.). *Cognitive Structure and Conceptual Change* (pp. 211-231). Orlando: Academic Press, Inc.
The major tenet of the conceptual change theory was set out in this paper as the belief that learning is a rational process. Conceptual change epistemology was compared to empiricist epistemology and individual learning is described as having generic structural features. The conditions for conceptual change include dissatisfaction with existing conceptions, presence of anomalous data, intelligibility, plausibility and fruitfulness of a new conception. Conditions for an accommodation were also set out. These were applied to the conception of Freudian psychology and extended to the concept of understanding. The authors distinguished three different ideas, minimal understanding, fuller understanding and accommodation and comment on the usefulness of the conceptual change theory to pedagogy.

Sutton, C. (1996). Beliefs about science and beliefs about language. *International Journal of Science Education, 18(1),* 1-18.
Sutton claims that tacit beliefs in scientific language influences the beliefs about the nature of science held by teachers and students. The paper explores the assumptions of scientific language and reveals a tension between scientific language, identified as labelling, and the learner's experience of language as interpretive. He suggests that science textbooks and classrooms should incorporate the interpretive voice of the scientists in the activities. Suggestions for future research were made.

Sweller, J. (1988). Cognitive load during problem solving: effects on learning. *Cognitive Science, 12,* 257-285.
Sweller in this paper pioneered the research on problem solving and schema formation. He reflected on the expert-novice literature and categorised these into three: memory of problem state configurations, problem solving strategies, and features used in categorisation. He considered schema acquisition as deriving from the type of problem learners solve or the means through which they solve these problems. He tendered that problem solving and acquiring schema require unrelated cognitive processes by selective attention, and that conventional problem types make heavy demand on processing capacity, leaving very small processing capacity for a dual task such as schema formation. Literature was analysed to show the consequences of different problem types on processing capacity. He detailed a production system designed to measure relative cognitive load imposed by different problem types. This was applied to an experimental situation and it was found that solving problems with non-specific goals transferred to other problems with fewer errors and faster performance at later times. Conclusions were drawn from the theoretical and empirical analysis.

Sweller, J. (2004). Instructional design consequences of an analogy between evolution by natural selection and human cognitive architecture. *Instructional Science, 32,* 9-31.
The paper examines how the human cognitive architecture and its processes are likened to evolution by natural selection and its processes. It considers the longterm memory as a central executive that is implicated in many of the cognitive processes save in novel situations and likens it to the genetic code. It paints a pictorial analogy of the two. The major function of instruction is therefore to provide the missing central executive in novel situations and to build up information in the longterm memory that will guide learning. It then reviewed ways cognitive load theory has devised to manipulate the cognitive architecture of man. These are given as, the worked example effect, the completion effect, the redundancy effect, the expertise reversal effect, the modality effect, the split attention effect, the imagination effect, the isolated interacting element effect, the element interactivity effect, the guidance fading effect, and the goal-free effect.

Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education, 20(5),* 597-608.
Construing alternative frameworks as 'generalised non-individual descriptions' of responses made by students, the author documents the study made with some A-level college chemistry students in England. They explored 15 students conceptualisation of the chemical bond. Data was from interviews of the subjects by colearners. Results showed that students commonly use the octet rule in explaining chemical reactions and bonding. The paper considered the different reasoning and assumptions that are bequeathed the students by the use of the octet rule. The author claimed that an interpretation of chemistry from the students' point of view of the octet rule will enable a teacher understand different conceptions of students (enumerated in the paper) and thus be in a position to use appropriate techniques and knowledge to challenge the alternative conceptions of the students.

Taber, K. S. (2001a). Shifting sands: a case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education, 23(7),* 731-753.
This paper reports an in-depth case study employing a longitudinal interview of students for two years. It traces the shifts in the cognitive structure of the students as well as the differential weighting in their conceptual profiles. It showed how students can hold more than one explanatory framework for an area of study. Implications of the result were unfortunately not elaborated upon.

Taber, K. S. (2001b). Building the structural concepts of chemistry: some considerations from educational research. *Chemistry Education: Research and Practice in Europe, 2(2),* 123-158.
The paper is introduced by making a case for an active construction of knowledge by students and an emphasis on the constructivist perspective on learning as the authentic perspective. The paper goes on to consider the nature of chemistry from the perspectives of its relationship to other disciplines and physics in particular, stating that the 'physical basis' of many chemistry concepts is a source of difficulty for students. Of particular interest is the author's discussion of sources of alternative conceptions in chemistry. These include among others 'model confusion', linguistic cues, and more importantly and most commonly, the author identified prior science teaching as the major source of alternative conceptions in chemistry. The paper then considers difficulties in learning about molecular models, atomic structure, molecular structure and lattices. The pedagogic obstacles to the learning of chemical structures were addressed and practical suggestions were made to teachers, authors and curriculum planners.

Taber, K. S. (2002a). Conceptualising quanta: illuminating the ground state of student understanding of orbitals. *Chemistry Education: Research and Practice in Europe, 3(2),* 145-158.
This paper describes work done with 16-18 year old English students aimed at understanding their conceptualisation of the atomic orbital concept and related ideas. Data was collected from a sample of fifteen students by means of interview. Students' difficulties were explored in the areas of the stability of atoms, adoption of the orbital concept, orbital shells and sub-shells, orbitals and probability envelops, relating orbitals

to energy levels, relating orbitals to electronic transitions, labelling orbitals and electronic spin. The results show that students struggle to make sense of the atom as a quantum system. The author recommended that the way these concepts are taught should be revised.

Taber, K. S. (2002b). Compounding quanta: probing the frontiers of student understanding of molecular orbitals. ***Chemistry Education: Research and Practice in Europe, 3(2),*** **159-173.**
This paper is a follow-up of an earlier paper where students' sense making of the atomic orbital was explored. Interviewing fifteen 16-18 year old chemistry students, the author sought to explore students' conceptualisation of the molecular orbital given their struggle with understanding atomic orbitals. The difficulties students have with the pi-bond, hybridisation, distinguishing atomic from molecular bond and resonance as alteration. The author contend that prior chemistry knowledge could serve as barrier to new understanding and that the conception of 'electron shells' impede students' understanding of the orbital concept, and so understanding of valence bond structures to delocalised bonds. The author thus identified two sources of inhibition to new learning, one deriving from the abstract nature of the discipline and the other from pedagogic practices (e.g. use of wrong models).

Tai, R. H., Sadler, P. M. & Loehr, J. F. (2005). Factors influencing success in introductory college chemistry. ***Journal of Research in Science Teaching, 42(9),*** **987-1012.**
With a sample of 1531 first year college students, the investigators explored the relationship between high school pedagogical experiences and performance in college chemistry. Data were collected through questionnaires with items that addressed about 87 variables concerned with various aspects of high school chemistry classroom. Using a multiple regression model to analyse the data, the investigators found among others, that students reporting greater emphasis on understanding during high school chemistry laboratory performed better than those who reported greater emphasis on memorisation. It was also found that repeating labs to cause understanding has a positive effect on later success than learning to successfully complete assignments; students reporting greater frequency of test questions requiring memorisation and class assignments with problems requiring calculations perform better at college than their counterparts. They also found that individualised student learning proved to be less beneficial to college chemistry performance. Given the seemingly contradictory results, the authors offered some explanations and concluded that high school pedagogical choices influences students' later performance.

Thompson, J. & Soyibo, K. (2002). Effects of lecture, teacher demonstrations, discussion and practical work on 10th graders' attitudes to chemistry and understanding of electrolysis. ***Research in Science and Technological Education, 20(1),*** **25-37.**
In an experimental study involving 138 10th grade Jamaican students the investigators determined the effect of a combination of lecture, demonstration, discussion and practical work on students' attitude and achievement in chemistry. The students were divided into two groups, an experimental and a control group. Whereas the experimental were taught using a combination of all the strategies, the control was excluded from practical experience. It was found that the attitude and achievement of the students at the end of treatment were significantly different in favour of the experimental group. No relationship was found between attitude, gender and achievement. The investigators conclude that practical work is important for a good understanding of electrolysis.

Treagust, D. F., Chittleborough, G. & Mamiala, T. L. (2003). The role of submicroscopic and symbolic representation in chemical explanations. ***International Journal of Science Education, 25(11),*** **1353-1368.**
Two experiments were conducted to determine the use and role of explanations in the learning of chemistry. One of the experiments determined the perspectives of the teachers whereas the other explored the perspectives of the students. Through observational techniques, interviews and audio recording, the researchers identified examples of submicroscopic and symbolic representations employed by the teachers in explanations during the lessons and these were examined in relation to the level of meaning intended, that is, relational or instrumental. They concluded after analysis that the needed for understanding at a relational level necessitates the use of the symbolic to explain the submicroscopic and the use of the submicroscopic and symbolic to explain the macro. They drew implications for pedagogy from the result.

Tsaparlis, G. (1997). Atomic and molecular structure in chemical education. ***Journal of Chemical Education, 74(8),*** **922-925.**
The author critically analysed the structural concepts of chemistry from the Piagetian developmental perspectives, Ausubel's theory of meaningful learning, the information processing theory, and the alternative conceptions movement. He arrives at the conclusion that the different perspectives are related. Implications for teaching and curriculum are offered.

Tsaparlis, G. (1998). Dimensional analysis and predictive models in problem solving. ***International Journal of Science Education, 20(3),*** **335-350.**
Using first year undergraduate students, the author investigated the validity of Johnstone-El Banna predictive model of problem solving. He employed the dimensional analysis to determine the task complexity of items in an organic synthesis test. He found that the model can only hold when some necessary conditions are applied. These conditions were enumerated and investigated in the investigation.

Tsarparlis, G. & Angelopoulos, V. (2000). A model of problem solving: its operation, validity, and usefulness in the case of organic-synthesis problems. ***Science Education, 84,*** **131-153.**
The investigator tested the validity and usefulness of the predictive model of Johnstone and El-Banna with a sample of 319 students (age 17-18years). The students were assigned to either the experimental or control group. Non-numerical organic synthesis problems having the same logical structure and of varying *Z*-demand were used for the investigation. Data was collected using an achievement test on organic synthesis. Students were classified according to their working memory capacities and the degree of embeddedness (disembedding ability). They checked to see that all the necessary conditions for the operation of the model were alright. They found that the model's predictive power was observed, although this proved more useful for students who lacked previous knowledge. It was also found that level of field dependency influenced the predictive power of the model.

Van Driel, J. H. (2002). Students' corpuscular conceptions in the context of chemical equilibrium and chemical kinetics. ***Chemistry Education: Research and Practice in Europe,3(2),*** **201-213.**
Following up on works done earlier on the particulate nature of matter and reviewing extensively work done by DeVos and colleagues, the investigator sought to introduce students to the idea of chemical kinetics. The constructivist view was adopted for the study with the use of some conceptual change strategies. Teaching sequences were developed and presented to 15-16 year old grade 10 chemistry students. Data was collected by means of audiotapes, and written answers. The students were allowed to perform experiments and explain their observations in corpuscular terms. Starting from the macroscopic, they probed students' progress in understanding of chemical equilibrium, chemical kinetics toward a corpuscle conception. They found that this method was able to guide the students towards a corpuscular understanding of these phenomena.

Van Driel, J., de Vos, W., Verloop, N., & Dekkers, H. (1998). Developing secondary students' conceptions of chemical reactions: the introduction of chemical equilibium. ***International Journal of Science Education, 20(4),*** **379-392.**
In an experimental research using the grounded theory approach, the authors explored the type of reasoning employed by 15-16 year old students in their second year of chemistry education in the Netherlands. Teaching strategies that can promote conceptual change were explored. They identified students' preconceptions and the reasoning behind these in the concept of chemical reaction by means of audiotapes and students' written responses. They demonstrated the use of anomalous data in promoting conceptual change among students. Discussed the role of anomalous data and learner's motivation in relation to the result of the study. They suggested the use of situational factors in motivating students to attend to important information (e.g. introducing experiments at the phenomenological level). Finally, the paper called for a careful selection and design of assignments as a strategy for conceptual change.

Van Gog, T., Paas, F. & Van Merrienboer, J. J. G. (2004). Process-oriented worked examples: improving transfer performance through enhanced understanding. ***Instructional Science, 32,*** **83-98.**
Reviewed literature on the effects of worked examples on learning and transfer and asserts that research has demonstrated unequivocally that learning through worked examples is more effective than through problem solving. Also claims that the format of a worked example determines the level of understanding attained, and that providing principled information interacts with students' prior knowledge and task complexity to affect understanding. The authors therefore made a proposal to design process- rather than product-oriented worked examples for instruction of students and formulated a model for such an instruction. The paper also gave detailed design, implementation and assessment guidelines for process-oriented worked examples of a complex cognitive task. They reflected on the principles of cognitive load theory in relation to their proposal and raised issues for future research.

Van Merrienboer, J. J. G, Schuurman, J. G., de Croock, M. B. M., & Paas, F. G. W. C. (2002). Redirecting learners' attention during training: effects on cognitive load, transfer test performance and training efficiency. ***Learning and Instruction, 12,*** **11-37.**
Three experiments were performed using 26, 69, and 87 subjects of different backgrounds respectively. The three experiments tested the effects on transfer of skills and cognitive load during training of (i) decreasing extraneous cognitive load by the use of completion problems, (ii) increasing germane cognitive load by the use of high contextual interference and (iii) redirecting attention by simultaneously decreasing extraneous cognitive load and increasing germane cognitive load. It was found that decreasing extraneous cognitive load decreases

cognitive load during training and enhances far transfer because it helps in the construction of cognitive schemata; the high interference group also performed better on the far transfer task than the low interference group, with greater cognitive load during training; and that the completion-high interference group did better than their counterparts at training but less well in transfer. The results were discussed in the light of instructional designs.

Vazquez-Alonso, A. & Manassero-Mas, M. (1998). Response and scoring models for the 'Views on Science-Technology-Society' instrument. ***International Journal of Science Education, 21(3),*** **231-247.**
The authors suggested a new response model for the 'Views on Science-technology-Society' instrument, an instrument that assesses students' views on STS issues. The response model will allow multiple responses from students. A scoring model for the response mode was developed which will define a local system of meanings and weights. The paper documents the processes involved in this development and their implications.

Vogegelezang, M. J., & de Bouwmeester, S. (1987). Development of the concept of 'chemical substance' – some thoughts and arguments. ***International Journal of Science Education, 9(5),*** **519-528.**
The authors introduce the article by showing the trend in chemistry curricula being organised and taught first from the atom and molecule concept in the 1960s to substance concept, making a case for the validity of the latter. The requirements of such an approach were then described. Firstly to enable an understanding of chemical, reactions there has to be a distinguishing between thing and substance. Secondly, students have to transit from the notion of homogenous substance to chemical substance that is whether something is a pure substance or a mixture. A critique was made of the Nuffield curriculum of England, and the IPN of West Germany as well as some expressions of students, teachers and textbooks in relation to this concept. This article is one of the pioneering articles on the concept of substances in chemistry an issue that has proved very helpful in the understanding of students' representation in chemistry.

Watts, M. (1991). ***The science of problem solving: A practical guide for science teachers.*** **Portsmouth: Heinemann.**
This book is intended to be a guide for science teachers. It introduces the concept of problem solving by emphasising applicability of previously learned rules in new situations. The author makes a case for problem solving, discusses the types and dimensions of problem solving. The author then discusses approaches and skills required for problem solving. He details constructivism, group work and co-operative learning and their relationships; ownership of learning and transfer of learning. He gives a guide on how to teach problem solving and manage the classroom for problem solving. Finally, the methods of assessment of problem solving as well as research done in this area were addressed with an examination of how problem solving can be managed in the curriculum.

Welzel, M. & Roth, W. (1998). Do interviews really assess students' knowledge? ***International Journal of Science Education, 20(1),*** **25-44.**
Working with 26 students the investigators sought to explain the dynamics of students' cognitive processes, the influence of interviewers' questions and cues on the cognitive processes of the interviewee and how the expectations of the interviewer and interviewee interact to mediate cognition during interviews. They found that the interview revealed the dynamic nature of cognition and that changes in the context of the activity may change the level of performance. To the second issue, it was found that assessment outcomes were dependent on the actions of the interviewer and the interviewee. And finally, the expectations of the two parties mediate the effect of interviews. They inferred from these results that interview can only provide clues to the processes of cognition and made recommendations there from.

Wood, C. & Sleet, R. (1993). ***Creative Problem Solving in Chemistry.*** **London: The Royal Society of Chemistry.**
This book is intended to help 16-18 year olds to solve problems through group work. It has a documentation of 30 assorted problems and learning experiences in chemistry classified by data given, procedures to be adopted and goals to be attained. It also includes teachers' guide to the use of the book with detailed prescription of how the problems are to be used and students' organisation. The major skill it seeks to foster is communication skill and teamwork through problem solving. Intermediate skills such as seeking and selection of data and procedure, metacognition in problem solving, balance of criteria and discussion and presentation of results were encouraged. Although the authors recognised the place of prior knowledge in understanding, they failed to incorporate it effectively, specifying only prior chemistry knowledge.

Wu, H-K. (2003). Linking the microscopic view of chemistry to real-life experiences: intertextuality in a high-school science classroom. ***Science Education, 87,*** **868-891.**
This paper reviewed literature and identified a number of issues, which it set out to explore. These include, how microscopic representations are introduced, used and practiced in the chemistry classroom; how conceptual links among life experiences, chemical representations and conceptual entities presented and constructed by

members of a science classroom through discursive practices; and how the teachers' content knowledge shape his scaffolding strategies. The author discusses intertextuality as a strategy of making links between the macroscopic, the microscopic and the symbolic in chemistry, and the semiotic advantage of meaning making in the science classroom community. An ethnographic method was used to collect data over a period of seven weeks period from an eleventh grade classroom of 25 students and two teachers at different levels of experience. Data was collected using field notes and a video tape recorder. It was found that links were either initiated by the students or instigated by the teacher. Links could also be constructed by the teachers. It was also found that teachers' content knowledge mediates their scaffolding strategies and that limited knowledge may lead to a curtailing of useful discursive activities.

Yang, M. J. & Atkinson, G. F. (1998). Designing new undergraduate experiments. ***Journal of Chemical Education, 75(7),*** **863-865.**
This paper describes a series of checklists that an instructor might use to develop a new experiment. The issues covered include selecting objectives, the period before the experiment, the actual experiment, the cost and designing the write-up. The authors reveal these tips were based on actual experience and observations.

Appendix 2: List of Journals Consulted

1. Science Teachers' Journal information available on http://www.asta.edu.au/resources/journals
2. Behavioural and Brain Sciences information available on http://www.bbsonline.org/
3. Chemistry and Industry information available at http://www.chemind.org/CI/index.jsp
4. Chemical Education International full text obtained at http://www.iupac.org/publications/cei/
5. Chemical Education Journal full text available on http://www.juen.ac.jp/scien/cssj/cejrnlE.html
6. Chemistry Education: Research and Practice in Europe merged with University Chemistry Education to form Chemistry Education Research and Practice: full text available on http://www.uoi.gr/cerp
7. Chemical Society Reviews Full text available from Royal Society of Chemistry: from 1997 to present; Full text available from Royal Society of Chemistry Journals Archive: from 1972 to 2004; Full text available from SwetsWise Online Content: from 1997 to present.
8. Cognition and Instruction Full text available from Professional Development Collection: from 01/01/1984 to 1 year ago; Full text available from Psychology & Behavioral Sciences Collection: from 01/01/1984 to 1 year ago.
9. Cognitive Science, Full text available from Expanded Academic ASAP: from 01/01/1998 to 01/01/2002; Full text available from ScienceDirect Elsevier Science Journals: from 01/01/1995 to present;Full text available from ScienceDirect Psychology Backfile: from 1977 to 1994.
10. Contemporary Educational Psychology, Full text available from ScienceDirect Elsevier Science Journals: from 01/01/1993 to present; Full text available from ScienceDirect Psychology Backfile: from 1976 to 1994.
11. Cognition and Instruction, Full text available from Professional Development Collection: from 01/01/1984 to 1 year ago; Full text available from Psychology & Behavioral Sciences Collection: from 01/01/1984 to 1 year ago.
12. Education in Chemistry, http://www.rsc.org/Education/EiC/index.asp
13. Educational Assessment, Full text available from Professional Development Collection: from 01/01/1993 to 1 year ago; Full text available from Psychology & Behavioral Sciences Collection: from 01/01/1993 to 1 year ago
14. European Journal of Science Education(continued as International Journal of Science Education)
15. Instructional Science; Full text available from Springer LINK: from 01/01/1997 to present
16. International Journal of Science Education, Full text available from IngentaConnect: from 1999 to present (http://www.ingentaconnect.com/content/0950-0693); Full text available from Professional Development Collection: from 01/01/1999 to 1 year ago;Full text available from SwetsWise Online Content(http://www.swetswise.com): from 1999 to present; Full text available from Taylor & Francis Journals(http://www.metapress.com): from 01/01/1999 to present
17. Journal of Chemical Education, http://jchemed.chem.wisc.edu/
18. Journal of College Science Teaching, schmidt@periodicals.com;
19. Journal of Computer Assisted Learning, Full text available from Blackwell-Synergy: from 01/03/1997 to present; Full text available from IngentaConnect: from 1997 to present; Full text available from Professional Development Collection: from 01/03/1998 to 1 year ago

20. Journal of Experimental Education, Full text available from Expanded Academic ASAP: from 22/09/1997 to present; Full text available from PCI Full Text: from 1932 to 1995; Full text available from Professional Development Collection: from 01/01/1994 to present; Full text available from Psychology & Behavioral Sciences Collection: from 01/01/1994 to present

21. Journal of Research in Science Teaching, http://eu.wiley.com/WileyCDA/WileyTitle/productCd-TEA.html

22. Journal of Verbal Learning and Verbal Behaviour, continued as Journal of memory and cognition, http://www.sciencedirect.com/science/journal/00225371

23. Lab talk, http://www.dtl-inc.com/labtalk.htm

24. Learning and Instruction, Full text available from ScienceDirect Elsevier Science Journals: from 1995 to present

25. Physics Education, Full text available from Institute of Physics: from 01/05/1966 to present; Full text available from SwetsWise Online Content: from 1996 to present

26. Research in Science and Technological Education, Full text available from Professional Development Collection: from 01/05/1990 to 1 year ago; Full text available from Psychology & Behavioral Sciences Collection: from 01/05/1990 to 1 year ago; Full text available from Taylor & Francis Journals: from 01/05/2000 to present

27. School Science Review, http://www.ase.org.uk/htm/journals/ssr/index.php

28. Science Education, Full text available from Wiley Interscience Journals: from 1997 to present

29. South Australian Science Teachers Journal

30. Staff and Educational Development International

31. STSRN Missive

32. Studies in Higher Education, Full text available from IngentaConnect: from 1976 to 2005; Full text available from Professional Development Collection: from 01/03/1990 to 1 year ago; Full text available from Psychology & Behavioral Sciences Collection: from 01/03/1990 to 1 year ago; Full text available from SwetsWise Online Content: from 2003 to present; Full text available from Taylor & Francis Journals: from 01/01/1976 to present

33. Studies in Science Education,

34. The Curriculum Journal, Full text available from IngentaConnect: from 2000 to present; Full text available from Professional Development Collection: from 01/03/1998 to 1 year ago; Full text available from SwetsWise Online Content: from 2000 to present; Full text available from Taylor & Francis Journals: from 01/03/2000 to present

35. The Journal of the Learning Sciences, Full text available from Professional Development Collection: from 01/01/1991 to 1 year ago; Full text available from Psychology & Behavioral Sciences Collection: from 01/01/1991 to 1 year ago

36. University Chemistry Education (see Chemistry Education: Research and Practice in Europe)

Appendix 3: Summary of Citations and their Focus

Table 1a Summary of Citations on Science/Chemistry Teaching and Learning Theories

Citation	Type					Focus						Of particular interest
	Book	Curriculum package	Review	Position paper	Empirical	Cognitive Acceleration	Cognitive load	Information processing	Conceptual change	Alternative framework	Other	
Adey, P. (1987)				√		√					Piaget's theory	
Adey, P. (1988)			√		√	√					Piaget's theory	
Adey, P. (1996)				√		√					Piaget's theory	
Adey, P. & Shayer, M. (1993)					√	√					Piaget's theory	*
Adey, P & Shayer, M. (2002)				√		√					Piaget's theory	
Adey, P., Shayer, M. & Yates, C. (1989)		√				√						
Ahtee, M. & Varjola, I. (1998)					√					√		
Andersson, B, (1990)				√					√	√		
Bliss, J. (1995)		√				√					Piaget's theory	
Brünken, R. et al (2004)					√		√	√			Working memory	
Cassels, J. R. T. & Johnstone, A. H. (1984)					√			√			Assessment & Language (‡)	
Cokelez, A. & Dumon, (2005)					√				√		Perception & representation	
Danili, E. & Reid, N. (2004).					√			√			Working memory	
Demircioglu, G., et al (2005)					√				√	√	Attitude	
Driver, R. (1983)	√								√	√	Perception & representation	*
Driver, R. (1989).			√						√	√	Perception & representation	
Driver, R. & Easley, J. (1978)			√			√			√	√	Perception & representation	
Driver, R., et al (1985a).				√						√	Perception & representation	
Driver, R., et al. (1985b)				√					√	√	Perception & representation	
Driver, R & Oldham, V. (1986)			√	√					√	√		*
Gerjets, P., et al. (2004).					√		√				Working memory	
Johnson, P. (1998)					√				√	√		
Johnstone, A. H. (1980)			√				√	√			Working memory	
Johnstone, A. H. (1984)				√			√				Laboratory (‡)	
Johnstone, A. H. (1991).				√				√			Nature of chemistry	
Johnstone, A. H. (1996)				√				√				
Johnstone, A. H. (1997)				√				√			Teaching approach	*
Johnstone, A. H. & Al-Naeme, F. F. (1991)			√					√				
Johnstone, A. H. & Letton, K. M. (1982)					√		√				Working memory	
Johnstone, A. H., et al (1994)											Laboratory (‡), attitude	*
Johnstone, A. H. & Wham, a. (1982)				√	√		√	√			Laboratory	
Jones, B. & Lynch, P. P. (1989)					√					√		
Jones, M. & Gott, R. (1998)					√	√						
Kang, S., et al. (2005)					√				√			
Kirschner, P. A. (2002)			√				√					
Krnel, D. et al (1998)			√							√	Nature of chemistry, Piaget	*
Leo, E. & Galloway, D. (1996)				√		√						
Lynch, P. P. (1995)					√					√	Language (‡)	
Mayer, R. & Moreno, R. (2002)				√			√					
Mbano, N. (2003)					√	√						
Moreno, R. (2004)					√		√				Problem solving	*
Novak, J. D. (1978)			√	√					√		Piaget, perception representation	*
Nussbaum, J. (1985)			√							√		

Citation	Type					Focus						Of particular interest
	Book	Curriculum package	Review	Position paper	Empirical	Cognitive Acceleration	Cognitive load	Information processing	Conceptual change	Alternative framework	Other	
Osborne, R. & Wittrock, M. (1985)			√	√				√	√			*
Paas, F., et al. (2004)							√					
Pollock, E., et al.. (2002)					√		√					*
Posner, G. J., et al. A. (1982)				√					√			*
Renkl, A., et al. S. (2004)					√		√				Problem solving	
Renkl, A., et al. (1998).					√		√					
Ribeiro, M. G. T., et al. (1990)					√					√		
Rikers, R. M., et al. G. (2004)					√		√			√		
Savridou, H., & Solomonidou									√		Perception & representation	
(1998)	√					√						
Shayer, M & Adey, P. (1981)	√					√					Piaget's theory	
Shayer, M. & Adey, P.												
(Eds.) (2002)					√			√				
Sirhan, G. & Reid, N. (2001)					√			√			Ausubael's theory	
Solomonidou, C & Stavridou, H. (2000)									√		Representation (‡)	
Strike, K. A. & Posner,												
G. J. (1985)				√	√				√			
Sweller, J. (1988)							√				Problem solving	*
Sweller, J. (2004)			√	√	√		√			√		
Taber, K. S. (1998)					√					√		
Taber, K. S. (2001a)										√		
Taber, K. S. (2001b)				√				√		√	Nature of chemistry	*
Tsaparlis, G. (1997)			√		√					√	Piaget and Ausubel's theories	
Van Driel, J., et al. (1998)									√			
Van Gog, T., et al. (2004)			√		√		√					*
Van Merrienboer, J. J. G,							√					
et al. (2002)										√		
Vogegelezang, M. J., & Bouwmeester, S. (1987)			√								Perception & representation	*

Table 1b Summary of Citations on the Nature of and Approach to School Chemistry knowledge

Citation	Type					Focus						Of particular interest
						Nature			Approach		Other	
	Book	Curriculum package	Review	Position paper	Empirical	Level of thought	Structure	Language	Societal context	Students' context		
Aikenhead, G. S. (1986)				√					√			*
Bieron, J. F., et al (1996)					√					√	Attitude	
Cassels, J. R. T. & Johnstone, A. H. (1984)					√			√			Assessment	
Cassels, J. R. T. & Johnstone, A. H. (1985)					√			√				
Duncan, I. M. & Johnstone, A. H. (1973)					√		√					
Fang, Z. (2005)					√			√				
Garforth, F. M., et al. (1976a)					√		√					
Garforth, F. M., et al. (1976b)					√		√					
Han, J. & Roth, W-M. (2005)					√	√		√				
Hodson, D. & Bencze, (1999)					√				√			
Holbrook, J. (2005)					√	√			√		Conceptual change	
Johnstone, A. H. (1981)					√		√				Attitude	
Johnstone, A. H., et al. (1971)					√	√						
Johnstone, A. H. & Cassels, J. (1978)					√			√			Assessment	
Johnstone, A. H. & Letton, K. M. (1982)					√		√				Cognitive load	
Johnstone, A. H., et al. (1977a)					√		√					
Johnstone, A. H., et al. (1977b)					√		√					
Johnstone, A. H. & Reid, N. (1979)					√				√			
Johnstone, A. H. & Reid, N. (1981)		√							√	√		
Kellett, N. C. & Johnstone, A. H. (1974)					√		√					
Kerber, R. C. & Akhtar, M. J. (1996)					√				√		Attitude & Laboratory	
Kozma, J., et al.(2000)					√	√		√			Laboratory	
Lynch, P. P. (1995)					√			√			Alternative framework	
Monk, M. & Osborne, J. (1997				√					√			
Osborne, J. et al (1998)					√					√	Attitude	
Reid, N. (1999)				√						√	Attitude	
Reid, N. (2000)				√						√		
Snir, J., et al. (2003)					√	√	√				Conceptual change	
Stavridou, H. & Solomonidou, C. (1989)					√	√						
Sutton, C. (1996)				√				√				
Taber, K. S. (2001)				√				√				
Taber, K. S. (2002a)					√	√	√					
Taber, K. S. (2002b)					√	√	√					
Treagust, D. F., et al. (2003)					√	√						
Van Driel, J. H. (2002)					√		√					
Wu, H-K. (2003)					√	√		√				

Table 1c Summary of Citations on other Variables

Citation	Type					Focus							Of particular interest
							Assessment						
	Book	Curriculum package	Review	Position paper	Empirical	Problem solving	Technique	Instrument	Laboratory	Psychological Under-pinning	Attitude	General	
Aikenhead, G. S. & Ryan, A. G. (1992)					√			√			√		
Aikenhead, G. S., et al. (1992)		√						√					*
Arnold, J. C. & Arnold, P. L. (1970)					√		√						
Ausubel, D. P. et al. (1978)	√									√			*
Baddeley, A. (1997)	√									√			
Bennett, J., et al. (2001)					√			√					
Berg, C. A., et al. S. (2003)					√						√		
Blosser, P. E. (1988)			√			√							
Botton, C. (1995)					√			√	√				
Botton, C. & Brown, C. (1998)					√			√					
Boyer, R et al. (1989)					√							√	*
Bryce, T. G. K. et al,(1985)			√				√						*
Collins, A. M. et al. (1969)					√					√			
Cowan, N. (2000)			√	√						√			
Craik, F. I. M. et al. (1972)				√						√			
Danili, E. & Reid, N. (2005)					√		√						
De Jong, O. (2005)					√							√	
DeMeo, S. (2001)			√						√				
Domin, D. S. (1999)			√						√				
Donnelly, J. F. (1998)					√				√				
Dori, Y. J. & et al. (1998)		√				√							
Dori, Y. J. & et al.2003)					√	√							
Duschl, R. A. et al. (1997)					√		√						
Friel, S. et al.. (1978)			√				√						
Friel, S. et al.. (988)					√		√						
Gabel, D. (1999)				√								√	
Gardner, P. L. (1996)				√			√						*
Garrett, R. M. (1986)			√			√							
Garrett, R. M. & et al.. (1982)			√						√				
Gil-Perez, D, et al.. (1990)			√			√							
Hadden, R. A., et al. (1974)					√							√	
Hall, R. H., et al.. (1992)					√							√	
Handy, J. & et al. H. (1973a)					√		√						
Handy, J. & et al. H. (1973b)					√		√						

Citation	Type					Focus								Of particular interest
							Assessment							
	Book	Curriculum package	Review	Position paper	Empirical	Problem solving	Technique	Instrument	Laboratory	Psychological Underpinning	Attitude	General		
Inhelder, B. & Piaget, J. (1958)	√									√				
Hodson, D. (2005)			√						√					
Hollingworth, R. (2001)			√			√								
Johnstone, A. H. (1978)			√									√		
Johnstone, A. H. (1980)			√									√		
Johnstone, A. H. (1987)				√			√							
Johnstone, A. H. (1988)				√			√							*
Johnstone, A. H. (1993)				√		√								*
Johnstone, A. H. (2001)				√		√								
Johnstone, A. H. et al. (2001)			√						√					
Johnstone, A. H. et al. (2000)				√			√							
Johnstone, A. H. et al. (1980)				√		√								*
Johnstone, A. H. & Letton, K. M. (1989)				√					√					
Johnstone, A. H. & Letton, K. M. (1990)					√				√					
Johnstone, A. H. & Letton, K. M. (1991)					√				√					
Johnstone, A. H. & Reid, N. (1981).				√							√			*
Kempa, R. (1986)	√						√							
Kerber, R.C. et al. (1996)					√				√					
Krueger, B. et al. (1996)				√			√							
Lagowski, J. J. (2005)				√					√					*
Lambiotte, J. G. et al. (1992)					√							√		
Leat, D. & Higgins, S. (2002)					√							√		
Liu, X. (1996)					√		√							
Markow, P. G. et al. (1998)					√				√		√			
Maskill, R. et al. (1989)					√			√						
McClure, J. et al. (1999)					√			√						*
Miller, G. A. (1956)				√						√				*
Mintzes, J. J. et al. (1999)	√						√							*
Murphy, G. L. et al. (1985)			√							√				*
Myers, G. et al. (2004)					√						√			
Niaz, M. (1988)					√	√								
Niaz, M. (1989)					√	√								
Niaz, M. (1995)					√	√								
Niaz, M. (2005)					√	√								
Nicoll, G. et al. (2001)					√		√							*
Novak, J. & Gowin, B. (1984)	√						√							*
Pascual-Leone, J. (1970)					√					√				
Piaget, J. (1930)	√									√				
Piaget, J. (1970)	√									√				
Piaget, J. (1972)	√									√				
Piaget, J. (1977)	√									√				
Ramsden, J. M. (1998)				√							√			

Citation	Type					Focus							Of particular interest
	Book	Curriculum package	Review	Position paper	Empirical	Problem solving	Assessment: Technique	Assessment: Instrument	Laboratory	Psychological Underpinning	Attitude	General	
Reid, N. (under review)			√				√				√		
Reid, N. & Yang, M-J. (2002a)					√	√							
Reid, N. & Yang, M-J. (2002b)				√		√							
Rice, D. C. et al. (1998)					√		√						
Rips, L. J. et al. (1973)					√					√			
Roelofs, E. & Terwel J. (1999)					√							√	
Rosch, E. (1975)					√					√			
Rosch, E. & Mervis, C. (1975)					√					√			
Rosch, E. et al. (1976)					√					√			
Roth, W-M. et al. (1997)					√				√				
Rowntree, D. (1987)	√						√						
Rumelhart, D. E. et al. (1972)				√						√			
Sadler, P. M. (1998)					√		√	√					
Safayeni, F. et al. (2005)			√	√								√	*
Schmidt, H. (1990)					√	√							
Séré, M-G, (2002)					√				√				*
Solomon, J. (1989)					√				√				
Stamovlasis, D. et al. (2005)					√	√							
Tai, R. H. et al. (2005)					√							√	
Thompson, J. et al. (2002)					√				√		√		
Tsaparlis, G. (1998)					√	√							
Tsaparlis, G. et al. (2000)					√	√							
Vazquez-Alonso, A. et al. (1998)					√			√					
Watts, M. (1991)	√					√							
Welzel, M. & Roth, W. (1998)					√		√						
Wood, C. & Sleet, R. (1993)		√				√							
Yang, M. J. & Atkinson, G. F. (1998)				√					√				

The Higher Education Academy
Physical Sciences Centre

...enhancing the student experience in chemistry, physics and astronomy within the university sector.

Physical Sciences Practice Guides are designed to provide practical advice and guidance on issues and topics related to teaching and learning in the physical sciences. Each guide focuses on a particular aspect of higher education and is written by an academic experienced in that field.

This guide is produced in association with the Royal Society of Chemistry, Tertiary Education Group.

This report presents a summary of the main findings from the science education research literature. These findings are used to offer guidance in developing a curriculum in chemistry both at school and higher education levels. It is recognised that the purposes for chemistry education at school level are, in many ways, different from those for higher education.

The authors are based in the Centre for Science Education at the University of Glasgow.