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Theme Issue: ***Teaching Chemistry and Physics***
EDITOR'S INTRODUCTION
(RESEARCH/POSITION PAPER)
Methods and issues of teaching and learning

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THEME ISSUE: *TEACHING CHEMISTRY AND PHYSICS*
EDITOR'S INTRODUCTION

FACILITATING SCIENCE LEARNING IN THE INTER-DISCIPLINARY MATRIX - SOME PERSPECTIVES ON TEACHING CHEMISTRY AND PHYSICS

ABSTRACT: Chemistry and physics are often considered as two well established and closely linked scientific disciplines. As well as there being recognised common ground between the two subjects, it is generally accepted that key aspects of chemistry are supported by a foundation of physics. The present editorial article introduces a suite of papers exploring aspects of the theme 'teaching chemistry and physics'. It is suggested that common perceptions of the relationship between chemistry and physics as neighbouring scientific disciplines may be over-simplistic. The present major division of science into biology, chemistry and physics is considered to be both historically contingent, and possibly passé. In any case a subject such as chemistry can only be considered as a unitary scientific discipline to a limited extent, as within chemistry there are distinct disciplinary traditions (or 'paradigms'). It is known that students do not always integrate their science knowledge as teachers might hope, but this may reflect the way scientists themselves work within a paradigm. These papers on 'teaching chemistry and physics' raise some important questions that should be of concern to those teaching aspects of chemistry whether in school, college or university. [*Chem. Educ. Res. Pract.*: 2003, *4*, 103-114]

KEY-WORDS: *chemistry & physics; integration of knowledge; disciplinary structure; paradigms and disciplinary matrices; research questions; history of science*

PREFACE

I have the proud duty to introduce readers to the contributions in the first theme issue of the journal CHEMISTRY EDUCATION: RESEARCH AND PRACTICE (CERP), on the theme of '*teaching chemistry and physics*'. The papers in this issue cover various aspects of both research and practice, and include contributions from Canada, Denmark, Spain, Turkey, the UK and USA. It is traditionally the role of a guest editor to introduce the theme, and to discuss the contributions and help readers see how they relate to the theme. I am pleased to take on that task, and - in particular - to explain why I feel that the theme of 'teaching chemistry and physics' illuminates some key issues that should be of central concern to all of us who are committed to, and responsible for, chemistry education.

One of the major responsibilities of educators is to select material for curricula. The decision of what to teach, indeed what is most worth knowing and so worth teaching, must come before questions about the order and pace of teaching, and the techniques by which the material should be taught. It could be strongly argued that if the curriculum is not worth learning, then it matters little how well we go about teaching it, or whether we can assess the resultant learning in a valid and reliable way. We need to know, then, what we feel it is worth spending time and effort teaching in schools, colleges and universities. Now curricula are more than a list of subjects (Beck, 2000; Goodson, 1987), and it is quite possible to organise the same learning under different patterns of headings (cf. Aikenhead, this issue), but in practice organised education often starts with deciding which subjects should be taught.

Readers of this journal would presumably believe that chemistry is worth teaching and learning. Perhaps many readers would also have quite fixed ideas about what learning chemistry should (or even must?) involve. Perhaps it might be considered that at University level something called chemistry should include, for example, courses in physical chemistry, and that these should include kinetics, thermodynamics, photochemistry or whatever. Perhaps a college level course would be need to include such topics as atomic structure, mole calculations, or functional groups in order to be considered acceptable by most chemists.

The suggestion here is that once a subject is labelled (say as ‘chemistry’) this label will import many expectations about what should be taught. It seems that a kind of ‘nominative determinism’ is at work - if we call it chemistry then there is a core of material we should not exclude.

Now this may indeed be quite reasonable from the perspective of the profession of chemistry. Professional bodies must make decisions about when someone can be called a chemist, and the criteria will naturally include knowledge of chemistry. This invites a ‘common core’ approach to chemistry courses, the minimum entitlement that a chemistry student might expect to enable them to move onto the next stage in professional training. Certainly in the UK national school curriculum the chemistry element is designed to be acceptable to colleges offering post-16 chemistry courses, those courses also having a common core to make them acceptable to universities, which themselves offer chemistry courses acceptable to the Royal Society of Chemistry as suitable preparation for chemists.

Yet it is easy to see how this channels thinking, *and so* channels curriculum design, *and so* - in due course - helps to maintain the existing disciplinary structure of science. The papers in this volume will hopefully help the reader critically question *the extent* to which this is a good thing. If the current disciplinary structure of science is the most effective one, providing some kind of optimum match between human knowing and an underlying knowable reality, then this stability is to be welcomed. If, conversely, the current disciplinary structure of science derives from a less-progressive state of knowledge, and is now outdated, then too great a degree of permanence is counter-productive. Too much stability stifles innovation and creativity. Too much *re*production of culture (be that science or any other aspect) could close off opportunities to produce new culture.

This reminds me of the flippant adage that the purpose of the University is to safeguard the future existence of the University! Of course the same raison d’etre applies to most institutions *to some extent*. Universities are however usually supported by public funds and so the main way to safeguard the continuing existence of the Academy (at least in a democratic context) is to make sure that it is seen have *other* purposes more in tune with the needs and aspirations of the wider society.

It should also be remembered that although chemistry education is partly about the education of chemists, *most* learners of chemistry in school and college do not become, or even aspire to become, chemists (e.g. Reid, 2000). For this majority, material essential to the education of chemists may often be far from necessary for their intellectual and personal (let alone career) development (see Aikenhead, this issue; Warwick & Stephenson, 2002). If we want the most suitable education for our children and young people, i.e. all of them, then we may find the traditional academic discipline structure is not the best place to start planning curricula.

CHEMISTRY, PHYSICS OR SCIENCE?: A BIOGRAPHICAL CONTEXT FOR A THEME

An editorial article can allow an author to be personal in a way that is often otherwise restrained in academic writing, and to some extent this introductory article will be personal: at least in as far as biography (mine) explains the choice of theme and illustrates its importance. In particular I need to explain why 'teaching chemistry and physics', rather than, say, 'teaching chemistry and biology' which might seem to be a theme that offers similar insights.

The choice of 'teaching chemistry *and physics*' is a contingent one, contingent upon the background of the guest editor. I am, *inter alia*, a chemist and a physicist. I am a chemist in at least two senses: I hold a university degree in chemistry, and am a Chartered Chemist (through the Royal Society of Chemistry in the UK). I also have considerable experience of teaching chemistry in a school and college context. But I probably do not consider myself a 'chemistry teacher' as such for two reasons. Firstly, due to the structure of the English education system (and the 'laws' of supply and demand), my post graduate teaching qualification was in chemistry and physics, and much of my teaching experience has been in physics. I am a physicist in the sense of being a Chartered Physicist, and have certainly taught more physics classes than chemistry classes over my career. Indeed, in schools I taught some biology, as well as some environmental science and electronics. So when I worked as a school teacher I would have seen myself as primarily a 'science teacher' rather than as a chemistry teacher or a physics teacher.

In the UK few students follow 'science' degrees *per se* (i.e. they may read chemistry or geology or astrophysics or genetics or chemical engineering, etc.), but in many state schools teachers are appointed to teach 'science', albeit often with a 'specialism' of biology, chemistry or physics. This in itself creates an important issue for teacher education - in terms of the development of a professional identity as a science teacher (cf. Aikenhead, this issue), and induction into the professional persona of science teacher. Indeed it might not be an exaggeration to suggest that in the UK system - depending upon the traditions, ethos and curriculum arrangements in a particular school - teachers may be *either* seen as teachers of science (in many 11-16 state schools) or as teachers of chemistry (or physics etc.) in many private schools and institutions with post-16 students.

When I moved from school to college teaching I continued to teach chemistry *and* physics, but also become involved in two new areas. For one thing I began to be more involved in teacher education (and so started a new shift in professional identity), but I also began, for perhaps the first time in any meaningful and substantial sense to teach *about science*. In the UK system most young people who go to University (i.e. around 18 years of age) have studied traditional college courses comprising of a selection of subjects (e.g. chemistry, physics and maths; biology, chemistry and physics; biology, chemistry, geography and maths, etc.) which are examined separately. But some colleges also provide 'Access' courses for mature students who - for whatever reason - did not attain good academic qualifications on leaving school but wished to return to study and to apply for university. I was asked to 'teach science' as an input on such a course.

The Access students selected a specialism from, at that time, English literature, history or social studies, but also studied a range of subsidiary subjects. I was asked to provide a course of twelve two-hour 'science' inputs. I considered producing a programme with four sessions each of biology, chemistry and physics - but dismissed this as I could see little educational value in what was likely to be covered in such a course (either very little breadth or minimal depth). Instead I developed a module of 'Science Studies'. The aim was to give a flavour of science (or perhaps the sciences?), by considering the creative, human and controversial nature of issues and events in science.

The Science Studies module looked at competition and co-operation in the 'race' to uncover the structure of DNA, the development (and response to) of Darwin's ideas about natural selection, the status of the chemist Lovelock's Gaia theory, the 'dissent' over whether HIV was 'the' cause of AIDS, and similar topics. The amount *of* science taught was limited, but the students learned *about* the processes and 'progress' of science. Although the course did not provide a good grounding across biology, chemistry and physics, it did provide students with an opportunity to find out *about* science. Most of the students enjoyed the module, whereas their school experiences had often left negative impressions of science. Some even decided to apply for science-related University courses despite the 'arts' bias in their college course (and so we later added a specialist science strand to the course). Although I felt this was very much a success story, it gave me cause to reflect upon my other teaching - of chemistry, and of physics - where I felt that - by contrast - my students were learning very little 'about science'.

My own research into students' learning of science highlighted a related concern. When I explored students' ideas about chemistry topics that *I* considered to be heavily 'physical' in nature I found that *the learners* often failed to conceptualise them in the same way. Indeed some explicitly wanted to avoid having to consider thinking about physics during chemistry lessons as if it was an added burden - an extra demand on their limited cognitive apparatus. These students seemed to compartmentalise their 'chemistry' and 'physics' knowledge as though they were separate and unrelated domains (Taber, 1998).

My research did not allow me to estimate how common that mentality is - something that makes an interesting research question. However, in at least one case I found that this tendency to compartmentalise knowledge was occurring even within chemistry. One student suggested that single and double bonds were part of organic chemistry whereas ionic and covalent bonds were found in inorganic chemistry. Although there are clearly limits to the extent to which data from individual students can (or should) be generalised, such findings do suggest that this is a phenomena worthy of further study. Indeed the belief that the degree of integration of knowledge could be a key indicator of science learning underpins some of my current research thinking (ECLIPSE, 2003).

So my personal experiences as a teacher and researcher led me to think about the relationship between science and the distinct scientific disciplines, and to consider the way students understand the relationship between the sciences. Because of my own biography, the main context for my thinking about this latter issue was in terms of the overlap between the two subjects I had taught substantially - chemistry and physics.

THE SCIENCES AS HISTORICALLY CONTINGENT DISCIPLINES

I feel that the biographical contingency of my proposing an issue of CERP on 'Teaching Chemistry and Physics' has an interesting parallel with the historical contingency of the 'subjects' themselves. I would suggest that the disciplinary structure of science is to a significant extent an accident of human history.

I used to consider this view was somewhat self-evident, until I once raised it in a public forum and discovered that some colleagues find the idea at least counter-intuitive, if not clearly false. I believe this is more than an academic argument, as the position one takes on this matter surely influences views about how science (or a science) should be encouraged to develop, *and* the nature of education in science and/or the sciences (see, for example, Aikenhead, this issue). In view of the potency of the position taken on this matter, it seems important to clarify the issue.

The counter position would be that the disciplinary structure of the sciences is largely a ‘natural’ (or even neutral) matter. The primary distinctions between a discipline which is concerned with the nature of the universe in terms of energy, matter and their interactions; a discipline concerned with the properties and reactions of different substances; and a discipline concerned with the living world *could* be considered to develop because these are obvious, identifiably different foci for the scientific enterprise. Of course, young people do not intuitively appreciate the difference between chemical and physical phenomena, and need to learn to interpret these phenomena in terms of the conceptual frameworks of mature science (Stavridou & Solomonidou, 1989).

My own view is that once something we would recognise as ‘science’ became well established, and grew to encompass more than any individual ‘scientist’ could master, the appearance of some form of disciplinary structure might well be inevitable. I can even be convinced that (what we might recognise as) biology-chemistry-physics lie on some form of continuum. However, I do not feel that the three-fold division was inevitable, nor that the commonly accepted boundaries between chemistry and biology (on one ‘side’) and physics (on the other) are inescapable. To my mind significantly different disciplinary structures could well have arisen. Just as an extra-terrestrial visitor is as likely to map the earth with the Southern hemisphere at the top as at the bottom (or even use a graphic convention that puts the rotational axis on, say, the horizontal or across the page from bottom left to top right), I would expect her alien conceptualisation of science or sciences to be likely to be noticeably different from our modern (late 20th-early 21st century) Occidental way of thinking.

So I would suggest that our present conceptualisation of the sciences arises from historical contingencies that could easily have been different: the structure we have represents something that evolved from the particular decisions of the particular scientists, scientific organisations, and editors who have been influential. Surely much in science could be different but for historical ‘accidents’.

At this point I must make it clear out that I am not arguing that *our science* is itself completely arbitrary. This is *not* a relativist argument that in a different history there might only be four elements, that burning would be due to the release of phlogiston, and objects would fall in order to find their natural place. There are positions between the extremes of (a) ‘everything goes’ and magic and science are just different ways of seeing the world, and that (b) there is an absolute reality that science is increasingly mapping in perfect detail. The former position is surely no more than a ‘stalking horse’ (e.g. Feyerabend, 1988), and although sometimes seen as Kuhnian, it goes far beyond the views of Kuhn (1970). The second position is so naive that it can surely not be considered as defensible. It seems undeniable that the biases of our cognitive apparatus, as well as the conditioning (i.e. learning) of our social worlds must influence the way we conceptualise the natural world. For an example of the former effect, just consider the notion of ‘light’, a physical phenomena anthropocentrically discriminated from near-IR or near-UV by the contingency of the evolution of the human visual apparatus. For the influence of our social world consider the colours of the rainbow. Few observers would objectively make out seven distinct colours - and it has been suggested that Newton was influenced by religious considerations.

Most scientists must surely, tacitly at least, work on the basis that there *is* an external reality that one can strive to ‘know’, and that such reality is objectively knowable to some meaningful extent. However the entities that science creates (Ogborn, et al., 1996) to model the world are nevertheless human constructions. Some of our modelling may map onto the natural world quite well (so there are regularities in nature which quite well match our models of ‘electrons’, ‘helium molecules’, or ‘gravitational field strength’). Other models may have limited ranges of application (so changes of state such as ‘melting’ best describe changes in pure substances), but nevertheless do map onto real phenomena. In other cases it becomes clearer than our models are more arbitrary. I would suggest that the labels ‘acid’, ‘oxidising agent’, and even ‘organic’ are more clearly cultural artefacts. There is no single regularity in nature which fits well with all the historical meanings of a term like ‘acid’ which has clearly changed its meaning according to the convenience of chemists. Chemists have not been making progress towards a better understanding of what the natural phenomena acids are, rather we have changed our collective mind about what it is most helpful to label an acid.

In a similar way the traditional biology-chemistry-physics discipline structure of ‘western’ science is hardly written in stone. The place of geology as a separate discipline is a case in point. Other examples of distinct, or not so distinct, sciences might include metallurgy, mineralogy, genetics, botany, zoology, anatomy, biochemistry, biomechanics, biophysics, geochemistry, environmental science (or sciences?), ecology, molecular biology, physiology, neurology, and so on. It seems clear that the status of such subjects as sciences in their own right; branches of better established disciplines; or areas of inter-disciplinary studies is both (a) labile over time, and (b) unlikely to be the subject of consensus among the scientific community (communities?) The distinction, within chemistry, between inorganic, organic and physical chemistry is no longer sacrosanct in some universities. And - whilst most ‘natural scientists’ would probably not consider social scientists such as economists or historians to be part of the scientific community - the demarcation of science and non-science is itself hardly impermeable. For example, there is much in psychology that is truly scientific - but, for example, classical psychoanalysis would probably *not* be recognised by most scientists as part of the scientific enterprise. Again, historical hindsight is a wonderful gift - phrenology and animal magnetism were respected in their day, just as were the æther, caloric and melancholy.

Whereas my view of the importance of historical contingency in the disciplinary structure of science derives from my general reading about science over many years, I have invited for this issue of CERP a paper from a scholar who has studied the history of science much more systematically. Glen Aikenhead is well known for his wide-ranging writings in science education, but he was invited to contribute to the present volume for his particular interest in cross-cultural aspects of science and science education. Prof. Aikenhead’s contribution puts the contemporary disciplinary structure of science within its historical perspective.

Aikenhead’s position paper shows how the familiar division of science into well recognised disciplines owes a great deal to choices that were - whilst not exactly arbitrary - to some significant extent political. A knowledge of the historical development of the discipline structure of science - something that is seldom a formal part of the education of chemists or other scientists - can help us question how well this structure is optimal for the progress of science. Such questioning should make us aware of both the potential for further evolution, and of the possibility that other sciences (from other cultural and historical perspectives) are not necessarily inferior to ‘modern’ Western science.

Appreciating changes in the way science has been considered to be structured over time, and how this has often been influenced by policy decisions of key institutions, invites us to speculate how this structure may evolve. Such speculation may be admitted for argument’s sake, to provoke a response in the reader. So perhaps quantum mechanics and particle physics may evolve into a distinct science separate from ‘classical’ physics, which could itself absorb much of physical chemistry. Perhaps molecular science will be recognised as a major disciplinary area comprising of much of chemistry, pharmacy and of biochemistry? Perhaps much of inorganic chemistry will become part of a wider materials science? Medicine could become largely dominated by genetics. Perhaps part of biology and psychology (psychiatry) will form a new behavioural science, whilst other parts of biology (neurology) and psychology join with computer science and cybernetics to form a new cognitive science (cf. Gardener, 1977). The major divisions in the natural sciences could then be focused on interactions at different level of analysis, such as the inter-personal (behavioural science); the intra-personal (cognitive science); the somatic (genetic science); the sub-microscopic (molecular science) and the quantum (particle science). Of course such a structure would not map perfectly onto clear phenomenological divisions in the world: but the point is that it could arguably do it as well as, or indeed perhaps better than, our current disciplinary structure!

Such a perspective is particularly important in our multi-cultural societies. Accepting that there might be other valid understandings of what science is, or could be, is essential if we are not to have a superior, imperialist and prejudiced view of the ideas and beliefs of students from different cultural backgrounds. To my mind there is an important distinction between the reasonable belief that the science of the dominant culture has generally progressed and become more sophisticated over time; and the uncritical assumption that because it *is* dominant, 'our' science is clearly superior to the different sciences of other cultures. Long successful traditions may often have valuable ways of knowing, and may generate useful (and systematic) knowledge about the world, even if that knowledge is structured and demarcated differently to 'ours', and was derived without the use of electron microscopy, radio-telescopes or gas-liquid chromatography.

THE CHEMISTRY-PHYSICS INTERFACE

Perhaps one of the clearest examples of the historical contingency of scientific disciplines is the 'border' or interface between chemistry and physics. A physical chemist may often seem to have much more in common with a chemical physicist than with an organic chemist. Topics such as radioactivity and thermodynamics are often studied and taught under the headings of both subjects. In their contribution to this issue, Toomey and Garafalo suggest a considerable list of topics that might be considered as the 'common ground' between physics and chemistry courses. They also refer to 'a common set of skills ... necessary for success in both disciplines'. In his contribution Josephsen goes one step further and explores the common ground in university practical work which could be useful in the training of students across a range of science specialisms. In his Danish context this forms part of an approach to undergraduate science which allows students to delay specialisation until the third year of their course. It seems reasonable that there is considerable common ground across the natural sciences, and especially across chemistry and physics.

A common view of the relationship between the sciences is that physics provides the fundamental science upon which chemistry is based - and that chemistry plays a similar role for some aspects of biology. To the extent that this is true it seems clear that higher-level (e.g. university) study of chemistry should require prerequisite knowledge drawn from physics as well as from chemistry: i.e. there are topics in school/college *physics* which are important in understanding degree level chemistry. This is reflected in Pitt's contribution (this issue) which describes how one university responded to the challenge of students entering the university lacking this desired background knowledge. Pitt's paper describes his University's practice of providing a suitable course of foundation physics upon which undergraduate understanding of subjects such as chemistry and chemical engineering could be built.

Such an approach is based upon the now widely accepted notion of 'knowledge construction' where learners need to have secure 'foundations' in understanding basic concepts, before they can make sense of, and develop understanding of, more complex material (e.g. Taber, 2000). This perspective is explicitly applied in two of the contributions in this issue. Toomey and Garafalo's paper, referred to above, applies this constructivist perspective to show how a wide range of material that would conventionally be thought of as part of a physics course can be an important part of the curriculum in first year undergraduate chemistry: including material that would not commonly be given curriculum 'space' in chemistry courses.

The second contribution drawing heavily upon the constructivist approach is a report of some findings from my own work (Taber, this issue). I discuss some college level students' responses to a diagnostic instrument on ionisation energy, a chemistry topic where the need for building understanding upon physical foundations would seem especially important. The enquiry (part of a Royal Society of Chemistry project which attracted collaboration from a wide range of schools and colleges in the UK) suggests that many students understand ionisation energy in terms of alternative conceptions that are inconsistent with basic physical principles.

In particular, the paper shows support for two previously reported alternative conceptions. The widespread use of a 'full-shells explanatory principle', where chemical processes are explained in terms of the 'needs' of atoms to obtain octets of electrons, or fill their shells, has been suggested as the central conception in a common alternative conceptual framework in chemistry. This anthropomorphic, 'social', mode of discussing and explaining chemistry - rather than thinking in terms of the physical interactions between molecules, atoms, ions, etc. - seems to be widespread. The second common principle seems to be physical rather than social, but still represents an alternative to the teachings of physics. Learners commonly think of the nucleus giving rise to a set amount of attraction (depending upon the magnitude of nuclear charge) which is then spread over the surrounding electrons.

In the paper (Taber, this issue) it is argued that appropriate learning about ionisation energy should be based upon prior learning of the underpinning physical principles (cf. Pitt, this issue; Toomey & Garafalo, this issue). However, the paper also considers the extent to which within a subject such as chemistry there may be concepts which evolve to be *inherently chemical* and which may become divorced from the physics that would seem to underpin them. This raises the question of whether it is acceptable for chemists to use some chemical notions which seem to be non-sense to physicists, but which 'work' within a chemical context.

I will provide an analogous example from biology education. It is not uncommon for students to acquire a notion of the 'energy rich bond'. The 'energy rich phosphate bond' has had common currency in biology education (Banks, 1970). The 'phosphate bond' is described as energy rich, so that breaking that bond (i.e. ATP to ADP) releases energy as part of the organism's metabolism. Of course, this leads to many students acquiring the idea that *energy is released when bonds break*, and so chemistry teachers (e.g. Hapkiewicz, 1991) may get rather irritated with this simplification (i.e. ignoring the rest of the changes in bonding during the reaction) - though the explanation seems to be convincing for many students. For a chemist the notion of 'energy-rich bonds' is anathema, but it *could* be considered as a 'biological concept' which works at a certain level of study within biology.

Of course these examples may be excused as having nothing to do with the relationships between chemistry and physics or chemistry and biology. After all the octet framework, the 'conservation of force' conception, and the energy-rich bonds are 'alternative' concepts developed by students, not real chemistry and biology. One could suggest that if teachers are teaching, or implying, such ideas they are either subject to misconceptions themselves, or showing poor pedagogic judgement. Yet Sánchez Gómez and Martín's contribution (this issue) may suggest that this could be a complacent and over-simplistic view. These authors consider the relationship between what they term classical chemistry and quantum chemistry.

Ideas drawing upon quantum theory are well known to be difficult to teach and learn, as has been discussed in the pages of this journal (Taber, 2002a, b; Tsaparlis & Papaphotis, 2002). Indeed Nakiboglu's contribution (this issue) highlights the difficulties that prospective chemistry teachers in Turkey have in making sense of concepts related to orbitals and hybridisation. Nakiboglu's findings suggest that less than 10% of students in his sample could be considered to have acquired a sound understanding of these chemical concepts. This paper contributes to an increasingly international literature suggesting that orbital ideas are an area of real difficulty for learners at college and university levels. In a sense Sánchez Gómez and Martín's paper discusses the outcome of chemistry education's failings in this area.

Sánchez Gómez and Martín suggest that there is a branch of science, quantum chemistry (QC) which draws heavily upon physics, and which is fundamental to modern chemistry (and would be assumed to be part of the science of chemistry). This in itself is not likely to be a controversial position, but they also argue that most chemistry fails to draw upon current knowledge in QC (even when relevant), and that most chemists have little understanding of QC - and instead rely on visualisable models of molecules that are out-dated and not strongly supported by quantum mechanics. In other words, most chemists apply 'folk molecular theory' - something that works for chemists, but is poorly founded on modern physical principles. In this sense many professional chemists may be little different from the UK college level students (Taber, this issue) explaining ionisation energy in terms of octets and force-sharing heuristics - explanations that they can understand, and apply, and that seem reasonable, and - sometimes at least - even give the 'right' answers.

Sánchez Gómez and Martín go beyond describing the current divorce (of common understanding, of common practice, of common theoretical underpinnings) between QC and classical chemistry. As well as putting forward a good case for suggesting that we now have the technology to make QC relevant, and applicable, to many more chemical problems, Sánchez Gómez and Martín also explore the development of this schism. By taking a historical perspective, these authors are able to suggest how important cutting edge ideas of great chemists (Lewis, Pauling) are still forming the conceptual base of many modern chemist's thinking, although these ideas may be well past their 'use-by' date. The history of science shows us how readily potentially productive ideas which should form the basis of moving a science forward, can in time become conceptual fossils that block epistemological progress (Bachelard, 1940/1968). A prime example is the common conceptualisation of the 'atom', an idea which has been central to the development of modern chemistry, but which is used and taught in chemical education in ways that impede an understanding of modern chemical theory (Taber, 2003b).

In a sense this brings the discussion full circle. I began this editorial article discussing how the disciplinary structure of the sciences was historically contingent. Sánchez Gómez and Martín remind us that the ideas that we teach and use in our chemistry must also be seen as being historical, part of the development of our subject, rather than absolute, and too closely reflecting reality. Great steps forward, be they the formation of new sciences, or the development of new theoretical constructs, can become obstacles to progress if they become too entrenched.

THE INTER-DISCIPLINARY MATRIX

In his influential book on the structure of scientific revolutions Thomas Kuhn (1970/1962) talked of scientific paradigms. As has been pointed out, he used the term rather flexibly (Masterman, 1970), but it was usually taken to be something similar to Lakatos' (1970) notion of research programmes. Kuhn later (1977) attempted to clarify his ideas by preferring to refer to the disciplinary matrix, a complex of features which collectively defined the scientific discipline into which a scientist was inducted. From a Kuhnian perspective, chemistry and physics became separate sciences when the induction (or professional training) of chemists and physicists came to involve different conceptual frameworks, different practical and analytical techniques, different norms and modes of writing-up, deferring to different authorities in the field, reading different literature etc.

Yet, it is obvious from such a description that although chemistry and physics are no longer part of a single discipline, neither can chemistry be seen to be a single discipline itself. The arrangement of the chemistry department on three different floors of the chemistry building (physical at the base, then inorganic, then organic) during my own undergraduate education signified something much more than a convenient way of using ground space! Even within a subject such as chemistry there is too much variety to think of all chemists as working within the same discipline. To take a single example from the present collection of papers, it is clear that Quantum chemists are not sharing a Kuhnian paradigm (or disciplinary matrix) with 'classical' chemists.

This presents a problem for chemistry education at the undergraduate levels, for if (according to Kuhn) chemists are inducted through the disciplinary matrix, then we need to ask 'which one'. In reality, of course, degree level chemistry is nowadays just a preliminary, and chemists are inducted into various chemical disciplines through their post-graduate training. This leads to an interesting set of research questions about undergraduate chemistry education:

- to what extent are universities able to provide a *coherent* degree in chemistry that provides a suitable background for post-graduate studies?,
- to what extent is undergraduate chemistry education perceived as coherent by students? - a question that might be even more pressing in a course such as the Natural Sciences Basic Studies as described by Josephsen (this issue);
- to what extent are undergraduates made explicitly aware of the issues of disciplinary structure within chemistry, and of its significance? - a question that might be especially relevant where the students are looking to be chemistry *teachers* rather than specialists within chemistry.

The set of papers presented here suggests more questions than answers. As chemistry educators or science educators we have parallel questions to ask about the school and college levels. We often assume that there is some coherence across the science our students learn, but their teachers from different disciplinary backgrounds may well be operating with very different assumptions and perspectives. Some of the papers in this issue focus on the potential common ground in science education, and the way that chemical knowledge *can* be built upon aspects of physics - others highlight the way chemical knowledge may take on an identity of its own, distinct from, and operating divorced from, these underpinning physical principles. When this happens it is not surprising that this may be reflected in student thinking, and even student preferences to keep their learning about chemistry and physics conveniently compartmentalised.

Again this suggests the need for more work to explore how, when and why students integrate or segregate knowledge, and the extent to which this relates to disciplinary structure, teaching approaches or personal learning styles. From a reading of the contributions in this issue of CERP we can not even be assured of whether the integration of knowledge (such as physics with chemistry) is automatically to be desired. If Kuhn is right about the disciplinary matrix, then asking learners to try and make consistent sense of teaching from across the 'inter-disciplinary matrix' of science may be unreasonable and even counterproductive.

So the overall conclusion to be drawn from this theme issue may simply be that there is much more work to be done on understanding the significance of the disciplinary relationships within science for teaching and learning. The papers in this issue illuminate the complex nature of a theme such as 'Teaching Chemistry and Physics', and highlight some key areas for future inquiry. Perhaps the other strong message is that we should look more to history (cf. Niaz & Rodriguez, 2000). The history of science tells us how the disciplinary structure came to be as it is. This is an important perspective that helps us understand the contingent nature of this structure, and to accept that it may be far from optimum for the development of our science, or for the science education of our students.

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