THE PROBLEMS WITH SCIENCE EDUCATION: "The more things change, the more they are the same" (Alphonse Karr 1808-1890)

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Introduction

If we look at the problems facing science and maths teachers today, and the relationship between these two disciplines, then we would have to say that nothing much seems to have changed in 20, 30, 40 years, even though everything has changed. In fact, to quote Alphonse Karr "The more things change, the more they are the same." Of course, I used Google to find the source of this quotation, one of the profound changes in accessing information in the last decade. I want to try and identify what I see as some of the major problems for students learning chemistry today, one of which is mathematics. Some concerns about science, technology and maths education (STM) are shown in Table 1, although many of these are not unique to Ireland I also want to cast a critical, but not I hope a jaundiced eye, on the state of Irish science education as I see it.

Table 1: Concerns about STM education

1. Falling numbers in many countries choosing science at second and third levels - not just an Irish problem!
2. Shortage of qualified science teachers (but not in Ireland!)
3. Poor image of science in society and the media.
4. Growing skills shortage in high-tech industry.
5. Curriculum change doesn't seem to help matters.
6. Much science education research but little evidence of it in the classroom and lecture hall.
7. Science teaching driven by examinations.

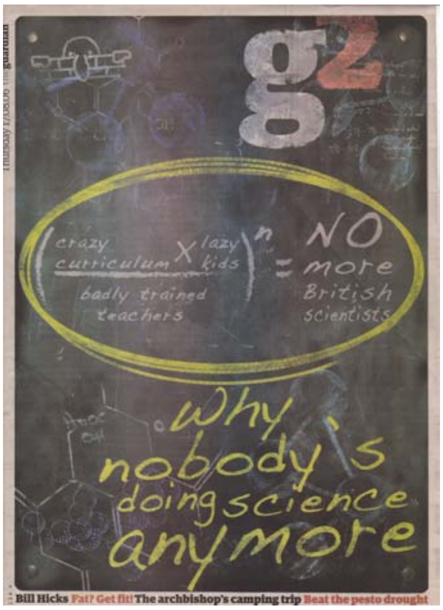
Figure 1 from a recent issue of The Guardian shows that our concerns in Ireland are shared across the water. The following quotations are from this article.

> "It is this perception that's to blame: that physics and chemistry are boring, prohibitively hard, too abstract and too male, in a spotty, won't-get-a-girlfriend kind of way that appeals to neither sex."
>
> "Science lessons have always been thought of as boring, but what seems to have changed is adolescent toleration of it…Compared with the interior life of an adolescent, even the mysteries of the Liebig condenser start to look tame." (Brockes, 2006)

My Main Thesis

Our teaching of science and mathematics at second level (and perhaps even more so at third level) is not sufficiently informed or directed by what has been learned through research on teaching and learning in the last 20-30 years. Most of us still tend to teach as we were taught and focus on the content and structure of the subject rather than on the process of learning and cognitive development and the cognitive status of our students. Think back to what and how you were taught science at school and ask: "is it really any different today?" In Ireland the Leaving Certificate (LC) Biology syllabus has just been changed – it had remained unchanged for over 30 years! The combined LC Physics with Chemistry is still waiting for revision after 30+ years.

Figure 1: "Sir, can we do something easier?" (The Guardian 17/8/06)



Over fifty years ago I remember separating sand and salt in my first exposure to Chemistry – I still see this being done in the latest Junior Certificate (JC) Science course. It was probably there a hundred years ago as well, but Chemistry as a discipline has changed almost beyond recognition since I was at school.

To make the point about the lack of impact of science education research I would like to quote Alex Johnstone, now retired, but a leading light in chemical education research in the U.K. for over thirty years.

> *"The more I have studied chemistry, chemical education and the psychology of learning, the more I have become aware that we are trying to share our beautiful subject with young people in an apparently* ***'logical'*** *way and, at the same time conflicting with what we know about the way people learn ('****psychological****')."* (Johnstone, 2000)

The Need for Literacy <u>and</u> Numeracy

There are two essential pre-requisites for science education: literacy and numeracy. You cannot study any science without being able to read and write and also use numbers. These are the foundations of science education and weaknesses in either area will seriously disadvantage a student of science. Science used to be an elite pursuit, even at the lower secondary level, but now we expect everyone across the ability spectrum to study science. This means that science and mathematics are always taught in a mixed ability context in school, even if in practice there is some streaming.

In Ireland science is offered at higher and ordinary level at both the Junior Certificate and Leaving Certificate levels, and with mathematics there is an additional foundation level. In reality many teachers are teaching science and mathematics to mixed ability classes, and whole class teaching, rather than group work, is the norm in Irish classrooms. These two facts are to a large extent incompatible. There is always the problem in simultaneously turning off both the higher and lower ability ends of the spectrum. Much third level teaching is now also done in mixed ability classes, except perhaps in Oxbridge and Trinity College. As third level expansion continues this will become worse.

The Current Situation in Ireland

Over the past two decades in Ireland everything seems to have changed. The Celtic Tiger was born, suffered some growing pangs as a teenager but still continues to thrive. Ireland has never been wealthier – its GDP is way above the EU average and a recent survey showed us to be the third wealthiest country in the world. Our economic growth rates still top the EU table, even though we can't compete with China or India. At the same time there have been massive social changes in Ireland – in the place of the Catholic Church in Irish society, not least in education, and many social problems have been the fruit of our recent prosperity: increase in marriage breakdown, drug abuse, alcoholism, organised crime, indiscipline in schools etc. We have more millionaires and property magnates but also many people living in social and material deprivation. The gap between rich and poor has grown wider with increasing prosperity. Most of our cities have been rebuilt, although the transport infrastructure and schools have not kept pace with population growth and suburbanisation. The Irish population now exceeds 4.2 million and 10% of this are non-nationals. The birth-rate in 2005 went up to 63,500 and at 15.3/1,000 population is the highest in the EU, and 23% of the population in 2005 was in full-time education.

The Irish economy continues to boom and in 2004 exports were up by 350% since 1990, the work force was 1,952,000 and unemployment was only 4.5%. The exports in 2004 were worth €83,892 billion, and of these 44.6% were chemicals and pharmaceuticals and 29.6% ICT. The Irish economy has been driven by the high-tech industries in the last two decades, illustrating the importance of science education at all levels.

Table 2: The current situation in Ireland

1. Falling school population (at the moment) – but due to recover by 2020
2. 90% take Junior Certificate Science (not compulsory, boys > girls)
3. 50% do the Transition Year Option
4. 80% stay on to do the Leaving Certificate
5. >95% LC cohort take LC Mathematics (at three levels, 17.7% at HL)
6. Not all schools offer all the LC sciences: Biology>Physics>Chemistry
7. Popularity of LC science subjects:
   Biology>>Physics>Chemistry
   48.8% 14.4% 13.9%
8. 70% go on to the 3rd level (not all at university)
9. Highest % of 3rd level graduates in the EU

Table 2 summarises some features of science education in Ireland in 2006. In the last decade all the sciences subjects have been revised: Junior Science (2002), LC Chemistry and Physics (2000) and LC Biology (2002). Despite all this change when I visit schools around the country on teaching practice supervision, as I have done for the last 28 years, I still see many of the same problems I saw in the early 80s: poor laboratory facilities, inadequate equipment and resources, no technical assistance. In some schools the facilities are excellent, mainly in new schools, but the average falls short of what is required. The Task Force on the Physical Sciences which reported in 2002, identified the need to renew and maintain laboratories and equipment as a major priority for the government. In 2006 essentially nothing has been done in this area and most of the recommendations, like the report, are gathering dust. At the same time massive funds have been injected since 2000 into scientific research through SFI, PRTLI and other programmes, and this investment is set to continue for another cycle. However, this money has gone selectively to third level, to specific areas of science and technology, and to certain institutions. In general, those who have, have been given more. Apart from the STARS programme for teacher-researchers, these massive funds have not gone in science, technology and mathematics (STM) education either at third level or at second level. As I have pointed out before, unless we ensure that the lower levels of STM education are adequately supported, then we cannot guarantee into the future that there will be enough graduates to take up the new research opportunities. The equivalent body to SFI in the USA, the National Science Foundation (NSF), spends a significant part of its budget on science education R & D, at second and third level. We should be doing the same otherwise the research pyramid in Ireland will have no foundations.

The two most effective things the government could do to improve science education in Ireland would both support the science teacher by firstly providing technical assistance in schools and secondly providing a coherent programme of career-long, continuing professional development (CPD). About 20 schools in Ireland out of 720 have technical assistance, and although there is in-service provision and support when a new syllabus is introduced (a major improvement on the past), this is cut back after a few years. One person each supporting chemistry, physics and biology in schools is not enough. One can only look with envy at the UK's new network of Science Learning Centres and the National Science Learning Centre at York, which opened for business at the end of 2005. The funding of £52 million was split equally between the UK government and the Wellcome Trust. These centres were provided on top of an excellent system of in-service education already provided by local authorities, professional bodies and others. We are not just lagging behind in provision for science education; we are not even in the race!

Too many Irish bodies have deplored the falling numbers and poor results in the sciences and mathematics and urged the government to do something, to implement its own Task Force Report for a start. The answer has been to pump money into third level research facilities, projects and personnel – at the end of the pipeline, and ignore almost totally the oil fields, wells and production facilities (to use a metaphor from the oil industry). This is unsustainable and although the efforts to promote science through Science Week Ireland, the Discover Science and Engineering Programme, STEPS, and other initiatives, are very valuable they cannot replace investment in schools and in teachers. As I said in a talk I gave in 1985: “The teacher is the key to excellence” in science and maths teaching.

Why are Science and Maths Important?

For the last decade in Ireland there has been a litany of concern about the falling numbers doing science and maths, particularly the physical sciences, about the needs of high-tech industry and the prospect of a major skills shortage in the early 21st. century. This culminated in the Physical Sciences Initiative in 1999 and the setting up of the Task Force on the Physical Sciences, chaired by Danny O’Hare. This sounds good: problem identified, high-powered task force set up to identify the problems and suggest solutions, and then action based on the recommendations. Unfortunately the most crucial step - implementation of the recommendations - has not been carried through, except in a few minor aspects. So the situation has remained essentially the same and the same complaints and concerns continue to be heard, particularly in August when the examination results come out. One ‘new’ proposal this year was the introduction of bonus points for science and maths for specific courses, something I proposed 10 years ago, though this time the Minister of Education and Science, Mary Hanafin, came out in support of it.

Figure 2: The August media frenzy

THE IRISH TIMES

10-16 D'Olier Street, Dublin 2

Wednesday, August 16th, 2006

online: www.ireland.com

Worrying trends in Leaving Cert

Continuing high failure rates in ordinary level maths and in science subjects at ordinary level are the most striking features of the Leaving Certificate results published today. In all, more than 4,500 students failed maths, making them ineligible for admission to many third-level colleges. In another worrying trend, solne 15 per cent of students failed ordinary level chemistry with the failure rate also high in biology (13 per cent) and physics (9 per cent).

IT 16/8/06

Poor marks in science, maths in Leaving Cert results

Various reports have indicated major future skills shortage in the IT and pharmachemical industry, particularly as the first generation of employees retires. However, Ireland does have one of the highest proportions of people with a technical qualification in the EU. Is there a mismatch between the qualifications achieved and the jobs available? The numbers and quality studying to be technicians has dropped dramatically due to a falling birth rate and an expansion of places in universities. Students who would have done certificate courses in the past are signing up for Science degrees with low points, so that the ITs cannot fill their courses and have very low cut-off points. The poorly qualified students (down to 300 points) do not always cope well with degree courses and either drop out or struggle through to gain poor degrees. Industry does not usually want to employ new graduates, whatever their subject or class of degree, they want either experience (a Catch-22 situation) or a higher degree, often a PhD. So we find a situation where students are encouraged to do science and then find on graduation that they cannot find a relevant job in Ireland without further study. Also the pay, conditions and career structure in science do not compare well with careers in other areas. Negative experiences by graduates, letters in the papers about failures to find jobs, high drop-out rates in science courses, etc. all feed back into the system and further discourage young people from taking up science, already perceived as both difficult and time-consuming.

If there is a real skills shortage then this must be reflected in demand and in pay and career prospects. Why do students want to be doctors, pharmacists, lawyers and business people? The main driver is not altruism! The best students will not choose science unless it is seen as an attractive career in every aspect, including pay and conditions. Importance is not measured merely by words and slogans, and students are not easily deceived if the words are not backed up by hard evidence of interesting, well-paid and rewarding careers in Irish companies for science and maths graduates.

Science and maths are linked indissolubly, and to some extent they sink or swim together. Mathematics is the language of much of science and science provides many of the examples and areas of application for mathematics. It is impossible to do any science if one is not numerate and knows some mathematics. In some areas a lot of mathematics is needed e.g. theoretical chemistry or physics. Despite the concerns about the number doing higher level mathematics and the high failure rate at ordinary level, I believe one often unrecognised advantage that Ireland has, is that virtually everyone studies some mathematics throughout their school career. Although mathematics is, I believe, technically not compulsory, for all practical purposes it is. Every school leaver has done mathematics to some level, whether they leave at 15/16 or 17/18, unlike many other countries. This is not true in most countries. Most students (>90%) do general science up to the Junior Certificate (more boys than girls), but this is not true at the Leaving Certificate where 48.8% do Biology, 13.9% Chemistry and 14.4% Physics (see Table 3 and Figure 2). Figure 3 shows the grades breakdown for the LC science subjects.

Every LC student does not take a science subject but many do and we should be grateful that so many continue with a science subject to the end of schooling. The broad nature of the Irish curriculum is again something we should be grateful for, and I speak as someone who was educated through the A level system. Most LC students do 6-7 subjects across the sciences and humanities, and as I have said essentially everyone does Mathematics, along with English and Irish. This gives a broad foundation for third level and employment, and avoids the perils of early specialisation. They also have the option of doing all subjects at Higher or Ordinary Level (Mathematics and Irish also at foundation level), allowing some flexibility and adjustment to the abilities of different students. Around 80% stay on at school to take one of the LC options. (A fuller report on these data is given by Childs, 2006.) Table 4 highlights some of the positives in STM education.

The fact that everyone continues with Mathematics until the end of schooling (either at the end of compulsory schooling or after the LC examination) is a major and unsung plus of the Irish education system. Table 5 shows the 2006 LC Mathematics results (compare the numbers with Table 3). The numbers doing the Higher level are comparable to those doing LC Physics and Chemistry and the majority take the ordinary level paper. But almost everyone does some mathematics to the end of schooling!

Table 3: Changes in LC science subjects 2002-2006 (Source: DES)

Biology		**Chemistry**		**Physics**		**LC**	
	Cohort	**Total**	**%**	**Total**	**%**	**Total**	**%**
2002	58,489	22,064	37.7	6,497	11.1	8,651	14.8
2003	56,229	22,669	40.3	6,698	11.9	8,806	15.7
2004	55,183	24,027	43.5	7,229	13.1	8,152	14.8
2005	54,069	25,362	46.9	7,366	13.6	7,944	14.7
2006	50,995	24,885	48.8	7,071	13.9	7,335	14.4

New Biology syllabus from 2004 onwards

Table 4: Some positives in Irish STM education

All students at Junior Certificate level and most students at Leaving Certificate level (>95%) take Mathematics.
~50% do the Transition Year Option between junior and senior cycles.
>80% stay on for the senior cycle and >50% do some science.
The LC course is a broad course (6-7 subjects) avoiding early specialisation and career choice.
>60% go on to third level.

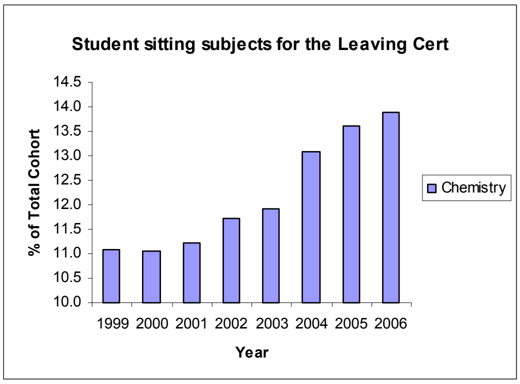
Table 5: LC Mathematics results (2006) (Source: DES statistics)

	No.	**% LC Cohort**	**%ABC**	**%Fail (E, F, NG)**
Higher level	9,018	17.7	82.2	3.3
Ordinary level	35,112	68.85	65.7	11.5
Foundation level	5,104	10.0	73.2	6.4

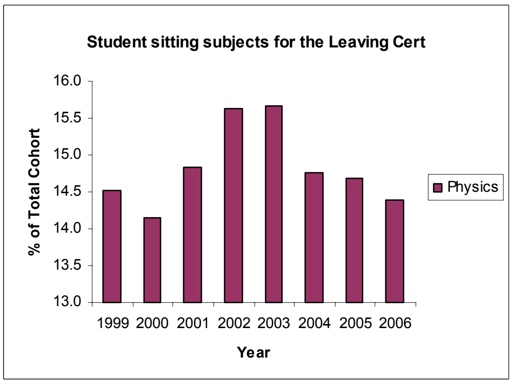
Apart from symbols, numbers, and equations science and mathematics also share another aspect: the importance and role of visualisation in presenting ideas and data. Science and mathematics use graphs, diagrams, shapes etc. to visualise their subjects. In addition to the mathematical diagrams used in Chemistry, for example, we would be lost without diagrams and models and computer images of molecular and crystal structures. The ability to think and visualise in 3 dimensions is an essential skill of the modern chemist, usually done now on a computer screen. The understanding and interpretation of such diagrams, drawn in 2 dimensions but representing 3 dimensions, is not a trivial skill and must be learned and practiced. This is part of the symbolic or representational area of Chemistry, which has always been a vital part of the subject. The importance of visualisation of ideas is a common area of interest to science and mathematics, and at schools both subject areas teach the drawing and interpretation of graphs. However, an area of cognitive confusion to students is when different teachers and subjects present the same material in different ways, use different symbols and language e.g. slope or gradient or dy/dx?

Figure 3: Change in % of total LC cohort doing science subjects (1999-2006)
(Source: DES; graphs courtesy of Mark Glynn)

a) Chemistry



b) Physics



c) Biology

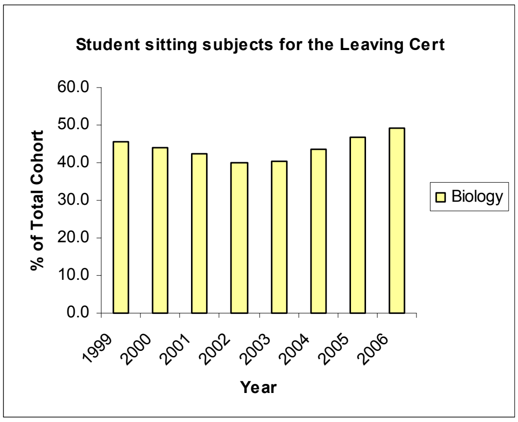
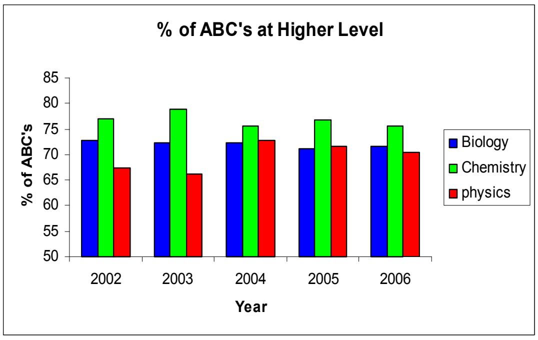
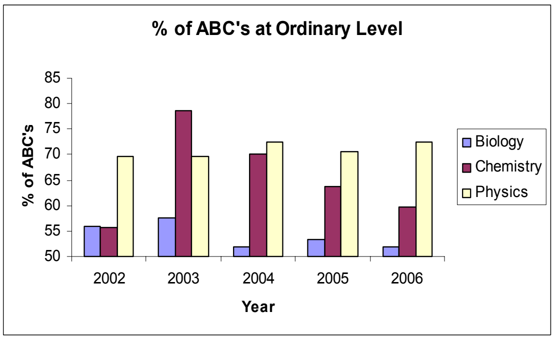


Figure 4: Percentage of students in the science subjects getting good grades (ABCs)

a) Higher Level



b) Ordinary Level



The Transition Year Option

Another positive aspect of the Irish system is the Transition Year Option (TYO). This is an optional year between the junior and senior examination cycles. It is not examined formally and is meant to encourage the student's personal, social and intellectual development. Research has shown that the TYO helps students mature and improves their LC results, it also means that they enter third level one year later, which also benefits their third level experience as they are intellectually and socially more mature. However, I believe that the TYO has been a largely-wasted opportunity to promote science. Students make up their minds what LC subjects they will study either in their 3rd year (JC year) or in their 4th. year (TYO year). The TYO thus defers their choice by one year and provides an opportunity to 'sell' the sciences through suitable TY experiences. This requires work and imagination on the part of science teachers and because the year is not specified in detail, teachers must decide their own programme and produce their own resources. In some schools they effectively do a 3 year LC (which is not allowed) or introduce them to LC material. This does not always attract students into the LC sciences! What is needed is a new approach – student-centred, context-based, activity-based – not constrained by the needs of a syllabus or an examination. Science teachers in other countries would give their teeth for such an opportunity to teach science rather than teaching to an examination. The lack of suitable science teaching resources has been detrimental, as most teachers are too busy to develop their own courses and materials (although some have and done an excellent job). This is why in 2002 I started the TY Science project, using some of our 4th science education students, to develop science modules for the TYO, which teachers could pick and choose from for their own situation. Three modules have already been developed, piloted and made available to teachers (Forensic Science, Cosmetic Science and Science of Sport), and others are in development (Science of Survival, Environmental Science). Almost simultaneously Dr Mark Glynn, Education Officer at Pharmachemical Ireland, also developed some new resources for the TYO, which are available on their website. We cannot blame the JC Science course for putting off students from studying science further (which it undoubtedly does) without taking the opportunity the TYO offers to teach science 'outside the box' and to show students the excitement and enjoyment of science, as well as the applications and the relevance of science for everyday life and careers. My plea to science teachers is, *"Please seize the day and use the TYO to sell science to your students."*

JC Science, a combined (not integrated) course with separate strands of Biology, Chemistry and Physics is taken by most students, although Science is not compulsory at JC level. It is unique as a subject at JC level in feeding into five different LC courses: Agricultural Science, Biology, Chemistry, Physics and Physics & Chemistry (a combined course). Students may take any of these courses but may not take Physics & Chemistry with either single subject Physics or Chemistry. After syllabus revision students may take both Agricultural Science and Biology. All these syllabuses have been recently revised except for Physics & Chemistry, which has been unchanged for over 30 years (and it shows). A new syllabus has been drawn up by the NCCA and has been revised but not yet approved by the Department of Education and Science. This is the most innovative of the LC science syllabuses and introduces a context-based approach for the first time. The old Physics & Chemistry syllabus is long past its sell-by date and is dying year by year. The new syllabus would extend the choice available and might encourage some schools to offer and more students to choose a physical science. All the five science subjects are not available to all students and many schools do not offer Physics or Chemistry at all. Biology is the most available subject and this in part accounts for its dominance at LC level.

Everything is not rosy in Irish STM education and Table 6 lists some negatives. The second level system, particularly in the senior cycle, is driven by the LC examination and the need to get enough 'points' to gain entry to third level. The decrease in numbers at school has effectively eliminated the 'points race' from 2006, except for the most popular subjects like medicine, law, pharmacy. The points race has also seen the rise of the grinds schools (private cramming schools) and these schools are the major feeder schools to Irish universities. Schools overall still have poor laboratory facilities as the major recommendation of the Task Force was not implemented and very few schools have technical assistance, although almost everyone (except the Department of Education and Science) recognises that this would be the single most effective measure to improve practical science teaching in Irish schools. The examination system is centralised and there is no room for alternative syllabuses or approaches, so there is only one JC Science syllabus, one LC Biology syllabus etc., even though offered at different levels. This means there is very little real, independent curriculum development in Ireland. In addition, curriculum change is badly managed and poorly implemented. The new JC Science syllabus, which involved major changes in assessment and teaching approach, was examined first in summer 2006 but teachers hadn't seen proper guidelines, sample examination papers or details of the 3rd year project until well into the 3rd year of the course.

Table 6: Some negatives in Irish STM education

- Driven by the state examinations and the need to get 'points'.
- Poor laboratory facilities and resources in many schools and no technical assistance.
- Centralised examinations system, 'one size fits all', no room for innovation or alternative syllabuses.
- Curriculum development poorly implemented in practice.
- Many reports on science education, but little action.

Areas of Interest in Science Education Research

Table 7 lists some current areas of interest in science education research (Bennett, 2003). I would like to add two others: Problem-based learning and mathematical skills. In my opinion four key difficulties in the sciences are: communication skills (language), conceptual skills (thinking), calculation skills (mathematics), and practical skills (experimentation). Each of these four areas provides its own stumbling blocks for beginning and more advanced students (including university students) and when all four are combined in a topic e.g. volumetric analysis and many other science topics, then we really have problems!

I want to look at each of these areas in turn in relation to the teaching of Chemistry, since I have been teaching chemistry for over 36 years and before that was a student of Chemistry for 13 years (from starting secondary school to doctorate level), and have had three children go through the Irish education system, all of whom took honours maths and one or more honours in the Physical Sciences. I have also had a side interest in chemical education – the teaching and learning of Chemistry – since my first teaching job at Makerere University, Kampala, Uganda in the early 70s.

Table 7: Areas of interest in science education research (Bennett, 2003)

- Constructivism
- Cognitive development
- Practical work
- Context-based approaches
- ICT
- Language
- Attitudes
- Gender issues

1. The problem of language in science

For the professional in any discipline the language, symbols and terminology are not a problem – we have absorbed them and mastered them over many years. For the student the language of science is a forbidding thicket or bottomless swamp. They don't understand what we say or what they read. Chemistry is a foreign language, which has to be learned before you can make progress. There are several inter-related problems relating to language. (See Table 8).

Table 8: Some problems with language in science

- Science has a specialised vocabulary,
  e.g. molecule, ion, photosynthesis, refraction
- Science uses familiar words with different meanings,
  e.g. equilibrium, energy, volatile
- Science introduces a whole range of symbols and symbolic language,
  e.g. Hg, S, σ, Δ, $\sum$, $\int$
- Science uses many logical connectives,
  e.g. consequently, conversely, respectively

Science has a specialised and esoteric vocabulary, it uses familiar words with different meanings (a recipe for confusion), it employs a wide range of symbols and symbolic representation, and it uses many logical connectives which are essential for the sense of the argument.

The use of symbols, particularly in Chemistry the symbols for the elements, chemical formulae and equations, as well as other symbols, both mathematical and representing variables etc. is a major problem for students. For them it is like reading Russian in the Cyrillic alphabet would be for us – unintelligible. The chemical symbols are the alphabet of Chemistry; chemical formulae are the words and equations the sentences. The Chemistry language has its own syntax and grammar. It is hard to make any progress in Chemistry without mastering this aspect of its language. (See Table 9).

Then there is the technical vocabulary of science, usually complex and unfamiliar to students, with words like **mole, element, frequency, solution, dissolve, precipitate, filter, photosynthesis, atom, molecule …** and finally the words and terms in English which have different meanings when used in science, **parate, solution, velocity, force, weight**. Added to this are the symbols for physical quantities (e.g. wavelength, concentration) and the mathematical symbols that we use in science. It doesn't help that different sciences use different symbols for the same quantities, e.g. frequency in Chemistry (υ) and Physics (f)! Misunderstandings of words lead to misconceptions and confusions (see Selepeng and Johnstone, 2001 and earlier papers by Johnstone's school). The problems of language are greater for students whose first language is not English, but who are doing science through English (see Childs and O'Farrell, 2002). This is going to become a major problem across the curriculum in Irish schools in the next few years as the number of children with English as a second language increases, but the problems are enhanced in STM with its specialised vocabulary.

Table 9: Symbolic language of Chemistry

Alphabet	H, Sn, C, Ti, S, Br
Words	H_2O, CH_4, H_2SO_4
Sentences	$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$

To study Science is to learn a foreign language and unless one masters the language one cannot properly understand the Science. Having taught undergraduates for many years I know what problems they have with handling the alphabet of Chemistry (symbols for the elements), the vocabulary of Chemistry (chemical formulae) and the sentences and grammar of Chemistry (writing and balancing chemical equations). Many studies have shown that students have a problem with this and many students never properly master it and so cannot function beyond a certain level in Chemistry. Try asking your students to write down the formula from the name and vice versa for some common substances. The only ones you can guarantee are H_2O and CO_2. This applies also to Biochemistry and Biology where many chemical formulae are used. We need to pay more attention to the mastery of this new language when students start Chemistry, we need to reinforce it and we need to deliberately make sure that they know both technical terms and words with other everyday meanings. We cannot assume that students have good linguistic skills and weaknesses in reading and writing English will also spill over into Chemistry. Testing and practising comprehension of passages in textbooks or newspapers is a valuable diagnostic and teaching tool.

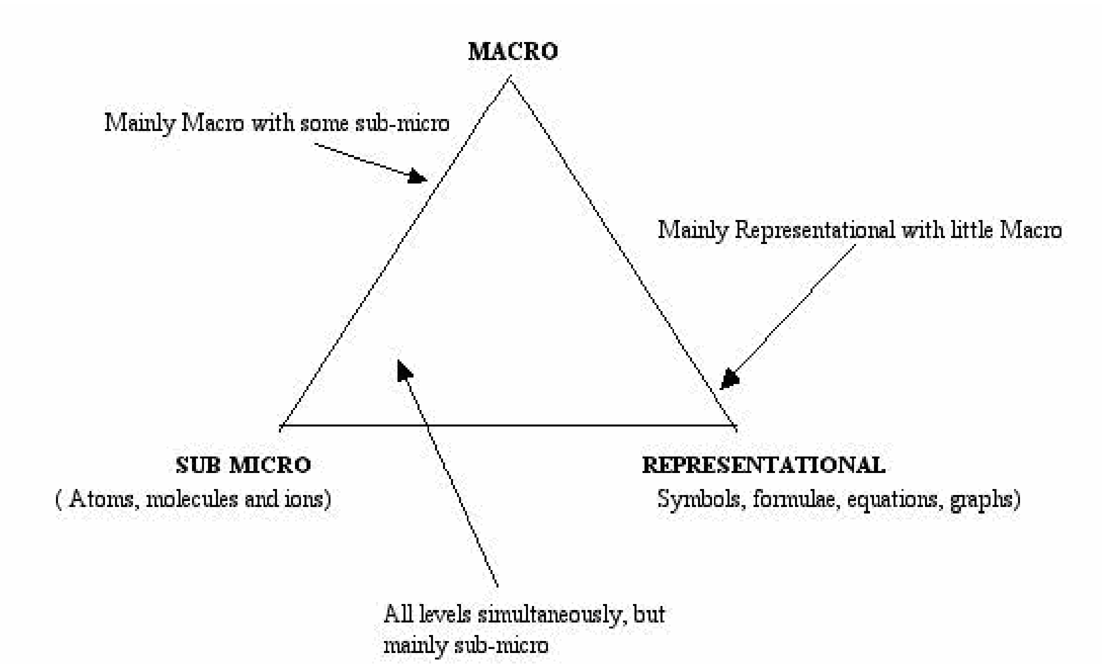
2. The problem of thinking

Chemistry and the other sciences and mathematics are concept-heavy and some of the foundational concepts, that professionals take for granted, are **not** elementary for students e.g. the inter-related concepts of atom, molecule, element, compound in Chemistry. We cannot master modern Chemistry (or Physics, Biology, Biochemistry etc.) without a good understanding of the particulate theory of matter. When we write chemical equations, when we use the mole concept, when we think about reaction kinetics etc. we need a robust understanding of the particulate nature of matter to make sense of reality. Alex Johnstone identified this with his model of three levels of understanding important in Chemistry (shown in Figure 4): the **macroscopic** (what we see, smell, feel in the real world), the **sub microscopic** (the invisible world of atoms and molecules) and the **representational or symbolic** (the written and mathematical representation of behaviour at the microscopic level). Students usually function in the area of the macroscopic, what Piaget called the **concrete**. They can see that copper (II) sulphate crystals and their solution are blue, that adding a base produces a blue-green solid etc. They can see blue litmus turn red in an acid and feel the rise in temperature when an acid neutralises a base. Understanding what is happening at a molecular level, writing an equation for the reaction, and explaining what is happening requires higher level thinking and capacity to think abstractly, symbolically and to visualise at a sub microscopic level. This is what professional chemists do all the time without consciously thinking, as it has become part of their mental apparatus.

Johnstone (2006) makes the following important observation:

> Teachers, and other chemists, flit around and inside the triangle with ease, giving us a powerful way of thinking about our discipline, but can early learners follow us inside the triangle without the onset of overload or with 'rationalisations' which lead to 'Alternative Frameworks'? We might have to rethink our curricula to begin with a treatment of one corner only followed by the use of a side, before we lead the students to the middle of the triangle.

Figure 5: Alex Johnstone's Three Conceptual levels of Chemistry (Johnstone, 2006)



Peter Mahaffy has suggested that this triangle needs to be hybridised to the chemists' favourite shape, the tetrahedron, by adding in the human, societal, dimension, as shown in Figure 6 overleaf (Mahaffy, 2006).

Another influential idea with respect to thinking from Alex Johnstone is that of the working memory capacity and memory overload as applied to science education. This model is shown in Figure 9 (see Johnstone, 2006). This model has a number of implications for science teaching and student learning. Firstly, overloading the working memory space means that students cannot learn and their brains 'freeze'!

Secondly, Johnstone (2006) has used this model to investigate:

1. function of language in science education
2. problems of learning in a laboratory
3. multi-level learning (see below)
4. assessment of science learning
5. problem solving

Figure 6: Peter Mahaffy's learning tetrahedron (Mahaffy, 2006)

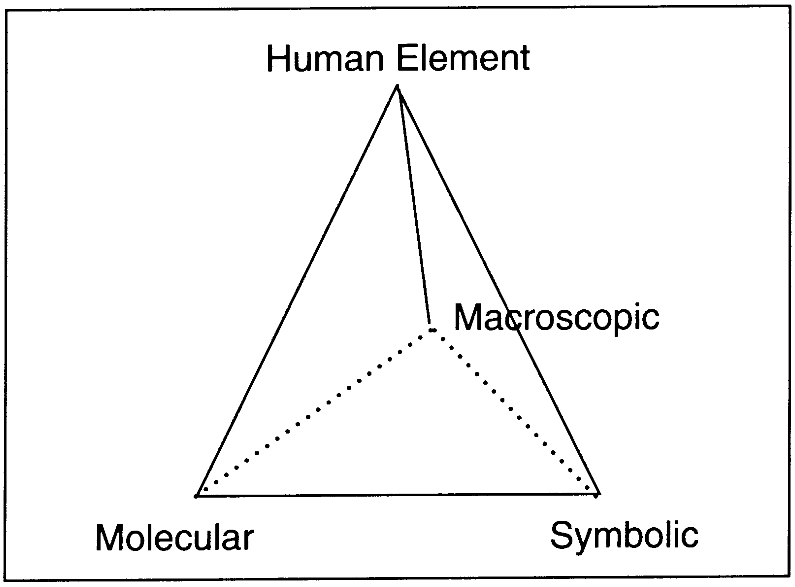
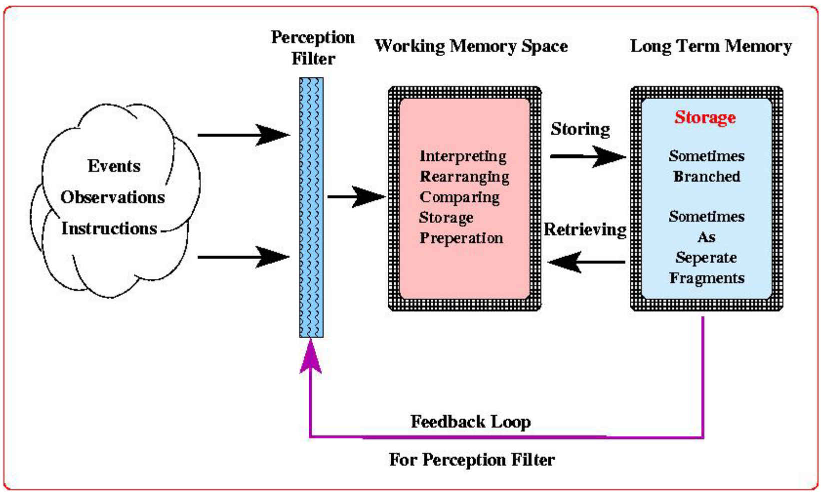


Figure 7: Johnstone's working memory model (Johnstone, 2006)



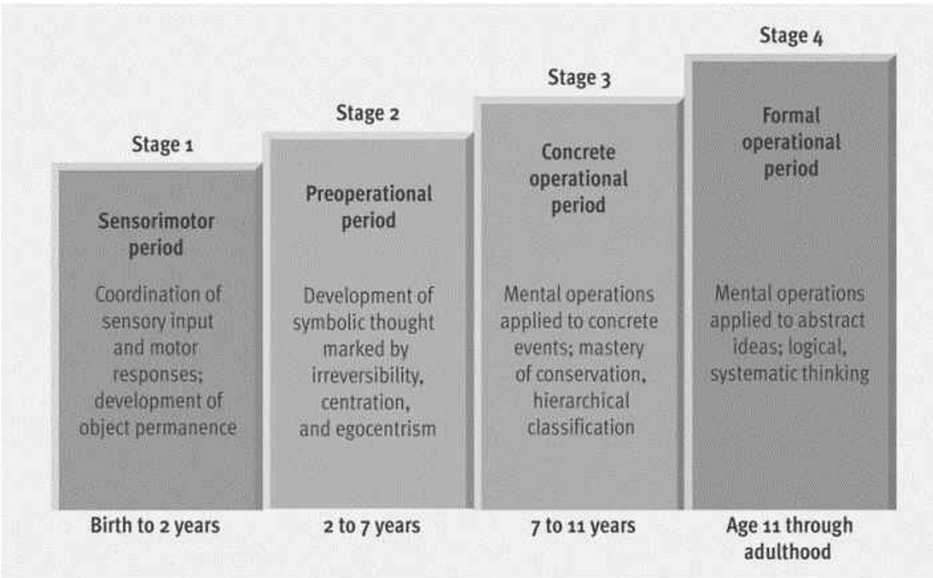
However, there is a more fundamental problem of thinking that Shayer and Adey identified in the 1970s (Shayer and Adey, 1981). They said this is the introduction to their important book on the "science of science teaching":

> *"…there is a chasm set between the expectations expressed in the curriculum objectives and the cognitive skills of many pupils."* Preface v

> *"there is a massive mismatch in secondary schools between the expectations institutionalised in courses, textbooks, and examinations and the ability of children to assimilate the experiences they are given."* Preface vi

They set out to test Jean Piaget's ideas of how children learn in the context of science for a larger sample of English children across the whole ability range, in contrast to Piaget's original smaller and narrower sample. Piaget's work has been very influential in some circles, although out of fashion in others, and he identified stages in a child's intellectual development. Figure 8 shows one representation of the classical Piagetian stages.

Figure 8: Piaget's stages of cognitive thinking
(**faculty.plattsburgh.edu/…/101Ovds/M13-1c.htm**)



Shayer and Adey's finding were startling as although they confirmed Piaget's work in broad outline, since they used it as their research paradigm, the detail was quite different (see Figures 9 and 10 from Shayer and Adey, 1981). What their results showed was that children developed later and by age 16, the end of the junior cycle and first exposure to formal science, only 30% of the population had reached the formal operational stage i.e. when they should be capable of abstract, conceptual thinking. Many authors quote and apply Piaget's original stages, where formal operational thinking is arrived at from age 11 upwards. Classical Piagetian theory would appear to overestimate the percentage of a school population that is capable of formal thinking of the type required in science and mathematics. Further analysis by Shayer and Adey (see Figure 10) showed that if one streamed children, then the higher streams did develop sooner and had higher percentages in the formal stages.

Figure 9: Piagetian stages in a broad British child population (Shayer and Adey, 1981)

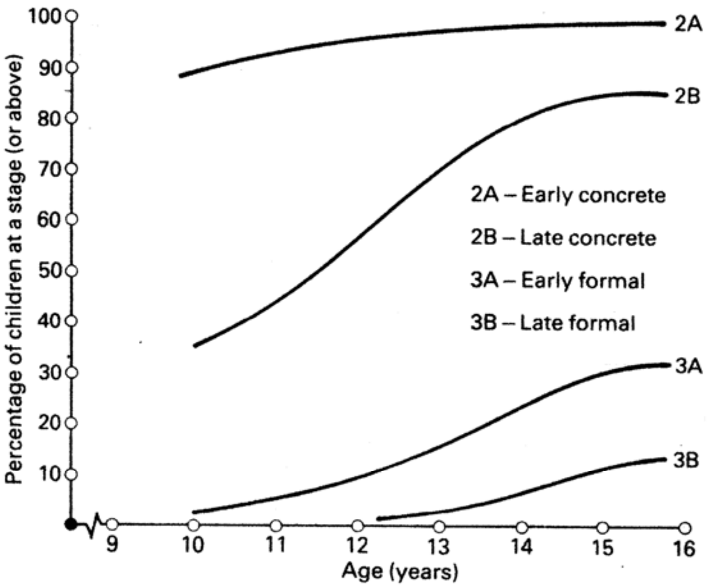
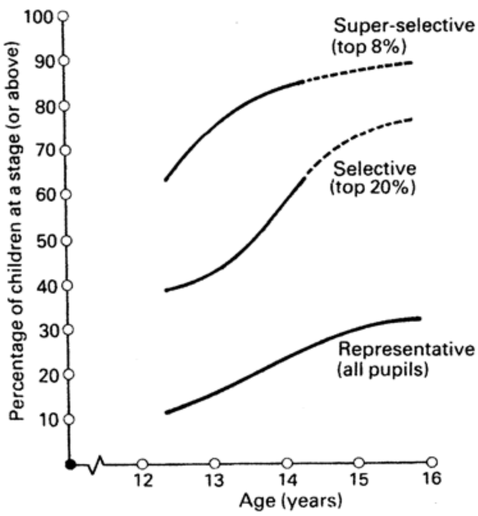


Figure 10: Proportion of pupils with early formal thinking in three different schools populations (streams) (Shayer and Adey, 1981)



If you select pupils for intellectual ability, then they are more mentally developed at a given age! Other studies in the USA and other countries have shown similar results. The percentage of students reaching formal operational stages by the end of schooling or even in the early years of third level education is much smaller than many people assume (see for example Renner et al., 1976). Instead of leaving it there Shayer and Adey and their co-workers went on to investigate whether thinking skills could be taught and whether the development of cognitive skills could be accelerated (see Adey and Shayer, 1994 and Shayer and Adey, 2002.) This led to the CASE (Cognitive Acceleration in Science Education) and CAME (Cognitive Acceleration in Mathematics Education) projects, which have demonstrated that thinking skills can be taught and that they lead to improved performance in examinations in other areas as well as in science or mathematics. Teaching materials have been published (Adey et al, 2001). These have become very influential and widely adopted projects in UK secondary schools and worldwide.

Philip Adey has summarised their experience in a UNESCO monograph (Adey, 1999) and the quotations below warn of the dangers of a centralised, examinations-driven curriculum on thinking skills:

> *"A specified curriculum can act as a cage, trapping the educational system in a stagnant annual repetition of the same material"* (Adey, 1999, p.8).

> *"Teaching for the development of reasoning in children is the antithesis of teaching for the recall of factual content. The development of critical thinking, or higher-level reasoning, in children requires by definition that children be given an opportunity to exercise their own minds, to engage in critical appraisal, to risk opinions in a sympathetic atmosphere and then have their opinions challenged in a rational but respectful manner.* (Adey, 1999, p.25).

I think we should take these warnings seriously in relation to the Irish STM curricula. A stark headline in the education supplement of *The Guardian* in January 2006 said: **"Children are less able than they used to be"** and quoted new research from Michael Shayer, now retired from King's College, London, which shows that 11- and 12-year-old children in year 7 are '*now on average between two and three years behind where they were 15 years ago',* in terms of cognitive and conceptual development. Crace (2006) and went on to say: "*'It's a staggering result,'* admits Shayer, whose findings will be published next year *[2007]* in the *British Journal of Educational Psychology*.

> *Before the project started, I rather expected to find that children had improved developmentally. This would have been in line with the Flynn effect on intelligence tests, which shows that children's IQ levels improve at such a steady rate that the norm of 100 has to be recalibrated every 15 years or so. But the figures just don't lie. We had a sample of over 10,000 children and the results have been checked, rechecked and peer reviewed.*

He went on to speculate about the reasons for this decline:

> *We can speculate but there's no hard evidence. I would suggest that the most likely reasons are the lack of experiential play in primary schools, and the growth of a video-game, TV culture. Both take away the kind of hands-on play that allows kids to experience how the world works in practice and to make informed judgments about abstract concepts.* Crace (2006)

It is interesting that these findings, based on a large sample of 25,000 children in private and state schools, run contrary to the continuous improvement in examination results in the U.K. over the same period.

I think that we need to think much more about our students' capability to think and their cognitive level at different stages of their science and mathematics education.

3. The problem of mathematics

> "The professional physicist or chemist tends to take a predatory view of mathematics as a servant or tool." (Shayer & Adey, 1981, p. 142)
>
> "Mathematics is the door and key to the sciences."
> Roger Bacon, 1267

These two quotations make the point that numeracy and mathematical skills are essential to the physical sciences. However, mathematics is often a problem for the science teacher because introducing mathematical ideas in a scientific context often creates problems for students. They are not able to transfer the concepts and skills from one domain to the other e.g. from x and y to T and log k. Much mathematics teaching is disconnected from and out of phase with the needs of science courses – we need a 'just in time', 'need to know' approach to maximise the transfer to science.

Mathematics learnt by drill and practice is often not understood and cannot be applied in new contexts. Many ideas in mathematics require abstract, formal thinking and many students even at 3rd level are not capable of it, if the findings of Shayer and Adey and other workers are correct. This means that we cannot assume that school mathematics will be available to students at 3rd level, in either mathematics or science courses, and we need to allow for this and for the cognitive development of students. Many universities get around this by having 'maths for chemists' and 'maths for physicists', sometimes taught within and by the science department and tailored to the needs of particular students. However, one of the problems may be inability because of basic cognitive inadequacy. We assume that most students entering 3rd level at age 17 or 18 will be capable of formal operational thinking and will be able to understand and use mathematical ideas. If only 30% of them are actually capable of this level of thinking, then the other 70% will be struggling and can only cope by memorisation and cramming fro examinations, and rote application of algorithims. It may be that we need to teach thinking skills in first year at 3rd level to enable students to cope with their courses.

In a study of mathematics skills of college students in the Philippines (Leongson and Limjap, 2005), the researchers found:

- that 61% of the college freshmen were at the concrete level. This study also reveals that as an individual goes through the four successive cognitive levels of performance, expertise on reasoning develops progressively.
- evidence that there are certain logical operations that are not fully developed even at the college level. One example is Ratio or Proportional Thinking.
- that more than 50% of the college students have inadequate understanding of the concept of ratio and proportion as they exhibited ambiguous reasoning patterns during the interview.

If this is generally true then it explains why using mathematics in science contexts seems to present massive problems for students. Most of them may just not be able for the cognitive demands made upon them.

4. The problem of practical work

Children leave primary schools looking forward to science and practical work – by the end of year 1 they think science is boring! What has happened to turn them off and destroy their innate curiosity and interest in science? This is one of the most urgent questions we have to address in science education. We cannot build a knowledge-based economy based on science and technology if a majority of students are turned off science early in the second-level cycle, and thus never go on to study science when they have a free choice. The uptake figures for LC science subjects discussed already indicate this clearly. One problem is that practical work is often not done or not done properly – and making it mandatory does not mean that it will be done properly. Repeating recipes from the textbook is not an experiment, and doesn't develop scientific skills. Copying out the method, results and conclusions from the textbook or board does not develop interest or scientific method. There are practical reasons why science teachers do not do enough practical work – poor facilities, lack of resources, lack of time, lack of technical assistance (Figure 10). The Task Force (2002) made six recommedndations and the first and most expensive one was to do with improving laboratory resources (Table 10).

Figure 11: The problem of limited resources

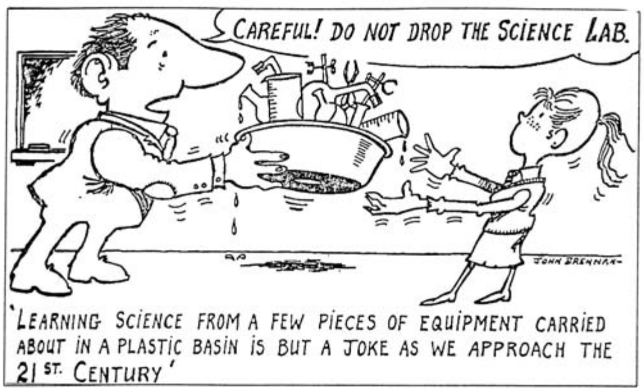


Table 10: The Task Force on the Physical Sciences recommendations

1. Planning and resources for school science
2. Equity of access
3. Teaching and learning of science
4. School curriculum and assessment
5. Promotion of science and careers
6. Science education at third level

But it is also important to get the philosophy of practical work correct as well, so that it is not just a series of routine, unexciting and predictable exercises. In addition Johnstone's work has shown that much practical work makes cognitive demands that students are not capable of at junior and senior cycles, or even at university. They are overloaded with instructions and ideas and the need to remember practical skills as well as theory at the same time. Johnstone has developed and tested practical solutions to these problems to make practical work more meaningful for students.

Conclusions

1. Each of the areas identified in this talk need attention to improve science (and mathematics) education:

- language skills
- thinking skills
- mathematical skills
- practical skills

In science education they are inter-connected and mutually dependent areas. In chemistry the mole concept illustrates this very well and is a major problem area for students at all levels. In my experience most students do not fully understand it even at the end of a chemistry degree.

- Many students find this impossible to master at 2nd or 3rd level – unless they can use a simple algorithim, a magic formula to solve straightforward exercises.
- Solving mole problems involves several steps (see Johnstone, 2000) and also involves proportion, a notorious stumbling block in mathematics.
- Johnstone (2006) says *"Mole questions inevitably come well outside Working Space Memory and so we see in the literature a plethora of papers lamenting student's inability to solve them."*
- Involves all our problem areas to some extent and thus presents a major problem to average students.

2. We need to focus more on developing understanding by improving students' conceptual skills than on rote-learning for passing examinations.

3. A knowledge-economy focusing on innovation and creativity cannot be built on the ability to succeed in routine and predictable examinations.

4. We need to put into practice at all levels of education what has been learnt from research into science and mathematics education.

5. Many areas of research recommend more opportunities for discussion by students in theory and practical lessons to enable real learning to occur.

6. We need to be aware of where our students are in their cognitive development and design our curricula and teaching methods accordingly.

7. If only a relatively small percentage of students reach formal operational level by age 17/18 (30-40%) and if the percentage of students entering third level is >60%, then there will be an increasing mismatch between 3rd level curricula in science and mathematics and the students' cognitive abilities.

A cautionary tale from 3rd level on the danger of research-led universities:

> Attending a college whose faculty is heavily research-oriented increases student dissatisfaction and impacts negatively on most measures of cognitive and affective development. Attending a college that is strongly oriented towards student development shows the opposite pattern of effect. Astin (1993, p.363).

And a final word from Alex Johnstone:

> Perhaps it is time for the 30 years of science education research to break out from its introspectiveness and repetitiveness and be applied to making the learning of Chemistry an enjoyable and exciting experience for all young people (Johnstone, 2006)

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