CHAPTER 1

An Introduction to Chemical Pedagogy

1.1 Introduction

This book discusses a wide range of approaches that have been employed in teaching chemistry. The book consists of two sections. The first section, '*Perspectives on teaching and learning*', might be considered 'background' as it discusses general issues relating to the teaching of chemistry which underpin the various 'pedagogies'. The second section, '*Teaching strategies and methodologies*', concerns broad strategies that have been employed, and more specific types of activity that can be included, in lessons and lectures. Effective teaching begins before entering the classroom, so this book includes consideration of planning teaching as well as designing or curating teaching resources.

1.1.1 A Note on Terminology: Teachers, Learners, Classrooms and Pedagogy

This book is about teaching of chemistry, wherever that takes place. University teachers are often called lecturers (or readers or professors). There may also be laboratory demonstrators or teaching associates or assistants who have some teaching responsibilities. College teachers may be called lecturers in some kinds of colleges (but not usually in sixth-form colleges). But, like school teachers and academic tutors, they are still teachers. The learners may, in different contexts, be referred to as students or pupils or school children – or perhaps even apprentices or trainees in some circumstances. Where I discuss generic matters I will often tend to simply refer to teachers and learners, using these terms inclusively – but I will sometimes

---

Advances in Chemistry Education Series No. 12
Chemical Pedagogy: Instructional Approaches and Teaching Techniques in Chemistry
By Keith S. Taber

Published by the Royal Society of Chemistry, www.rsc.org

use 'student' synonymously for 'learners' for stylistic reasons (to avoid expressions like '. . .the learner's learning. . .'). I will also sometimes use 'classroom' to mean the location of teaching – so, not only rooms that are formally designated classrooms but also lecture theatres/halls and teaching laboratories, seminar rooms and tutorial offices, and so forth. I will also sometimes use the term 'class' to refer to groups of learners that are formally organised to attend sessions together, even if this is several hundred undergraduates in a lecture theatre or a small tutorial group meeting with an academic.

This is done to aid readability, so that I do not need to make each possibility explicit at each reference. In a similar way, as explained in Section 1.6.1, I use the term 'pedagogy' generically, regardless of the age of learners, to refer to the 'science' of teaching. Some people still prefer to reserve that term for only the teaching of children. I will refer to pedagogy regardless of the age of learners, which (given that age is more like an electronegativity scale than a dichotomous distinction between cations and anions) avoids debates about whether, for example, 16 or 17 years are children or adults. 'Pedagogy' is in wide usage, and is now widely understood, as a more general term, so I trust language purists will forgive this convenience.

Two other terms that are used quite frequently in the book are 'expert' and 'novice'. There is quite a lot of research into the nature of expertise (Cianciolo *et al.*, 2009), and it is known that an expert has engaged with a field so extensively that their cognition has been considerably changed. The experience of extensive deep engagement automates processes so that the expert 'sees' the crux of an issue ('cutting through the noise') and often has effective intuitions about the relative merits of potential options (including summarily disregarding many possibilities that a novice would actively consider). None of this is magic, of course, but rather the way experience changes the structure of the brain – that is, learning! Such expertise is of course to be welcome, but can make it very difficult for the teacher, as a subject matter expert, to appreciate the complexity of material 'from the learner's resolution' (Taber, 2002). Indeed, in one study exploring challenges faced by learners in Dutch schools studying the topic of redox, the researchers felt that core ideas had become so obvious and self-evident to teachers that teacher subject matter expertise could be considered a source of difficulty in teaching chemistry (De Jong *et al.*, 1995).

Some teachers, at least at the school level, may feel that they are not really 'experts' – that the real experts are the bench (or computational) research chemists. But even at the middle school level, someone who has extensive experience in teaching a topic at a certain level in relation to a curriculum specification does become an expert in that material. Learning to teach a topic well requires a lot more than knowing the subject and leads to a pedagogic expertise that would not be immediately available to a genuine expert in the field itself. Certainly, in relation to the classroom context, we have relative experts and novices. Organisations such as the Royal Society of Chemistry recognise chemists who go into teaching as a career as professional chemists, just as much as bench researchers or industrial chemists, and the field of chemistry education has its own specialised knowledge base, skill set, 'tool kit', and so forth – just as much as, for example, photochemistry or biochemistry.

Teaching is a complex activity and so the topic of pedagogy is a somewhat fuzzy one. Differences in how certain terms (such as 'direct instruction', 'constructivism' and 'learning style' – discussed in Chapter 3) are used both in terms of different authors sometimes denoting the same approach with different labels and different authors using the same terms with somewhat different meanings are unfortunate, but beyond this source of confusion, the whole area concerns perspectives and approaches that involve considerable overlaps. So 'problem-based learning' encompasses 'problem-solving' and may sometimes overlap with 'enquiry learning' or 'case-based learning' or 'team-based learning' and may sometimes (but not always) seem synonymous with 'project-based learning'.

So, when describing pedagogic techniques and strategies I am not dealing with material akin to 'natural kinds' such as elements that could be neatly organised in the periodic table, but more like groups of people whose identities may be multifaceted (*e.g.*, such as a teacher who is also a wife, a liberal, a soprano and a gardener) and may even be seen as contentious (as when one person's freedom fighter and liberator is another's terrorist and criminal). One chapter in this section (Chapter 3) discusses some of the key educational debates relevant to teachers in terms of the underlying issues, going beyond the labels commonly (but often imprecisely) used.

1.2 The Role of Laboratory Work

It is often said that 'chemistry is a practical subject', and it is certainly true at the school level that many learners seem to particularly enjoy practical work. Sometimes chemistry teaching is split between laboratory and classroom work, so that classes have to be scheduled for either practical or 'theory' lessons. Of course 'practical' is not always understood to mean laboratory work, and indeed, in some areas of chemistry, field work in the environment may be very valuable.

In a university setting, laboratories are usually designed to be suitable for benchwork, but not for teaching based on the teacher presenting ('lecturing') to the class. Teaching laboratories are costly and valued resources, such that a chemistry department will not wish to have many highly equipped labs empty much of the time, and so laboratory classes are often scheduled at particular times (rather than lecturers being able to move classes between classrooms and teaching laboratories whenever they see this as most useful in their teaching). There are also health and safety, and security, considerations in favour for scheduling lectures, tutorials and seminars away from the lab. So, it is not unusual that at the start of an academic term, semester or year, learners may be given a timetable showing when they will be in labs, and this may be somewhat independent from their lecture programme. This can mean that practical laboratory experience of a topic may be somewhat distant from the class teaching on the same material.

In schools, it may be more common for science classrooms to double as both laboratories and standard classrooms, sometimes requiring a compromise in terms of the optimal organisation of both types of activity. Ideally, a science classroom would have a laboratory area at one end, with a linked preparation room and stores, and a normal class teaching space at the other – but often a hybrid teaching space is provided.

Where the school chemistry teaching can all take place in a room designed for laboratory work, then the teacher has the ability to integrate laboratory activities with other types of learning activity. However, even here, school timetables may be restrictive. If a school class has only a 45–60 minute lesson, then many substantive practical activities will only be possible by designating whole lessons for the practical work. Thus, the common notion of 'theory' and 'practical' lessons and consequently the common opening salvo from arriving learners: 'Miss/Sir, are we doing an experiment today?'

This book does not contain a dedicated chapter on laboratory work, and there is indeed another book in this series specifically about 'Teaching and Learning in the School Chemistry Laboratory' (Hofstein and Hugerat, 2022). However, techniques related to laboratory work (*e.g.*, 'prelabs', see Chapter 8, Section 8.4) or which can be applied in practical work, are discussed at various relevant points in the book. There is also a discussion of the qualities of teacher demonstrations and when these might be more useful than learner practical work (see Chapter 8, Section 8.3).

1.3 The Structure of the Book

Writing a book requires deciding on one sequence for the text and decisions about what to clump together and what to separate into different chapters. As the book developed, I made a number of changes to my intended plan, and I am aware that my final structure is necessarily one option among many. In particular, I decided to move away from a large number of chapters such that each specific technique, such as concept mapping or jigsaw learning, would have its own chapter, as that would likely have led to excessive repetition across chapters given the level of overlap in purpose and rationale found between different pedagogical approaches. Rather, I (ultimately) decided to organise the material into just twelve chapters that, at least to some degree, allowed me to collect together those techniques that had core ideas in common. I am aware that this has resulted in some rather substantive chapters, but I believe that should help impose some structure on the field for the reader new to the topic and embed accounts of specific techniques and strategies within a wider narrative (*cf.* Chapter 7, Section 7.11). Readers can choose to just read those individual sections of most interest to them, although each section is somewhat supported by the wider context of its chapter and, in turn, the volume as a whole.

I hope that I have found a sensible structure that will seem coherent to readers, and I have been generous in including cross-referencing both back from Section B ('the pedagogies', in effect) to Section A ('the principles', in effect) and between related approaches. This is especially relevant to a topic such as pedagogy, as sometimes one instructional approach may seem to have much in common with another, or may even seem to encompass a teaching technique that is otherwise seen as distinct and discrete. This should be a familiar enough situation for the chemist, where the same substance may be understood as, say, both an oxidising agent and an acid, and where a complex structure may be perceived as containing several different functional groups, or may even be conceived as, in effect, a higher-order structure built up of several distinct subunits.

1.3.1 Perspectives on Teaching and Learning

In this section of the book, there are 4 chapters that collectively provide background for Section B:

- This chapter introduces the purposes and scope of this book. It examines what we mean by pedagogy and learning and introduces the key ideas of meaningful learning and high-level cognitive skills. A range of complementary potential aims are discussed for teaching chemistry to learners (not all of whom will be working towards careers as chemists, or in areas where chemical knowledge/skill is needed).
- In writing this book, I am assuming that readers are looking to be informed by the scientific evidence about effective teaching, and I cite a range of studies in relation to the different teaching approaches considered in Section B. Yet, there are major challenges in carrying out research into teaching which complicate chemical education research (CER). Chapter 2 explores these issues, certainly not to suggest that teachers *cannot* learn from research, but rather offering some important 'health warnings' about interpreting study conclusions. A major difference between CER and laboratory chemistry is the inability to automatically generalise from one classroom to another in the way we expect from one laboratory to another. The chapter stresses the importance of investigating pedagogy in different contexts and through complementary approaches.
- Chapter 3 acknowledges some major debates that have raged about educational ideas in recent decades. Although some of the 'heat' of these debates is more about labels than what actually happens in classrooms, there are some important substantive questions raised in these discourses. Whilst I cannot pretend to be neutral in these debates, I hope my own views are informed by classroom experience and wide reading of research and scholarship. I have tried to present a balanced account here, but would recommend readers interested in finding out more about these topics to seek to read a wide range of sources.

- Chapter 4 offers an account of what I describe as ‘optimally guided instruction’, which is offered as a distillation of key ideas to inform teaching. In particular, this chapter explores what is meant by ‘scaffolding’ learning, as this notion is referenced a good deal in the second section of the book when considering various teaching strategies and methodologies. The term ‘scaffolding’ is widely used in education, but often so loosely such that just about any support offered to learners is labelled as a ‘scaffold’. Genuine scaffolding needs to be carefully matched to the needs of specific learners and has a dynamic aspect – that is the extent of scaffolding is modified in response to the learner’s development.

1.3.2 Teaching Strategies and Methodologies

The second section is divided into a set of chapters that each discusses a range of related pedagogic strategies and/or techniques.

- Chapter 5 considers the challenge of designing teaching sequences – of moving from curricular aims (as discussed later in this present chapter) and objectives to a teaching programme. Planning teaching is seen as having several levels of structure. This chapter discusses the use of conceptual analysis as a technique for informing the logical sequencing of material.
- Chapter 6 considers the diversity of learners (between courses, between classes, and even within a class) and the task of matching the teaching to the learners. Having determined the teaching programme (*i.e.*, as discussed in Chapter 5), there is still a need to ensure that the treatment is at the right level for a particular group of learners. The chapter discusses forms of assessment (diagnostic and formative) that can support the teacher in this task, and various approaches to differentiation that may be needed given that every class comprises a diverse range of somewhat unique learners.
- Chapter 7 looks at the presentation of chemistry in teaching, given the teacher’s key task starts with making the unfamiliar (the electrochemical series, amines, infrared spectra, *etc.*) familiar (Taber, 2002). That is, things that had been unfamiliar (and perhaps abstract and obscure) to learners prior to teaching should, after teaching, start to seem familiar. The chapter considers the role of models and representations, including simulations, as well as language (*e.g.*, analogies) and the notion of multi-modal teaching. The chapter includes a plea for the importance of helping learners become epistemologically sophisticated – so as to avoid, for example, the common problem of learners confusing a model with what it is meant to represent and struggling to make sense of the often strictly inconsistent multiple models and representations commonly used in chemistry and chemistry teaching.

- Chapter 8 considers choices about how to present chemistry in class. One issue is when teacher demonstrations may be more effective than learner practical work; another is how to best prepare learners to learn effectively when they are working in the laboratory. For reasons that will become clear to readers, the traditional formal lecture is not usually an effective way of helping learners understand complex abstract ideas, so, even at the university level, an ideal teaching programme would likely limit lecturing to a modest number of keynote sessions making up only a minority of class contact time. However, it is also assumed that, in many institutional contexts, pragmatic and logistical reasons will leave many lecturers with little choice but to teach *via* lecture courses. The challenges of effective lecturing are considered, as well as both ways to make lectures more interactive, or even to subvert them by 'flipping' teaching.
- Chapter 9 then considers the classroom that (is not organised in 'lecture' mode and) actively engages multiple voices – those of learners as well as teachers. The chapter considers the potential role of learners as adjunct teachers in various contexts (such as teaching assistants) and explains the strategy known as dialogic teaching. The chapter both introduces general approaches and some key examples of types of learning activity. The use of group-work is introduced as a potentially productive alternative to individualised working, and as an approach that has special value in many contexts – such as for example, teaching the skills of argumentation in chemistry. Teaching about scientific explanations in chemistry acts as a context for introducing the technique of 'Predict–Observe–Explain'. Finally, the chapter looks at the specific technique of 'jigsaw learning' in some detail.
- Chapter 10 considers the role of teaching and learning resources, and how these may be either designed, or curated from what is already available. The value of belonging to teaching communities that share resources is discussed. The chapter then explores how learning resources – including textbooks – can be used to provide scaffolding for learners and exemplifies how this might work in terms of developing exercises that support learner progression. Two especially flexible approaches are discussed in some detail, DARTs (directed activities related to texts) and concept mapping.
- Chapter 11 considers some broad strategies for organising chemistry teaching that are commonly applied at the level of whole units or courses. The strategies discussed are context-based approaches, enquiry-based teaching, case-based learning and problem-based and project-based teaching strategies. These approaches are often especially useful for developing (what are often referred to as) 'transferrable' skills that are highly valued by employers. The use of historical materials in teaching chemistry is also discussed in this chapter.
- Chapter 12 closes the book following up some themes that have recurred in the text. One of these is the place of 'learner voice' both in

terms of the learners' rights and in terms of teaching for learner autonomy. Another theme is creativity in teaching and learning. Many of the examples discussed in the book showcase the ingenuity of chemistry teachers in devising new ways to support learners and teach the subject. Here, the focus is more on the scope for providing learners with tasks that allow them to engage creatively with the subject. Finally, the chapter reiterates how the diversity of teaching contexts means that although the book can offer teachers many ideas, and the research literature offers some evidence of examples of their effectiveness, the teacher needs to approach such advice and guidance as sources for building testable hypotheses regarding 'will that work well here?'

1.4 The Rationale for the Structure

It may help some readers orientate themselves towards the text to know something of my reasoning in developing this order of material.

1.4.1 Why so Much Pre-amble?

If the first section (on perspectives on teaching and learning) is to be considered 'background' to reading about pedagogic strategies and techniques, then it might seem that it is given rather a lot of space in the book. Some readers may question why so much of the volume is given over to general issues, rather than presenting the pedagogies themselves. An alternative structure might have been to simply include a very brief introductory section – keeping the 'theory', so to speak, to a minimum – and to quickly move on to what the title of the book promises: accounts of instructional approaches and teaching techniques. I have chosen not to do this partly because of my assumptions about the background of many readers.

I am addressing this book to scientists – natural scientists. I expect *some* readers of this book will be educational researchers – themselves undertaking studies into the effectiveness of various teaching approaches. But, when I refer here to scientists, I primarily have in mind teachers: teachers *of chemistry* working in settings such as a school, college or university. The work of teaching is not the same as the work of the research chemist, certainly, but many teachers with a scientific background value adopting *a scientific approach* in their work. There is today much less conviction than there once was that there is any single set of procedures of rules or practices which set out a unitary scientific method (Feyerabend, 1975/1988). And attempts to transpose what is often seen as the gold standard of scientific work, the controlled experiment, to teaching are highly problematic (as is discussed in the next chapter, Chapter 2).

My own view of what is characteristic of scientific activity relates less to any specific method and is more in terms of *scientific values*. The scientist including the teacher who wishes to see their work as falling within a broad sense of science:

- remains open-minded;
- looks to arguments from evidence;
- seeks to apply a critical lens;
- accepts the possibility of alternative explanations; and so forth.

Of course, there is much scholarship that shows both contemporary and historical scientists falling short of this ideal. There are many examples of actual scientists being biased, being influenced by cultural or personal factors, or not recognising the role of metaphysical commitments (taken-for-granted assumptions about the way things are) in their thinking. Scientists are human, and none of us are perfect, so practice does not always match ideals – but nonetheless in our scientific work *we aspire* to adhere to scientific values.

So the ‘scientific’ chemistry teacher wants to know if there are better ways of doing things and looks to be open to evidence. And evidence needs to come from the experience of practice, and, in particular, that especially disciplined type of experience known as research. And, although I have suggested there is no specific method that all scientific research needs to follow, there is something common to the sciences, and that is the relationship between ‘theory’ and ‘empirical investigation’ (such as, but not just limited to, experiments). In science, there is a dialectical relationship with **theory** both *informing*, and being *developed in response to*, **empirical work** – and so therefore **empirical work** both *informing*, and being *motivated by*, **theoretical developments**.

So, I knew when I planned this book that, if it was to be more than a bestiary of teaching approaches, it would need to include sufficient background on the nature of learning and the key debates about how teaching that best facilitates learning can be developed. To offer an account of instructional approaches to teachers adopting a scientific mindset, it would be necessary to link those approaches to the grounds on which they were proposed.

1.4.2 Why Not Integrate the Background Material into the Accounts of Pedagogies?

It would still have been possible to organise the book by teaching approaches and techniques and then feed in background material into the different examples. Yet this would have been less efficient, as often the same principles and considerations are called upon to explain the rationale of a number of the approaches discussed. For example, many of the techniques discussed would sometimes be described as forms of ‘constructivist teaching’ (discussed in Chapter 3), so both (i) material about the nature of constructivism as a perspective on learning, and (ii) the debates around both the nature and merits of teaching that might be described as constructivist apply to many of the topics discussed in later chapters. So, instead, when discussing specific techniques where this is particularly pertinent, I refer the reader back to material in the first section.

1.4.3 Grouping Strategies and Methodologies

My original plan for the book had three sections, separating out the more large-scale strategies form the more discrete techniques. However, I abandoned this approach as writing proceeded, deciding it made more sense to collect together approaches that seemed more closely related. In part, this change of mind reflected the nature of the subject matter. In a natural science, such as chemistry, we deal with 'natural kinds' such as elements and compounds and analysis allows us to be sure whether a sample is indeed an element or a compound or indeed a mixture. The social sciences, such as educational research, often deal with more fuzzy, shifting kinds of things. What counts as a course or a programme or a teacher or a professor or a class or a lesson or a lecturer is not fixed in some form found in nature, like the structure of a NaCl lattice or the frequencies associated with the sodium D spectral lines, but is a matter of convention – and changes over time, and sometimes from place to place.

I recognised this from my own research, but writing this book reinforced it: the same pedagogy may be described in different terms, and sometimes the same label is given to different kinds of teaching that have little in common. This text necessarily reflects some of this fuzziness. Social phenomena, such as teaching, are also very complex – so, the same lesson can sometimes deserve several distinct descriptions (perhaps both 'constructivist' and 'dialogic'), and the same learning activity might reasonably be seen as an example of several different teaching techniques. For example, jigsaw learning (discussed in Chapter 9, Section 9.8) encompasses group work and an element of peer-tutoring.

This complicates the text, but I do not think it undermines the message of the book. Even though there may sometimes be confusion over labels, there are some important, and clear, underlying principles that can inform good teaching regardless of how we choose to describe them. This fuzzy nature of the subject matter has meant that in places I have allowed myself to repeat key points in different contexts where I thought this was important to aid the readability of the text, so although I have used a great deal of cross-referencing, I have also sought to avoid relying on readers needing to keep jumping about the book to make good sense of the text. If I have judged this balancing act well, then each chapter will stand reading on its own, but each chapter will also offer a richer read in the wider context of the whole book.

1.4.4 Could I be Underestimating my Readership?

I was at times aware during the drafting of the book that some readers may be highly experienced (and skilled) teachers, and some of the things I was setting out (and exemplifying) may seem *so* blatantly obvious to these readers that I might seem to be insulting their intelligence. Surely, it is just common sense, for example:

- that you need to analyse material you plan to teach in order to identify prerequisite learning (see Chapter 5) and then check it will already be known to learners (see Chapter 6);
- that one can devise sequences of exercises that have an inherent gradient of cognitive demand (see Chapter 10, Section 10.6);
- that when introducing new concepts it is useful to use non-examples (and be explicit about why they are not examples) as well as examples (see Chapter 10, Section 10.7.1)...

One of the principles which has informed my work as a teacher, and which I have referred to at various points in the text (and you may indeed recognise it from earlier in the chapter) is how when one gains experience in a domain and become something of an expert, a lot of things come to seem obvious common-sense and become part of one's 'automatic' perception and behaviour; things that may actually seem novel, complex, *and* difficult to novices. A useful motto for a teacher is – *never take for granted; rather, always be explicit*. The kind of things we can too easily take for granted are that learners

- have actually studied topics they are meant to have previously studied,
- have correctly understood concepts they have previously been taught,
- remember the things they have previously studied,
- appreciate which previous topic(s) and ideas the teacher thinks are (obviously) relevant to what is currently being taught.

If I am advising readers to adopt a cautious approach in their teaching; then, I should do the same in my writing. I hope that highly experienced readers will forgive passages which seem to be stating the obvious and appreciate that what is now obvious to them may still be useful guidance for less experienced colleagues. Perhaps I have made some misjudgements here and included some material which would be immediately apparent to *any* reader. If so, I can only offer as defence that, in general, in teaching it is better to err on the side of assuming too little of our learners than risking assuming too much. I have tried to follow the same tenet in writing the volume. Reiteration of basics seldom does harm, but omitting material that learners (or readers) are not aware of, can frustrate learners and learning.

1.5 Not Just a Technical Approach to Teaching Chemistry

It could be argued that if there have been studies demonstrating that certain approaches have merit, then that is what (perhaps, all) the scientific teacher needs: evidence of efficacy. Yet, there are several problems with that approach.

One is the distinction between being a technician who is skilled in employing an established technique and being a professional teacher who looks to develop and customise teaching in their own classroom, laboratory or lecture hall. It is widely recognised that when teachers are trained in and asked to follow a 'method', the actual implementation varies considerably (which is understandable given the diversity of teaching contexts that teachers are working in) and this can often mean that even when indicators of some method (*e.g.*, learning by enquiry) are present, its essential logic can become undermined. Teachers need to understand *why* they are being asked to teach in a certain way if they are to reflectively adopt an approach within diverse local circumstances, whilst retaining its essential essence.

Another problem is the nature of the evidence on which teaching practice is based. Much of the research in the literature offers limited bases for generalisation. There are two issues here. One is that there are many flawed studies, where compromises (or sometimes mistakes) have been made regarding matters such as comparison conditions, sampling, independence of those giving ratings or evaluating outcomes, use of statistics, and so forth. Sometimes, this may reflect a lack of researcher competence. But, generally, such compromises are a reflection of the conditions under which educational researchers work (*i.e.*, not usually in carefully controlled laboratories) and the complex nature of the subject matter.

Furthermore, there is a real fundamental issue concerning replication: it is simply not possible to replicate work in education in the sense that you can do in chemistry, as people, classes, year groups, schools, university departments, and so forth are not as interchangeable as samples of salts or aliquots of acid. So, even when a study is well designed and executed faithfully, its results may not be directly generalisable to other teaching and learning contexts.

The consequence of this is that literature needs to be read critically, and I have included a chapter (Chapter 2) in this section which develops these ideas and highlights some of the inherent challenges in building up research evidence from studies of pedagogy. For readers with no direct experience of research in education (and perhaps even some who have), I hope this chapter will provide useful background for when critically reading and reflecting on the research literature.

Two key points to keep in mind when reading educational research studies carried out in specific teaching and learning contexts are as follows:

(i) the conclusions of many studies need to be read against certain provisos (which may not be obvious just from reading the abstract or conclusions) reflecting constraints and limitations inherent to the study;
(ii) what works in one teaching context will not always transfer directly to a very different context.

As long as these points are borne in mind, the literature provides a very valuable evidence base for identifying potentially useful teaching approaches and techniques that are worth testing out in one's own teaching context.

1.6 Pedagogy?

This is a book about pedagogy as applied to the teaching and learning of chemistry. Although 'pedagogy' is not a term regularly used by most teachers, it is the term often used for the formal study of teaching. We might say, it is *the 'science' of teaching* – a notion that may appeal to many teachers of natural science subjects, such as chemistry.

1.6.1 Pedagogy or Andragogy

Yet the word *pedagogy* comes from a term used in 'Ancient' Greece for a leader *of children* – its roots relate to those of paediatrics as the branch of medicine that has a particular concern with medical care for the young. So, we might think that, strictly, pedagogy applies to school teaching, but not to those teaching adult learners – in universities, for example. The term *andragogy* is sometimes used for the study of the teaching of adults – especially where the focus is on what is particular to adult education. However, word meanings are fluid, changing over time with use. Regardless of its origins, the term pedagogy has become widely used to refer to the study of teaching *in general*, regardless of the age of the learners.

This book is concerned with methods for teaching chemistry, and the principles underpinning those methods. It is written with both school teaching and college/university teaching in mind. There are, of course, differences between the challenges faced by school teachers and university lecturers – but then there are also different challenges facing the school teacher working with a class of children aged 11, fresh from primary school, and the teacher (who could in some schools be the same person) working with a class of learners aged 18 preparing for high stakes examinations who have elected to study advanced chemistry courses. There are also differences when the university teacher is working with a small tutorial group or giving a lecture on a 'service' course to several hundred undergraduates with a broad range of interests and diverse 'major' subjects, or giving a lecture to a final year chemistry honours class following a specialist option, or working with a class following a taught master's programme in, say, analytical chemistry. Following what is fairly common practice, then, I will use the term pedagogy in the broad sense to refer to teaching regardless of whether the learners concerned are children or adults – or indeed adolescents that perhaps are not well characterised by either term.

There are also important similarities in all these cases in the way human cognition works: so there are common principles that inform the teaching of conceptual material (indeed, not just in chemistry but also across many other subjects such as biology, history, geography or the theory of music). So *much* that is discussed in this book is relevant to teaching very different groups of learners and could be applied in teaching well-beyond chemistry. However, as this book is written for chemistry teachers, I use many illustrations from chemistry teaching: using examples of subject matter from the chemistry curriculum and citing studies carried out in chemistry teaching and learning contexts.

1.6.2 Teaching Chemistry at Different Levels

I have deliberately not attempted to separate out approaches most suited for school teaching from those more suited for university teaching.[†] I do not think that would be a valid or helpful distinction – although where I discuss research I will describe the contexts where cited studies were carried out. I think that not only the principles (the 'theory') but often also the specific approaches and techniques are relevant to all chemistry teachers, although individuals will need to decide which of those approaches are feasible in their teaching context and which are likely to be most valuable in their own teaching. It is also likely that just *how* a teaching approach is best applied (or indeed sometimes customised to local conditions) will be quite different in diverse teaching and learning contexts. Teaching is not the kind of activity that can sensibly be planned and prescribed centrally – it always needs to respond to the specific curriculum, the specific course, and the specific learners.[‡] Perhaps this is not so different from a chemical process like crystallisation or fractional distillation where certain general principles always apply, yet the precise procedures followed will be modified according to the mass of the sample concerned and the specific reagents involved.

This book is certainly not a teaching manual (a book of instructions) but rather a source of information that the professional teacher can selectively apply according to local needs and the perceived relevance of an approach. I therefore do not set out to tell teachers what to do, but hope to describe and explain a range of options that can inform professional decision-making.

1.7 The Curriculum and Educational Aims

Perhaps the core aim of the chemistry teacher is to teach chemistry – but of course it is never quite so simple. The curriculum sets out what is to be taught, but the curriculum should be designed with a consideration of more general aims that the curriculum specification responds to. Aims are broad – as opposed to more specific objectives. In this volume, I will refer variously to teaching objectives, learning objectives or educational objectives to refer to detailed specified targets. Examples could be that learners should be able to

- identify how periods and groups are represented in the periodic table;
- recall that the tetrahedral bond angle is c.$109^\circ 28'$;
- calculate molar masses from chemical formulae;
- determine chemical shift from a mass spectrograph.

An obvious aim perhaps is that learners should learn some chemistry. Even leaving aside the key questions (explored in Chapter 5) over *which*

[†] I am assuming that university teachers who choose to read this book will be sympathetic to the argument why traditional lecturing (in the sense of a teacher talking at learners for 50 minutes or so without interruption) is a limited pedagogy (as discussed in Chapter 8).

[‡] That truism does not necessarily stop central authorities seeking to decree what should happen in classes, of course.

chemistry (no course could include everything) and at what level of detail different topics are to be treated (Taber, 2019), there is a more fundamental question about what we mean by *learning* chemistry.

Many years ago, there was a good deal of discussion about the importance of *learning for understanding*, and today most teachers would agree that we want learners to be able to understand, not just be able to parrot back, the ideas they are taught. Some key notions introduced into educational discourse were (i) the contrast between 'rote' and 'meaningful' learning and (ii) the idea of a hierarchy of 'levels' of intellectual skills related to different kinds of learning. I briefly review these principles next.

1.7.1 Meaningful Learning

The educational psychologist David Ausubel popularised the notion of meaningful learning. He made the distinction between rote learning and meaningful learning (2000). The distinction could be illustrated with the following pair of vignettes of (imaginary) classroom dialogue:

Teacher: *Does anyone know fluorine's atomic number? Yes, John?*	**Teacher: *Does anyone know fluorine's atomic number? Yes, Jane?***
John: Is it nine?	**Jane: Is it 19?**
Teacher: *Yes, good John. Can you tell us why it is nine?*	**Teacher: *Okay, Jane, why do you suggest 19?***
John: No, I am not sure.	**Jane: Because the nucleus of fluorine usually contains 19 nucleons. There are nine protons, and I think there are ten neutrons – at least in naturally occurring fluorine.**
Teacher: *Okay. What is the atomic number, what is its significance?*	**Teacher: *I see Jane, so nine protons, ten neutrons, making 19 nucleons all together – so why would the atomic number be 19 and not nine or ten?***
John: I am not sure, I just know it is nine in this case.	**Jane: Well, the neutrons are essential for a stable nucleus, even if not really that important for an element's chemistry – but all the nucleons are massive, so it is important that there are 19 nucleons as that is reflected in the mass of a fluorine atom and therefore in the mass of a fluorine molecule or of a molecule of a fluorine compound, and so this allows us to work out how many molecules we have in a weighed laboratory sample or where to look for a peak on a mass spectrum.**

Now, the question raised here is whether the reader would rather be the teacher of John or of Jane. John got the answer right, and Jane got the answer wrong – she seems to have confused atomic number (proton number) and mass number. Perhaps this is a 'slip' that she would not make on another day or perhaps she has actually mis-learnt the terms. Perhaps she had not actually previously learnt any meaning for the term at all and is now creatively offering her 'best guess' as she seeks to make sense of what could conceivably be labelled 'atomic number' in response to the teacher's question. However, even if she had learnt the wrong labels for the concept of mass and atomic number, she clearly has some understanding of the concepts, which may not be the case for John. Of course, John may just be embarrassed at being asked or may not currently be concentrating well due to some distraction in his life, or… We cannot assume from this one incident that he has not learnt this material, as research shows learners may be inconsistent in what they seem to know when asked at different times (Brock and Taber, 2016). Yet, for John's teacher, the signs are not good!

David Ausubel suggested that learning can take place in one of two ways – rote learning or meaningful learning. This is not an absolute distinction, and it may be more sensible to think in terms of the *degree of* meaningfulness of learning in a particular case, but the distinction is certainly useful. So, the categories of rote *versus* meaningful learning may be less like those of positive and negative electrical charge, and more like covalent and ionic bonding in that the meaningfulness of learning admits degrees of polarity. The difference concerns the *perceived* relationship between what is being learnt and what has been learnt before – the ideas already represented in a person's 'cognitive structure' – that is, the knowledge, beliefs and understandings a person has and how they are linked together. An extreme case of rote learning would be where a learner is asked to learn something that does not seem to relate to *anything* they already know.

1.7.2 What Might Rote Learning Look Like?

Consider the hypothetical case of a typical 11 year old who is exposed to the information that "^{88}Zr has a thermal neutron capture cross-section of 861 000 ± 69 000 barns" (Shusterman *et al.*, 2019).[§] We cannot expect the learner to make a lot of this information. It *could be learnt by rote*, so that the learner could later repeat the statement, but likely only with some effort – and this would probably require a good deal of rehearsal. This learner has little prior learning that can be related to this statement – not having heard of zirconium, or having learnt the symbolic system used to represent nuclides, nor indeed yet knowing what a nucleus or neutron is. By contrast, a

---

[§] I use the term information to refer to something objective that can be unambiguously represented in symbols, but may be (interpreted and so) understood in different ways – or not at all. That is the 'information' is fixed, but not how it is understood. This distinction is discussed in more detail in a chapter (Chapter 11: '*How are chemical concepts communicated?*') of another volume in this series, *The Nature of the Chemical Concept* (Taber, 2019).

graduate student working on neutron capture experiments would have an extensive background to relate to this same information, making it much more meaningful – and so be much more likely to recall the information, and, more importantly, would be able to apply it in pertinent contexts.

> L'atome ou la molécule électrisée, par contre, est beaucoup moins discrète, à telle enseigne qu'il a été possible, dans quelques cas, de déceler la présence d'un seul atome électrisé; un billion d'atomes non électrisés peut échapper à notre observation, tandis qu'une douzaine d'atomes électrisés se perçoivent sans difficulté.
>
> (Bachelard, 1973)

We can imagine even more extreme cases, as when being told something in a completely unfamiliar language (the quote above, from a philosopher and former chemistry teacher, will be much more meaningful to some readers than others – although, even here, any English speaker could have a good guess at the referents for a number of the words), whereas in the previous example, if the learner is familiar with English then 'has a' and 'of' give some sense of the kind of information being presented, and 861 000 and 69 000 will likely be recognised as (in everyday terms) large numbers. Yet, there is not enough here for the learner to fully 'make sense' of.

Ausubel focused on the *perceived* relationship between the information being presented and existing knowledge, as what critically matters is not just whether the learner has previously acquired some relevant prior learning, but whether *this is recognised* by the learner in the sense of making the connection.[¶] For example, a learner who has learnt about a basic model of atomic structure may not recognise what is meant by a reference to the 'valence shell' if they have previously only met the synonym 'outer shell'. In this case, they may actually know the answer to the question 'how many electrons would a calcium atom have in its valence shell' but fail to make the connection (valence = outer) and realise that they know the answer. This phenomenon of learners not making the expected links between teaching and prior learning – what has been called a *fragmentation learning block* or *fragmentation learning impediment* (Taber, 2001) – commonly occurs in many classrooms (see Chapter 6, Section 6.6.3). Teaching is intended to draw on material previously learnt, and the teacher assumes teaching will be understood as intended, but the connection may not be apparent to some in the class. (Perhaps a useful motto for teaching is that *one can probably never*

[¶] This need not be a conscious recognition. A good deal of cognition takes place 'preconsciously': we might say 'out of sight' of the conscious mind. A person may make an association 'automatically' rather than by doing a deliberate conscious search of memory. Consider when you see a friend's face or a model of the Apollo lunar module or a diagram showing a tetrahedral methane molecule: in each case, sensory data is analysed to allow you to know what you are seeing: but you are seldom aware of this process as usually it is achieved 'automatically' and the recognised image presented to consciousness (see Chapter 3, Section 3.7.7).

be too explicit! If in doubt, it is better to point out something that learners may have already appreciated, than to omit something relevant that they missed.)

Ironically, our hypothetical 11-year old who is asked to learn about the thermal neutron capture cross-section of ^{88}Zr may latch on to the reference to barns. The learner likely knows that in common parlance, a 'barn' is a building found on a farm, rather than an area of 10^{-28} m^2. So, there is a possible association there with prior learning – just not a helpful one in this case. Such 'associative learning impediments' (see Chapter 6, Section 6.6.3) are also common – when learners make associations that were not intended and may actually confuse matters. It may, for example, seem incredible to a scientific expert such as a chemist that a learner could confuse the nucleus of an atom with the nucleus of a cell,[‖] but the youngest learner does not have the wealth of background knowledge that makes such a confusion so unlikely.

Actually, in the zirconium case, the association with a farm outbuilding would not be entirely inappropriate, but was only likely to be helpful if the learner had an appreciation for the ironic humour of the scientists who had coined the term,[**]

> The chance of a nuclear reaction occurring wasn't measured in percentages, but in 'cross-sections' – a peculiar mix of size and probability. Cross sections were measured in 'barns' (from the phrase 'can't hit the broad side of a barn'). A barn was roughly the size of a uranium nucleus: about 10^{-28} m^2.
>
> (Chapman, 2019, p. 103)

If the zirconium example rightly seems rather fanciful, consider again the notion of electron shells. The concept of electron shells is often taught as part of an introductory model of atomic structure. The chemistry teacher referring to electron shells likely has in mind sets of abstract, diffuse, and perhaps interpenetrating, fuzzy regions centred on an atomic nucleus. The learner new to the atomic structure already knows from their everyday experience what a shell is – they are familiar with egg shells, shells around nuts and shells that protect some sea creatures such as many molluscs, and perhaps, if they watch police shows on television, about the shell casings that contain a bullet with its propellant before firing, and which are regularly sent for forensic examination to help solve a crime. These shells are substantial and have definite surfaces – quite unlike electron shells. A key feature of human

---

[‖] See for example, https://science-education-research.com/the-cell-nucleus-is-probably-bigger-than-the-atomic-nucleus/.

[**] I had not heard the specific phrase quoted by Chapman, but I was familiar with the variation that someone 'could not hit a barn door'. Looking on the World Wide Web, there seem to be several other variants implying a person has a very poor aim – including the intriguing 'he couldn't hit a barn door with a banjo', used, for example, to refer to strikers in football teams with poor scoring records.

learning is that it is often based on associations, such as similes and metaphors (see Chapter 7, Section 7.7). The unfamiliar *becomes* familiar by being compared to the already familiar.

If the teacher introducing the electron shell notion takes time to explore in what ways electronic shells are similar to, *and* in what ways different from, the shells familiar to learners then there is a good chance learners will appreciate and later remember the nature of these 'shells'. If not, associations will naturally be made with what is familiar, and learners may well consider electron shells as substantial, material, objects where electrons are located.[††] This is not speculation – this has been reported (Harrison and Treagust, 1996).

People are meaning-makers, and it is a basic feature of human cognition to seek to make sense of the world: so, when learners come across electron *shells* or *hard* water or electron *spin* or *shared* electron pairs, they are likely to try and make sense of these notions in terms of what is familiar.

The distinction between rote and meaningful learning has a number of implications:

- material is more likely to be retained if it is meaningful,
- learned material is more likely to be accessible (more readily brought to mind) if it is meaningful,
- learned material can be applied more widely if it is meaningful.

Research has explored how memories are represented in the physical substrate of the brain. One of the findings of this area of research suggests this is a multi-phase process. New memories have temporary links that allow us to access them in the short term, but which naturally decay. There is a subsequent process that can establish links between the representations of this new learning and other more well-established memory representations. So, material that cannot be readily linked with existing areas of knowledge is less likely to be consolidated in this way. The representations of that learning may exist in neural structures but without connections offering ready access.

Related to this, it is believed that when we are accessing memories, there is a kind of search process going on (at a preconscious level), which makes use of the way our memories are organised and interconnected. This suggests that the more strongly something is interlinked within a system, the more readily it can be found in a search. Much of what we learn is a bit like old paper files that have never been indexed or put into a proper storage system, but are simply 'archived' in random cardboard boxes in the basement or attic. Technically, we have not lost these memories, but in practical terms, we have forgotten them, just as we, almost, might as well have binned those dusty files.

[††] Again, the learner may not make this association consciously at the time, and it may only become clear later when they have reason to respond to a question or task that requires them to apply knowledge about electron shells.

Most significantly, what we can do with material we have learnt depends on our understanding, and that also relates to the way it is integrated into a network of ideas. Someone who had learnt that '*astatine is a halogen*' by rote and could later recall that as an isolated fact could use that knowledge to answer questions of the kind '*what is astatine?*' and '*can you name a halogen?*', but not much else. However, if '*astatine is a halogen*' is linked to other learning such that it also *implies* that, for example, *astatine is a chemical element*, and *astatine will form a diatomic hydride*, then the 'same' fact can potentially be applied much more widely (Taber, 2019). Our conceptual representation of the world might be seen as an extensive network of connections relating different concepts, and this is reflected in the technique of concept mapping which can be used as a tool to plan teaching, to assess learners, and as a study aid (see Chapter 10, Section 10.11).

1.7.3 A Hierarchy of Cognitive Tasks

Another notion that is well established in educational discourse is commonly known as 'Bloom's taxonomy'. Benjamin Bloom and his coworkers set up 'taxonomies' of educational objectives in relation to cognition, affect (and in particular, the development of values) and what were referred to as 'psychomotor' skills. The best known of these taxonomies (the one often just called "Bloom's taxonomy") is the taxonomy of educational objectives in the cognitive domain (Bloom, 1968).[‡‡] This set out six categories which were seen to be at different levels of demand. The three lowest levels involved recall, comprehension and application. Sometimes these skills are labeled 'LOCS' for lower-order cognitive skills. Consider the following three questions:

(1) what is the name of the property that describes the extent to which the atomic core of an element attracts bonding electrons in its compounds?
(2) what does it mean to say that oxygen is more electronegative than sulphur?
(3) deduce the bond polarity in the compounds formed between nitrogen and fluorine if the electronegativity of nitrogen is 3.0 and the electronegativity of fluorine is 4.0.

The first question asks for the recall of information and that is assumed to be a low-skill task as the information could have been learned by rote without any deep understanding. (Although as pointed out earlier, a learner is *more likely* to be able to recall the information when the learning is meaningful to them and well integrated into a structure of concepts.)

[‡‡] There have been more recent attempts to update and extend the original scheme (*e.g.*, Anderson & Krathwohl, 2001).

The second question asks for some level of understanding: the assumption being that one has to comprehend a statement ('oxygen is more electronegative than sulphur.') to explain it. Again, this is a matter of degree. A learner could learn by rote that any question of the form 'what does it mean to say that X is more/less electronegative than Y' should be answered, 'in its compounds X attracts bonding electrons more/less than Y'. That is, an algorithm could be applied. This would at least relate to a general principle, rather than a specific fact, even if it is still based on rote learning.

It is useful to note here that although that example may not seem to reflect understanding, understanding itself is not an all-or-nothing matter, and that people 'understand' concepts to varying degrees. In the example just suggested, we might feel that there were the first glimpses of an understanding that went beyond simple rote recall – even if we would seek a more nuanced degree of understanding.[§§]

There are at least two aspects of understanding that are important to teachers, and that we may consider subjective and objective. We judge objective understanding in terms of whether learners can provide creditable responses in assessment situations. However, learners have their own impressions of the extent to which they are making sense of teaching – which might be termed subjective understanding. It seems reasonable to assume that there will be a correlation between these different variables – but it is certainly not a perfect correlation. Students may not feel they understand an abstract concept even when they can apply it as required in the curriculum – they can get the right answers but still feel it does not make good sense to them. And then again, when learners are satisfied with their own understanding it may not be canonical (for example being satisfied to explain chemical processes in terms of what atoms want to achieve). Indeed, some alternative conceptions ('misconceptions', see Chapter 3, Section 3.2.5) may be so hard to challenge because they seem to make such good sense to many learners.

We usually assume that if someone has a good understanding of some concept then they should be able to apply that knowledge, and our second question only asked for application in a very limited context. Our third question offers a better reflection of what we might usually mean by being able to apply some learning. Again, if a learner was given a large number of questions of this type they *could* (that is, in principle) learn to answer them

---

[§§] There is an interesting philosophical question of whether understanding is actually qualitatively different from rote learning, or just a matter of *extent of* learning. That is, if one learns a great deal of complex material about a topic 'by rote' such that one can effectively answer a wide range of questions and perform a wide range of tasks drawing upon that knowledge, does it become understanding? This links to questions about artificial intelligence and the Turing test (and so the idea that dialogue with a sufficiently complex machine intelligence might appear as communication with another person). When we test understanding, we are really testing the degree of being able to give appropriate responses to our questions and tasks – and *in principle at least* we could always design a machine to pass such tests.

algorithmically, and we would be more impressed if a person can apply their knowledge to respond to a wide *range* of different forms of questions.

Another question we might ask is

(4) it is found that molecules of a compound of two elements have non-polar covalent bonds with no appreciable ionic character: what can we deduce about the electronegativities of the two elements?

If someone could give a canonical answer to our third question, but then had no idea how to respond to this fourth question, we might wonder just how deep their understanding was. In Bloom's original (cognitive domain) typology, the higher-level categories were analysis, synthesis and evaluation. One of Bloom's co-authors has since worked with a team to revise and develop the original taxonomy (Anderson and Krathwohl, 2001), for example re-designating the higher level as being *to create* (see Chapter 12, Section 12.4). For present purposes, however, I am going to collectively refer to these higher-level 'taxons' as higher-level cognitive skills. These have sometimes been referred to in chemistry education literature as 'HOCS' – higher-order cognitive skills.

1.7.4 'HOCS' – Higher-level Cognitive Skills in Chemistry Education

The significance of this general principle – that there is a range of cognitive skills that can be engaged in chemistry learning, and some may be considered of *higher* demand, 'higher-order', than others – has long been recognised in chemistry education (Zoller, 1993). Teaching to engage these HOCS neither necessarily requires a change in the subject matter taught, nor a complete avoidance of tasks that require recall, comprehension and application (LOCS). Indeed, it is not suggested that *only* HOCS (and not LOCS) should be engaged and developed, but rather that it is important to be aware of the profile of skills being expected from learners. In general, tasks that only engage LOCS are less likely to deeply engage learners and support substantive new learning. The general argument that has been made is that too often the balance of demand on learners in class has been weighed too heavily towards LOCS rather than HOCS. In a teaching sequence where new ideas are being introduced, we might expect early activities in the sequence to be LOCS-heavy (the learners are likely 'up to capacity' in engaging with the new ideas, see Chapter 3, Section 3.2.1) but that later activities in the sequence will show a shift towards more HOCS focused tasks.

The potential value of Bloom's taxonomy is as an analytical tool that could identify teaching that just kept learners busy by almost exclusively engaging the LOCS, the lower-order skills, without asking learners to undertake more demanding activities. (This might include 'student activity' in university lectures if students feel they need to be spending all of the lectures taking largely verbatim notes – see Chapter 8). One influential educational theorist, Lev Vygostky, has argued that conceptual development that goes beyond routine learning requires learners to have their thinking challenged (with suitable support to enable them to move outside of their 'comfort zone', something labelled as 'scaffolding') and such challenge is most likely when learner tasks require HOCS. Vygostky's idea will be discussed (especially in Chapter 4) and applied later in the book.

Moreover, as a planning tool, applying the taxonomy to identify the cognitive demand levels of proposed tasks enables teachers to ensure their classes were not exclusively engaging learners in activities limited to LOCS. This is not about what is being taught – acids, thermodynamics, functional group chemistry, ligand-field theory, or whatever – but about the way learners are asked to think when engaging with the material. This is why curriculum aims should be considered prior to developing the curricular content.

1.8 Curricular Aims in Chemistry Education

There is probably a range of things we might want from science education and more specifically chemistry education. We want to support the education of those who will go on to become research and/or industrial chemists or to take on other professional or technical work that relies on chemistry. In most schools, this will always be a minority, whereas on an honours degree course, this may be the aspiration (or at least, may have been the initial aspiration) of most of the students.

We also want to provide those who will not go on to work in areas that directly use their chemical knowledge and skills with a knowledge and understanding of chemistry to support their lives more generally. Understanding some chemical knowledge can obviously be useful in making decisions about aspects of health care, and in judging claims made in product advertising and in evaluating public claims and arguments concerning issues relating to global warming, pollution, and sustainable development, for example. Below, I discuss possible curricular aims for chemistry teaching under four subheadings:

- science as a component of culture,
- understanding the applications of science in the real-world contexts,[¶¶]
- teaching for cognitive development,
- teaching for the affective domain.

1.8.1 Science as a Component of Culture

There is an argument that education is partly about inducting people into the different aspects of their culture. Whilst we may think of chemistry as

---

[¶¶] Of course, the classroom is as much a part of the real world as anywhere else, but the term is often used.

having great importance in understanding the world, supporting technological developments and contributing economically to national wealth – chemistry *as culture* may not be so obvious.

At one level, we might point to the ubiquity of images and reference to atoms and molecules (such as representations of DNA). However, a more fundamental connection is that chemistry is a science. The natural sciences are a major activity in our societies, and so all people should be educated about science (Snow, 1959/1998). That is not just another way of saying that we need to teach *some* science – we *also* need to teach *about* science. Arguments to increase the teaching of *the nature of science*, especially within the school curriculum, have been made for many years and have indeed informed curriculum development in many national contexts (Jenkins, 1996; McComas, 1998; Duschl, 2000; Osborne, 2002; Taber, 2008; Hodson, 2014; Lederman and Lederman, 2014).

This is important, as where most non-scientists come into contact with science in the public domain is in relation to active scientific issues (perhaps labelled 'controversies' by the media) – and, often, in such situations neither weight of opinion nor logical argument from strong evidence determines public exposure to the various positions. Such contexts are often called socioscientific issues (Zeidler, 2014). For example, the voluminous accessible material available denying evolution by natural selection, or denying human influence on climate, or exaggerating the risks of vaccination programmes, does not reflect how such ideas are very much minority positions among scientists (and indeed virtually non-positions among those specialising in those areas of research).

For example, there is much contention between scientists on the details of how evolution works – but no experts in the field reject the notion that all life on earth evolved by descent from the same simple life forms (which is the main point of controversy in public debate). Of course, Charles Darwin was wrong in many details, in the same way that Isaac Newton and Antoine Lavoisier were in their work. Yet, we do not see Lavoisier widely condemned as a failure or charlatan (or worse) in public discourse because about a third of his proposed chemical elements are no longer considered to be elements today.[‖]

Science in the public arena, naturally, tends to focus on current science where work is actively being undertaken to answer pressing questions – what has been referred to as science in action (Latour, 1987) or science-in-the-making (Shapin, 1992). At the time of first drafting this text, the main news item for many months had concerned the COVID-19 pandemic. Scientific advice had been much referred to – but, as I was writing, this advice was uncertain about the most potent modes of transmission, the likely long-term effects of surviving infection, the efficaciousness of various treatments and different potential protective measures, the likely time-scale to producing an effective

---

[‖] Lavoisier was indeed condemned in his own lifetime, and sent to the guillotine, but that was due to his role in collecting taxes prior to the French revolution.

vaccine, and so forth. By contrast, most science taught in chemistry or other natural science classes, especially at the school level but also usually in undergraduate courses, concerns scientific questions that are (provisionally at least) closed as there is now a consensus answer.

Usually, these safe conclusions were contentious enough at one time, and positions were developed over time with a series of studies, arguments and counterarguments and often some degree of compromise between different scientists' initial positions. But none of that science-in-the-making is usually seen as relevant now that we 'know' the 'right answer' – once those particular scientific products (*e.g.*, theories, laws) were 'made'. In the years after a consensus develops, the textbooks are gradually revised accordingly and soon it seems very obvious why a particular view triumphed (as, surely, all the evidence supported it) and alternatives were discounted (as they clearly did not explain as much or as well). Learners may wonder how Joseph Priestley could be so close-minded as to reject the new chemistry of the Lavoisiers and hold on to the notion of phlogiston, whereas those who have studied the scientific debates at the time can appreciate the nuances of the available evidence, and the logic, of the different positions (Thagard, 1992; Chang, 2012). It is often said that history is written by the victors – and something similar happens in science. Messy and complex debates that may have lasted years become tidied into rational reconstructions of how we now 'know' some science or other.

This is understandable. The chemistry textbook author is trying to communicate chemistry – that is, chemistry as currently understood – clearly as possible, rather than write an account of the history of the ideas of the subject. Yet what results from this process has been described as a 'rhetoric of conclusions' (Schwab, 1958) that may indeed reflect the canonical position that was reached, but gives no insight into the nature and processes of science. That is, an approach that focuses on the current state of knowledge may misrepresent the nature of the science itself. Both may have value in chemistry education – but, arguably at least, for many learners who are not going to ever substantially call upon chemical knowledge in their work, insight into how science comes to positions by argumentation in publication, peer review, attempts at replication or new studies that build on existing ones, *etcetera*, is more valuable to their education than just learning some of that rhetoric of conclusions. A little of both is surely called for. One approach that has been recommended for supporting learners in developing insight into how science works is the study of a small number of detailed historical case studies (see Chapter 11, Section 11.5).

1.8.2 Understanding the Application of Science in Real-world Contexts

Even when the chemical community has reached a strong consensus on the science, this is not always sufficient to lead to agreement on how that science should be applied. Thus, there is a strong argument for including in the curriculum the study of socio-scientific issues: those issues where scientific knowledge is necessary, but not sufficient, for making judgments about public policies involving the application of science. Science can often enhance the quality of life, but there may be costs in terms of depletion of natural resources, deforestation and loss of habitat, damage to sites (and so sights) of natural beauty, loss of biodiversity, increased pollution, and so forth. Between the extreme positions that few people would adopt (no scientific development can ever justify any environmental impact; *versus* scientific progress is always worth any costs), there is a need to seek, understand, and balance different viewpoints that derive from various interests and value positions. If this is how science is applied in public life, then, the argument goes, learners should be taught about this complexity so they understand the role of science in society and can better fulfil their own duties in civic life (Sheardy, 2010).

This engagement in a civil activity is not just in terms of blatant political acts (voting, joining pressure groups, going on demonstrations) but making informed consumer choices. It may cost more to buy the less polluting or ethically responsible alternative, when a lot of apparently scientific claims (protein in shampoo, 'organic' vegetables, vitamins in skin-care products, motor oils with 'muscle molecule'[***]) may invite critical examination to see if they really offer enhanced value to the consumer, producer, or environment. More critically, many people will face decisions about health care choices – treatments with potential risks and likely (but not assured) benefits; treatments that usually extend life expectancy for the seriously ill, but sometimes only by constraining that life or which have unpleasant side effects. It is not possible to make objective judgements about what a person should do in such a situation (*e.g.*, that three months of extra life expectancy is worth a certain amount of pain or nausea or time in a hospital), as this will be influenced by individual beliefs, personal goals, family situations, and so forth. That is, it is a matter of values as much as science. Science education that prepares people for their adult lives should offer learners experiences of facing and addressing problems where science can *inform* decision-making, but only alongside the balancing of other considerations.

1.8.3 Teaching for Cognitive Development

Because the school curriculum tends to be organised into discrete school subjects reflecting the disciplines and higher education tends to often be

---

[***] I am no doubt showing my age in remembering television advertisements (commercials) for motor oil with 'muscle molecule'. In checking on my recollection I found a scanned motor racing brochure from 1974 (so long ago that motorsport was heavily sponsored by tobacco companies) posted online which reminded me that it was only 'Shell Super Multigrade' that "has the unique 'muscle molecule'". Whilst searching for this historical example, I found a reference to a current motor oil marketed by Castrol which includes "specially formulated" "intelligent molecules". It is implied that what makes these molecules intelligent is that they know to remain behind attached to the engine when it is turned off and the oil drains back to the sump. If true, this is surely an achievement worthy of a Nobel (though perhaps not so much in chemistry, as in physiology or medicine)?

(at least in many national contexts) primarily discipline-based, it is easy to lose sight of the wider purposes of education. One reason we educate children is to support their general cognitive development.

As everyone knows, babies do not have the ability to solve partial differential equations or deduce stoichiometric relations using titration nor to interpret infra-red spectra. We also know that such things can be taught to (some, at least, and perhaps in principle all) adults. Babies develop into adults who have cognitive abilities that babies lack. Indeed, there are much more basic cognitive skills that these young children lack.

Readers may be familiar with the ideas of Jean Piaget who over many years followed a research programme into children's cognitive development (Piaget, 1970/1972). Whilst some aspects of his thinking have gone out of favour, the gist of his work seems pretty secure. I used to show video clips found on the web to learners in my educational research classes of young children participating in Piagetian clinical interviews. In one standard task children sit with an interviewer at a model mountain, with various objects (*e.g.*, a model tree, a model goat, *etc.*) at its base. Because they are sitting on opposite sides of the mountain, the child and interviewer each see a specific set of objects. There is a transition point in development where a child can appreciate that the interviewer sees objects the child cannot and cannot see some objects the child can. Before this, the child's egocentric worldview means that they answer the questions about which things 'you' (the child) and 'I' (the interviewer) can see with the same list. The child looks around and reports the items they can see in both cases, even though it is obvious to any adult that some items near to the child are obscured from the interviewer's viewpoint because they are behind the mountain. The younger child is not (yet) able to appreciate another person's viewpoint.

This is also shown in another probe used by educational psychologists using a container with incongruent contents. So, for example, the interviewer may show the child a biscuit (or cracker) box – the type where the manufacturers put pictures of the biscuits on the outside to advertise the contents. But it contains something else: say, pencils or stones. When the child is asked what is in the box, they usually and quite reasonably suggest biscuits. But then they are shown the contents as being, say, pencils, and it is confirmed they now think there are pencils in the box. They are then asked what they feel their mother (for example) might think is in the box. A younger child reports 'pencils'. Once they know there are pencils in the box they cannot imagine that another person might think the biscuit box contains biscuits. Indeed, if asked if they remember what they thought was in the box before they were shown inside, they are likely to say 'pencils'. This is not a lie: at this stage in their development, their immediately recent perceptual experience of seeing the pencils dominates their thinking to such an extent that they do not appreciate that they had suggested biscuits just a short time earlier.

Piaget used many 'conservation' tasks, and his results have been highly replicable (even if various interpretations of their significance have been explored). A child agrees two pencils, side by side, are of the same length.

Then one is offset, and the younger child will suggest one is now longer than the other – whereas an older child ‘conserves’ length under the translation (that is, they appreciate that if they were the same length before, then simply changing the position of one does not change this). Two rows of tokens (buttons, coins) that are aligned are seen to have the same number of tokens: but if one row is now stretched out, then the younger child suggests that has more tokens (even though the transformation is undertaken as they watch, and the interviewer seeks to assure they are paying attention). Two lumps of modelling clay are modified till the child thinks there is the same amount of material in each lump. Then, one lump is squashed into a disc or rolled out into a cylinder shape, at which point the younger child suggests one lump has more material – until the moulded lump is returned to its original dimensions. Coloured liquid (dyed water) is poured into two similar containers till the child is happy there is exactly the same amount in each. Then, the material from one of the containers is carefully poured into a differently shaped container (think from a round to a conical flask) making sure the child is happy all has been transferred. Now, the younger child suggests there is more ‘coloured water’ in whichever container has the higher water level. Piaget showed volume is not conserved by the child (*i.e.*, they do not have a concept of the conservation of volume of an incompressible fluid).

Although the transitions are not abrupt, and the precise age at which different conservation principles are attained varies a little between individual children, the general patterns are highly reproducible. A young child does not see things that we as adults find so obvious we do not even have to (consciously) think about them. The contrast is so stark that the way the young child perceives some of these probes can seem incredible and amusing. Adults watching these interviews for the first time tend to find them fascinating and often tend to laugh at the children’s responses. But this is not cruel laughter: it is a recognition that the mental life of a young child is quite different from ours and is just a transitory phase. Piaget’s work revealed general patterns in conceptual development that all normal humans pass through.

When I used this material in class, the video clip I played finished with a probe involving the interviewer sharing out a treat such as a cracker. In this probe, a cracker is broken into two equal parts as the child watches and the interviewer places the two pieces down on the table in front of herself. She also divides a second cracker in the same way, but this time puts one piece to the side, and only one piece down in front of the child. So, there are three equally sized slabs of cracker in play, and the interviewer has two and the child one. The child is asked if the crackers have been shared fairly. Obviously not, as the interviewer has two pieces and the child only one. The interviewer then reaches across and breaks the child’s piece again into two parts. A younger child accedes that this is now fair, as he now has two pieces just like the interviewer.

The point about these probes is that young children systematically demonstrate that they cannot understand aspects of the world that seem intuitively obvious to normal adults. Any adult who thought that a row of five coins suddenly contained more coins simply because they were spread out more (*i.e.*, having watched the operation and seen that the only change being made was the increased spacing) would be considered very suspect – yet, it seems we all went through such a stage. In normal development, the child moves beyond that phase and acquires the appreciation of conservation principles (of a number of things, of the amount of material, and so on) that we all take for granted, and without which chemistry as a science could never have got started.

So, in summary, the cognitive abilities that adults have, and which are essential to understanding and doing science, are not present at birth, but develop during childhood. That much is unlikely to be in dispute, but it raises two very important questions for educators:

(1) to what extent is development a shift in the availability of cognitive functions, and to what extent is it simply a matter of having the 'content' available to function on? (That is, are the mental skills missing in the child, as Piaget would suggest, or is the deficit more about not having had the opportunity to acquire a 'database' of past experiences to apply the skills to.)
(2) to what extent is development a natural process that proceeds *regardless* of education?

These questions are not completely independent (as *if* cognitive development is just a matter of learning lots of stuff to think about, *then* formal education may be an effective way of introducing learners to diverse materials to learn about in order to facilitate that development), but they can be considered separately.

The first question distinguishes between two possibilities. One is that humans naturally have the capacity for sophisticated thinking, but cannot actually do this thinking till they have built up a suitable reservoir of experiences to think about. The other possibility is that a baby cannot think like an adult, not just because it does not know very much yet, but because its cognitive apparatus is intrinsically insufficient.

Piaget's research strongly suggested that babies did *not* have the cognitive ability to undertake sophisticated thinking and were not just lacking content knowledge to think about. Piaget characterised a series of stages of development (four main stages, with substages), through which all normally developing children pass through. Later research has suggested that Piaget's model may have over-emphasised *the extent* to which it was the development of apparatus, rather than access to a knowledge base, which was important – but in general terms his findings seem secure. Indeed, even with the Piagetian model, the development of general cognitive capacity that enables more sophisticated thinking is not seen as sufficient in the absence of relevant domain knowledge. A highly intelligent adult with only a beginner's knowledge of chess can be beaten by a child (but not a very young child) who has extensive experience of the game. A developing child may demonstrate more sophisticated thinking in one domain than another if they are much more familiar with that domain. Indeed the same is true of us adults. An expert in one field may make very naive decisions in a domain where they are a novice.

This might in part explain why a learner who seems able to engage enthusiastically with working out the various permutations of final league positions in, say, a football season, in terms of the various possible outcomes of remaining games, may glaze over and seem overwhelmed at the first suggestion that they undertake any mole calculations or balance an equation. This may not just be interest *per se*, or even primarily a matter of confidence, but rather that greater familiarity with a domain may provide a greater fluidity in mentipulating 'objects' (football teams rather than reagents, perhaps; or match scores rather than stoichiometric ratios). This is related to a key feature of human cognition known as 'working memory limitation', and the way in which familiar material (that is material that has become familiar through sufficient reinforcement and consolidation) becomes 'chunked' into complexes of information in long-term memory (these ideas are discussed in Chapter 3, Sections 3.2.1 and 3.2.2).

For chemistry teachers, the most important of these stages in Piaget's developmental scheme is the final stage, known as formal operations. A person who has reached formal operations is able to mentally represent formal classes abstracted from actual examples met and to undertake mental operations on these formal representations. This is essential in science where we deal with all kinds of abstractions (as classes, not just individual examples, *e.g.*, ideal gases, halogens, substitution reactions, delocalised bonds and oxidising agents) and carry out abstract mentipulations (*i.e.*, 'mental manipulations') on them (Taber, 2019). We expect learners to look at a line on a screen and deduce the sample had a component of atomic mass 16, or to look at a two-dimensional representation of a molecule and deduce molecular geometry, or to consider the molecular structure of an alkene they have never seen before, and yet deduce the structure of the product when it is involved in an addition reaction.

When we have become familiar with the concepts and symbolism of chemistry, that very familiarity can make it more difficult for us to appreciate how such material is experienced by a novice learner – 'at the learner's resolution' so to speak. Consider the process of writing a balanced equation for oxidation brought about using potassium dichromate, say. The learner may use the tool of identifying oxidation states of elements within molecules and ions, and then tracing changes in oxidation states of the element. This is a task we expect senior high school and college level learners to master, for example, to work out the change in the oxidation state of sulphur or nitrogen during a reaction. This requires:

- actual laboratory materials to be abstractly represented in the mind as samples of substances;

- those substances to be represented by formulae referring to individual ions and molecules,
  - often striking out those which appear in both reactants and products as we know they are not pertinent to the task in hand, even if the chemical process could not occur in their absence;
- calculating ‘oxidation states’ or ‘oxidation numbers’,
  - which in effect means *formally* treating a molecule or molecular ion as if it is hypothetically dissociated into atomic ions, even when that is not a viable process; and then
- calculating the change in that state.

The learner works out the change in the oxidation state *of an element* – even though often the element itself is present neither before nor after the reaction. (Something the teacher has probably repeatedly emphasised – sodium chloride does not have the properties of sodium or chlorine as it is a different substance – the elements are not there, mixed together, in the compound.) Babies cannot do this, and nor could most seven- or even ten-year-olds, not *just* because they do not know enough chemistry, but because their brains have not yet matured sufficiently to handle that kind of abstract thinking. Piaget suggested that the acquisition of formal operations happened around adolescence, but later studies suggested that in some populations many learners in upper secondary courses (say 14–16-year olds) had not fully acquired this level of thinking: something that offered one reason why so many learners struggled with science subjects (Shayer and Adey, 1981).

Readers who are teaching in Universities may at this point be feeling smug about the fact that they usually only admit learners who have passed through adolescence *and* have demonstrated their ability to undertake the abstract mentipulations so inherent in studying sciences. However, there has been work suggesting that there is a fifth stage of cognitive development beyond Piaget’s model (Arlin, 1975; Kramer, 1983), which allows ‘post-formal operations’: the kind of thinking necessary when dealing with fuzzy and ambiguous information, and when making decisions where sufficient evidence is lacking – or where technical information is insufficient and needs to be complemented by consideration of how people’s personal values get involved (socioscientific issues, see Section 1.8.1). That is, situations that are common in applying science outside of the academy, and especially in relation to social policy issues.

This was investigated by William Perry (1970) who undertook studies with undergraduates in prestigious US university colleges and produced a model of intellectual and ethical development which suggested that most undergraduates were far from *fully* developed cognitively. In particular, he found that often undergraduates (who would have passed through all of Piaget’s stages of cognitive development) struggled with teaching which embraced any ambiguity and multiplicity. Now, traditionally, science teaching seldom did this, except perhaps in areas such as quantum theory with its debates about interpretation (which are often ignored in practice as along as learner can use the ideas instrumentally). Learners do not tend to be taught, say, a series of models of acidity without being taught which one they are meant to apply – even if chemistry as a discipline may not actually have a canonical position that one model is correct.[†††]

By contrast, in humanities subjects, learners would often be assigned several readings by different thinkers who had written about a topic and who disagreed. But learners would often understand the task as being to work out which author was right and come to class expecting the teacher to confirm the right answer – and then to be disappointed and perplexed to later leave the class without being offered any definite resolution. The notion that there may not be a right answer and that sometimes one needed to adopt a position on a question informed by a personal system of coherent values as much as by any evidence available, came as a shock. Yet, this reflects what we find in society more widely where different, sometimes highly intelligent and well informed, commentators take opposing views on policy questions despite having access to the same data. Perry charted how undergraduates developed in this sense.

Now, this may seem something of great importance in arts and humanities education, but less relevant in chemistry where we do not assign different geometries to an ammonia molecule in the light of our political or religious commitments or philosophical leanings, but rather think that there is a definite right answer. Yet chemistry education needs to engage with how chemistry is applied in commercial and industrial contexts, and within contexts admitting concern for environmental and public health questions (see Sections 1.8.1 and 1.8.2), and it is in just such circumstances that training learners to be able to make the logical choice when all the necessary data is available and pointing to the same answer is not sufficient. So, if cognitive development continues into adulthood, then it is relevant to university teachers as well as school teachers.

Now Perry's work was undertaken some decades ago, and reading it now his findings seem overly pessimistic. Taken at face value, Perry's study suggests even undergraduates at elite colleges should have trouble coping with material that is not only commonly now included in chemistry degree courses, but also often in school science in those countries where a focus on teaching about sociocultural issues has entered the curriculum. There have been critiques of Perry's work, in particular from feminist perspectives, and his work has been built upon and developed: but without undermining his

---

[†††] That is, if learners learn a series of models of acidity, these tend to be understood as a historical progression from a quotidian notion of acid through models of increasing sophistication. Yet, this is misleading both in the sense that acidity is not the kind of thing we can move towards a 'right' model of (it is a concept that has shifted in response to the convenience of chemists) and that there is not one single model in general use which has now completely replaced the others (see Chapter 6, 'Conceptualising Acids: Reimagining a Class of Substances', in Taber, 2019).

basic argument. Despite this, anyone reading Perry today might suspect that if we repeated his work now we might well find that most undergraduates would be starting further along his scheme of development, and reaching the highest stages more readily.

Perry himself would likely be happy with such an assumption. Perry thought his findings were linked to the nature of the high-stakes assessment that learners prepared for in order to enter and graduate from the University. Although not using these terms, Perry noted that examinations at Harvard where he worked had historically tended to primarily test LOCS not HOCS (Perry, 1985). That is, cramming lots of information would support examination success, even without any deep understanding. But Perry also noticed how that was changing over time – something that surely has continued in most national contexts since Perry was working in the middle of the last century.

This links to my second question here – of whether education makes a difference. We think of 'development' of being a natural process, and certainly Piaget (though usually considered as an educational psychologist) had the mindset of a natural scientist, studying the natural development of an organism – in his case, the human. (Piaget's precocious early focus was on rather different organisms – he had already become recognised as something of an expert on molluscs by the time he completed his schooling.) For Piaget, cognitive development was a natural process. Yet, as pointed out earlier, his own estimates of when children moved between stages were found to be optimistic for many populations later studied – perhaps because Geneva-based Piaget's sample (including his own children) tended to be from educationally advantaged backgrounds in a developed European setting.

Lev Vygotsky, Piaget's contemporary working in the U.S.S.R., recognised the potential for a kind of natural experiment in the way the Soviet Union was 'modernising' practices in some of the very agricultural republics – and he dispatched his colleague Alexander Luria to investigate the thinking skills of largely illiterate people in some of these less 'developed' regions (parts of Uzbekistan).[‡‡‡] Luria's results strongly suggested that what passes for normal ways of thinking among adult populations was mediated by culture – that some of the ways of scientific thinking we take for granted are – at least – encouraged by education. There is room for discussion over whether Luria (working within a system that did not tolerate dissent well) found, as he suggested, that (i) development was being stunted by lack of formal education in what were seen as peasant societies not yet brought under effective soviet modes of organisation or simply that (ii) qualitatively different habits of mind are nurtured by different cultural contexts.

[‡‡‡] Vygotsky was not healthy enough to go on the field work, and he died of tuberculosis aged only 37, in 1934. Luria became very well known in his own right, especially for his case studies from his work in clinical neuropsychology.

One example concerns the syllogism – which is a core feature of logic (and central to scientific argumentation). A simple example of the kind used by Luria in his study was as follows:

> The bears in the far North are all white.
> Ivan went to the far North, and there he saw a bear.
> What colour was the bear that Ivan saw?

We would expect even a quite young child to immediately see the answer. Yet, Luria's adult informants would tend to respond along the lines that they did not know – after all, they reasonably pointed out, they themselves had never been to the far North, and they personally have not talked to Ivan.

This does not prove they were incapable of following the logic, but perhaps that they had not learnt to play this particular kind of 'language-game' (Wittgenstein, 1953/2009) and rather valued knowledge based on personal experience, or reliable informants known to be trustworthy, rather than deduced from hypothetical situations and posed as riddles. That is, this failure to engage with syllogism may not imply a lack of epistemological sophistication, so much as a cultural difference in epistemological values.[§§§] Whatever the explanation, the members of this culture did not tend to engage in this (for us) standard way of thinking – and it would clearly be very difficult to study or practice science without being able to draw logical deductions in this way. We all tend to take for granted that secondary and university learners have acquired this mode of thinking.

It is also worth mentioning IQ ('intelligence quotient') at this point. Whilst there are genuine questions about the extent to which IQ is a good measure of intelligence, or perhaps just some limited aspects of intelligence (Gardner, 1993; Kaufman and Grigorenko, 2009), it is certainly a measure that tends to correlate well with success at academic study. (The notion of intelligence is discussed further in Chapter 3: see Sections 3.6 and 3.7.3).

[§§§] Luria was working in the Soviet system and no doubt entered into the work already expecting to see that the communist system produced advantages that were not yet available to those people in the Asian regions that were just being 'collectivised' – converted into the soviet way of organising society. It is reasonable to suggest he had a bias. Had he simply concluded that these peoples had inferior levels of cognitive development we might wonder about his ability to maintain objectivity. The work can certainly be criticised from this perspective, but what I find convincing are the findings suggesting adults showed different habits of thought from those indoctrinated by formal education. For example, when asked to sorts a range of everyday objects, Luria's participants were less likely to classify all the tools (a class of objects) as belonging together, and all the furniture (another class) together, but rather to organise objects narratively – so a particular tool might be associated with an object it might be used to mend. That is not an inherently inferior approach, but just different. We might think of this as the difference between classifying hydrochloric acid as belonging with nitric, phosphoric, ethanoic and sulphuric acids, and instead suggesting that hydrochloric acid should be grouped with sodium hydroxide solution, universal indicator solution, a flat bottomed flask and a burette. That would still be an intelligent response, but not the one encouraged by the priorities of our system of formal education.

The 'normal' IQ score is 100 – but in order to keep it that way, there have to be periodic re-calibrations. The Flynn effect refers to a major study which pointed out how (had there not been such successive restandardisations) measured human IQ would have increased substantially over the twentieth century (Flynn, 1987). It seems likely that a major factor here is developments in education. Put very simplistically, educating people does not simply lead to them knowing *more*, but also makes them more intelligent.

1.8.4 Teaching for the Affective Domain

It is also important to acknowledge that although chemistry is a 'hard' science,[¶¶¶] and chemical knowledge is theoretical and conceptual – chemistry teaching relates to affect as well as cognition (Kahveci and Orgill, 2015). Indeed, there are several quite different ways in which affect is important in chemistry teaching and learning.

Science provides knowledge that might be seen as valuable in its own terms (that is, knowledge is better than ignorance, as a general principle), and which has practical value – as chemistry enables us to produce new materials with desired properties, and find less costly synthetic routes, and to construct batteries of greater capacity, and so forth. However, there is also an aesthetic response to nature that might be related to terms such as 'awe', 'wonder' and even 'beauty'.

Chemistry is sometimes seen as a poor relation here as physics encompasses the stars we see in the night sky (and has produced the horror of atomic weapons) and biology has trees and whales and dinosaurs and butterflies and helical shells and spider's webs – and so on. It is difficult to compete in awe and wonder terms: but chemistry does have a vast range of substances to explore and reactions to present, including the 'bangs and stinks' that are sometimes linked to school practical work in the popular imagination. Crystals are beautiful and colour changes can be impressive. Of course, for many of us chemistry becomes more wonderful once we have acquired some of its conceptual apparatus:

- appreciating how a substance such as sodium chloride can be a compound of two quite different elements, with properties unlike either of those elements;
- understanding something of the rearrangement going on when sulphur changes between monoclinic and rhombic forms;
- understanding why the 'same' metal cation gives rise to different colours as different ligands bind to it in solution;

[¶¶¶] That is a subject with 'hard data' concerned with 'objective' foci. Chemistry, along with physics and mathematics, is also commonly considered one of the more difficult ('harder') academic subjects (Johnstone, 2000), which is one reason why some less confident learners readily drop the subject.

- understanding how there can be stereoisomers that give mirror image crystal forms, and why only one of the forms may be biologically active;
- and so on. . . .

So, in part, we teach to share the wonder of nature.

We may also want to develop attitudes. This may include positive attitudes to chemistry, both as an area of human culture (*e.g.*, not seeing the chemical industry as producing ‘unnatural’ materials and being polluting, but as a means to improve the human condition), and as a desirable subject of study (something to want to continue with beyond the current course). We want to develop the attitude that chemistry is not only enjoyable but viable as a subject for progression. Of course, chemistry is a challenging subject, but we want to teach in a way that it is not perceived as being ‘too hard’ by learners.

We may also want to teach chemistry as a means to share and inculcate scientific values. Scientific work requires

- open-mindedness,
- a critical attitude,
- an ability to look for alternative explanations,
- full and honest reporting – and so forth.

Perhaps we may wish to use chemistry to teach and encourage extra-scientific values. Certainly, in a school, there is likely to be a mission of encouraging fairness, openness to diversity, kindness, empathy, and so forth. These are not *especially* related to chemistry as a science but to wider notions of moral behaviour and the kind of society we wish to live in – but if a school (or indeed a college or university) is to succeed in such a mission, then such considerations are not only for the assembly hall but must permeate into all aspects of the institutional life. Sometimes a teacher puts aside the next teaching move indicated to teach the chemistry at hand (see Chapter 5, Section 5.2.1) because it becomes apparent there is a more important life lesson to be addressed. Of course, as such values are extra-scientific, their relevance to the task of teaching may be subject to disagreement and change over time. I suspect many people who consider the formal inclusion within some national curricula of the required study of the adopted state political ideology as being an undesirable form of indoctrination, are fully supportive of the taken-for-granted community values that their own local schools seek to inculcate into children from a very young age: honesty, tolerance, generosity, caring. . .[‖‖‖]

[‖‖‖] Schooling is, in a sense, about indoctrination. If we seek to persuade learners that they should think for themselves and always engage with evidence critically, that is just as much indoctrination as seeking to persuade them that the leader, or party, knows best and that it is unpatriotic to criticise government policies or documents. Perhaps, my indoctrination is supportive enlightenment, whereas yours is oppressive brain-washing – though you may disagree. Indoctrination, like discipline, cannot be considered inherently good or bad without regard to the details.

In this regard, it might have once been thought quite radical to suggest that chemistry teaching should be framed within a particular stance in relation to certain environmental issues. Yet, so-called 'green chemistry' has (understandably) increasingly become seen as a key focus of chemistry education (Anastas *et al.*, 2009). If we are going to teach chemistry, it can be argued, it is critical we teach sustainable chemistry (Eilks and Rauch, 2012). Notions that may have once seemed external to chemistry itself can come to seem centrally important in teaching the subject. For example, deforestation is not a chemical topic, and the removal of indigenous people from their traditional lands is clearly not directly a matter of chemistry. Yet, if chemistry provides options or informed choices that impact on such matters, then chemistry education may be seen to include responsibility for teaching about such matters; and so then it may be considered that adopting a particular, extra-scientific position within teaching is justified.

Science itself is, of course, a cultural and social construction, and so will change over time. Just as it now seems odd how often early modern scientists referred to God in their scientific reports (something largely considered inappropriate today), it may in decades to come seem strange that anyone would have thought that values relating to sustainability, environmental protection or social justice, were once seen as extra-scientific.

References

Anastas P. T., Levy I. J. and Parent K. E. (ed.), (2009), *Green Chemistry Education: Changing the Course of Chemistry*, American Chemical Society.

Anderson L. W. and Krathwohl D. R., (2001), *A Taxonomy for Learning, Teaching and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*, Longman.

Arlin P. K., (1975), Cognitive development in adulthood: a fifth stage?, *Dev. Psychol.*, **11**(5), 602–606.

Ausubel D. P., (2000), *The Acquisition and Retention of Knowledge: A Cognitive View*, Kluwer Academic Publishers.

Bachelard G., (1973), *Le Pluralisme Cohérent de la Chimie Moderne*, 2nd edn, Librairie Philosophique J. Vrin, (1932).

Bloom B. S., (1968), The cognitive domain, in Clark L. H. (ed.), *Strategies and Tactics in Secondary School Teaching: a book of readings*, MacMillan, pp. 49–55, (1964)

Brock R. and Taber K. S., (2016), The application of the microgenetic method to studies of learning in science education: characteristics of published studies, methodological issues and recommendations for future research, *Stud. Sci. Educ.*, 1–29.

Chang H., (2012), *Is Water H_2O? Evidence, Realism and Pluralism*, Springer.

Chapman K., (2019), *Superheavy: Making and Breaking the Periodic Table*, Bloomsbury Sigma.

Cianciolo A. T., Grigorenko E. L., Jarvin L., Gil G., Drebot M. E. and Sternberg R. J., (2009), Practical intelligence and tacit knowledge: advancements in the measurement of developing expertise, in Kaufman J. C. and Grigorenko E. L. (ed.), *The Essential Sternberg: Essays on Intelligence, Psychology and Education*, Springer, (2006 journal paper (from Learning and Individual Differences)).

De Jong O., Acampo J. and Verdonk A., (1995), Problems in teaching the topic of redox reaction: Actions and conceptions of chemistry teachers, *J. Res. Sci. Teach.*, **32**(10), 1097–1110.

Duschl R. A., (2000), Making the nature of science explicit, in Millar R., Leach J. and Osborne J. (ed.), *Improving Science Education: the contribution of research*, Open University Press, pp. 187–206.

Eilks I. and Rauch F., (2012), Sustainable development and green chemistry in chemistry education, *Chem. Educ. Res. Pract.*, **13**(2), 57–58.

Feyerabend P., (1975/1988), *Against Method*, revised edn, Verso.

Flynn J. R., (1987), Massive IQ gains in 14 nations: What IQ tests really measure, *Psychol. Bull.*, **101**(2), 171.

Gardner H., (1993), *Frames of Mind: The Theory of Multiple Intelligences*, 2nd edn, Fontana.

Harrison A. G. and Treagust D. F., (1996), *Sci. Educ.*, **80**, 509.

Hodson D., (2014), Nature of Science in the Science Curriculum: Origin, Development, Implications and Shifting Emphases, in Matthews M. R. (ed.), *International Handbook of Research in History, Philosophy and Science Teaching*, Springer Netherlands, pp. 911–970.

Hofstein A. and Hugerat M., (2022), *Teaching and Learning in the School Chemistry Laboratory*, Royal Society of Chemistry.

Jenkins E. W., (1996), The 'nature of science' as a curriculum component, *J. Curric. Stud.*, **28**(2), 137–150.

Johnstone A. H., (2000), Teaching of Chemistry – logical or psychological?, *Chem. Educ.: Res. Pract. Eur.*, **1**(1), 9–15.

Kahveci M. and Orgill M., (ed.), (2015), *Affective Dimensions in Chemistry Education*, Springer.

Kaufman J. C. and Grigorenko E. L., (ed.), (2009), *The Essential Sternberg: Essays on intelligence, Psychology and Education*, Springer Publishing Company.

Kramer D. A., (1983), Post-formal operations? A need for further conceptualization, *Hum. Dev.*, **26**, 91–105.

Latour B., (1987), *Science in Action*, Harvard University Press.

Lederman N. G. and Lederman J. S., (2014), Research on Teaching and Learning of Nature of Science, in Lederman N. G. and Abell S. K. (ed.), *Handbook of Research on Science Education*, Routledge, vol. 2, pp. 600–620.

McComas W. F., (1998), *The Nature of Science in Science Education: Rationales and Strategies*, Kluwer.

Osborne J., (2002), Learning and teaching about the nature of science, in Amos S. and Boohan R. (ed.), *Teaching Science in Secondary Schools: Perspectives on Practice*, RoutledgeFalmer, pp. 227–237.

Perry W. G., (1970), *Forms of Intellectual and Ethical Development in the College Years: A Scheme*, Holt, Rinehart & Winston.

Perry W. G., (1985), Different worlds in the same classroom: Students' evolution in their vision of knowledge and their expectations of teachers, *On Teaching and Learning*, **1**, pp. 1–17.

Piaget J., (1970/1972), *The Principles of Genetic Epistemology*, trans. W. Mays, Routledge & Kegan Paul, (French, 1970).

Schwab J. J., (1958), The Teaching of Science as Inquiry, *Bull. At. Sci.*, **14**(9), 374–379.

Shapin S., (1992), Why the public ought to understand science-in-the-making, *Public Understanding Sci.*, **1**(1), 27–30.

Shayer M. and Adey P., (1981), *Towards a Science of Science Teaching: Cognitive Development and Curriculum Demand*, Heinemann Educational Books.

Sheardy R. D., (ed.), (2010), *Science Education and Civic Engagement: The SENCER Approach*, American Chemical Society.

Shusterman J. A., Scielzo N. D., Thomas K. J., Norman E. B., Lapi S. E., Loveless C. S. and Tonchev A. P., (2019), The surprisingly large neutron capture cross-section of 88 Zr, *Nature*, **565**(7739), 328–330.

Snow C. P., (1959/1998), The Rede Lecture, 1959: The two cultures, in *The Two Cultures*, Cambridge University Press, pp. 1–51.

Taber K. S., (2001), The mismatch between assumed prior knowledge and the learner's conceptions: a typology of learning impediments, *Educ. Stud.*, **27**(2), 159–171.

Taber K. S., (2002), *Chemical Misconceptions – Prevention, Diagnosis and Cure*, Royal Society of Chemistry.

Taber K. S., (2008), Towards a curricular model of the nature of science, *Sci. Educ.*, **17**(2–3), 179–218.

Taber K. S., (2019), *The Nature of the Chemical Concept: Constructing Chemical Knowledge in Teaching and Learning*, Royal Society of Chemistry.

Thagard P., (1992). *Conceptual Revolutions*, Princeton University Press.

Wittgenstein L., (1953/2009), in Hacker P. M. S. and Schulte J. (ed.), *Philosophical Investigations*, trans. G. E. M. Anscombe, P. M. S. Hacker and J. Schulte, revised 4th edn, Wiley-Blackwell.

Zeidler D. L., (2014), Socioscientific Issues as a Curriculum Emphasis: Theory, Research, and Practice, in Lederman N. G. and Abell S. K. (ed.), *Handbook of Research on Science Education*, Routledge, vol. 2, pp. 697–726.

Zoller U., (1993), Are Lecture and Learning Compatible? Maybe for LOCS: Unlikely for HOCS, *J. Chem. Educ.*, **70**(3), 195–197.