Foundations for Teaching Chemistry

Chemistry is a subject that has the power to engage and enthuse students but also to mystify and confound them. Effective chemistry teaching requires a strong foundation of subject knowledge and the ability to transform this into teachable content which is meaningful for students. Drawing on pedagogical principles and research into the difficulties that many students have when studying chemical concepts, this essential text presents the core ideas of chemistry to support new and trainee chemistry teachers, including non-specialists.

The book focuses on the foundational ideas that are fundamental to and link topics across the discipline of chemistry and considers how these often complex notions can be effectively presented to students without compromising on scientific authenticity. Chapters cover:

- the nature of chemistry as a science
- the chemistry triplet
- substances and purity in chemistry
- the periodic table
- energy in chemistry and chemical bonding
- contextualising and integrating chemical knowledge

Whilst there are a good many books describing chemistry and many others that offer general pedagogic guidance on teaching science, *Foundations for Teaching Chemistry* provides accounts of core chemical topics from a teaching perspective and offers new and experienced teachers support in developing their own 'chemical knowledge for teaching'.

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Foundations for Teaching Chemistry

Chemical Knowledge for Teaching

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For Philippa, dearly missed

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Preface

'Foundations for Teaching Chemistry: Chemical Knowledge for Teaching' discusses chemistry subject matter for those who are teaching or will soon teach chemistry topics at secondary school level. It offers an account of core ideas in chemistry informed by scholarship and research into pedagogy and students' learning difficulties with the subject. The aim of the book is to offer an account of foundational ideas in chemistry to help teachers (and those preparing to teach) consider the level of coverage suitable for presenting to school learners, informed by a deeper understanding of the core principles of the subject as well as some key findings from chemistry education research. The book is therefore intended to complement standard chemistry texts (that set out for students what they should know) by offering a 'teacher's-eye' perspective on the subject matter.

A common complaint about the school science curriculum is that the desire to cover a wide range of material often leads to students regularly moving between topics, giving little opportunity for deep engagement and insufficient time to come to fully appreciate abstract and, often, counterintuitive ideas. Those who make this criticism argue that a science education that included fewer topics but required deeper understanding and sought to help students integrate ideas across those topics would be desirable. Whilst such a curriculum would inevitably have gaps, it may better enthuse students with science, allow them to build up confidence in their ability to understand scientific concepts, and equip them with the skills to top-up their knowledge in later life.

That rationale has also informed this book: rather than seek to cover everything that might be in a secondary school chemistry course, it focuses on foundational ideas – those that are fundamental to and link to topics across the discipline of chemistry – seeking to offer a discussion of these ideas at sufficient level to help teachers think about the nature of the subject matter they are to teach as (relative) experts charged with communicating difficult ideas to relative novices. A recurring theme in this book is finding the optimum level of simplification for presenting complex notions, in order to support learners without compromising on scientific authenticity. Teachers who adopt the kind of thinking exemplified here will be 'tooled-up' to analyse other topics they may be asked to teach in order to develop their 'chemical knowledge for teaching' in those topics.

The tone of the book is to offer advice, based on experience as a teacher and as someone who has explored students' thinking about chemical topics. That is, the book is not set up as a manual telling teachers how they should teach concepts and topics (decisions that will depend on curriculum/syllabus, institutional context, age group, and the particular class), but rather as a kind of virtual mentor seeking to feed into the teacher's own thinking and decision-making.

Given the intended readership of the book, it is assumed readers will have some background in chemistry. Some readers will identify as chemists, and some will see themselves as scientists but not specialists in chemistry. Every reader will be unique. Some readers may already have detailed knowledge of some of the topics covered (but, I am assuming, will have less experience thinking about those topics as a teacher). In places I may refer to or assume specific background knowledge of ideas or examples not familiar to some particular readers, but where that background can readily be acquired from a chemistry textbook or internet source. There is so much chemistry reported in the academic literature that no chemistry teacher (or, indeed, research chemist) could possibly know it all: however, *Foundations for Teaching Chemistry* offers the foundations that can be built upon as and when a teacher needs to further develop their chemical knowledge for teaching.

1 Introduction – the rationale for reading about ‘chemical knowledge for teaching’

This is a book to support chemistry teachers and chemistry teaching. It is a book about chemistry but written from a particular perspective – that of an academic discipline that is *represented* in the school curriculum and explained through teaching. In a sense it is therefore a book that is also about education, about teaching, and about learning. The book is organised in terms of chemistry but conceptualised from the perspective of teaching.

Teaching is said to draw upon several different types of knowledge. Teachers need to know (i) their subject, and (ii) about pedagogy (how to teach), and (iii) about the particular context in which they teach and the specific students they are working with. No one can write a book customised to support learning about working in a particular school, with its ethos; timetable, organisational structure, and teaching facilities; teaching, technical, and support staff; and so forth, or its own array of young minds eager, or not so eager, to learn about a subject. These things have to be learnt *in situ*. Metaphorically, the teacher needs to acquire such knowledge from *in vivo* studies, within the teaching context, to complement what they can learn from the *in vitro* study of generalisable knowledge available from books and courses and seminars.

The more generic features of teacher preparation and teacher development therefore relate to subject knowledge and pedagogic knowledge: if you like, the *what to teach* and the *how to teach*. It has increasingly been recognised, however, that effective teaching cannot treat knowledge of a subject and knowledge of teaching as distinct domains on which a teacher independently draws. There has been much focus on what is sometimes referred to as ‘pedagogic subject knowledge’ or ‘pedagogic content knowledge’. If ‘subject knowledge’ (SK) is knowledge of the chemistry and ‘pedagogic knowledge’ (PK) is knowledge of (general) teaching principles and approaches, then ‘pedagogic content knowledge’ (PCK) is the *specific* pedagogic knowledge of teaching a subject, such as chemistry.

Developing knowledge through teaching

PCK (Kind, 2009) is not just knowledge related to teaching chemistry but is the knowledge developed for and about teaching specific chemical topics or ideas in particular kinds of teaching contexts (so teaching a topic to a mixed ability group of 11-year-olds requires somewhat different PCK to teaching 'the same' topic to a group of high attaining 17-year-olds). The use of a separate term – PCK – implies that something more is going on here than simply the *application of* knowledge from one domain to another. This can be illustrated by an example of what would not count as PCK. Taking one simple idea:

> After asking a question to the class, an effective teacher will defer choosing a student and inviting a response until after sufficient pause to allow all students to give some thought to the question.

This might be considered to derive from the domain of PK, and would apply in teaching chemistry as it would in teaching mathematics, history, and so forth. PCK then means something *more than* specifying:

> After asking a chemistry question to the chemistry class, an effective chemistry teacher will defer choosing a student and inviting a response until after sufficient pause to allow all students to give some thought to the question.

That would simply be *an application* of generally applicable PK. PCK goes beyond simple application to draw upon knowledge of the subject to hone the use of pedagogic skills and tools in specific teaching contexts. PCK is therefore a kind of higher-level knowledge base that draws upon and emerges from the application of PK to SK, rather than being simply a conjunction or hybrid of those two domains.

As another example:

> Students may be motivated by producing 'work' which will be presented to an authentic audience.

To the teacher the *real* work required of students is the thinking and learning involved in undertaking a task, and the task is often just a means to support that mental activity. Students are not trained to think as teachers and therefore often consider the notes and other texts they are asked to produce as the work. It is considered that in some contexts, with some learners, it is useful for activity to be directed towards some form of public product. Just doing the work because it is work and 'the teacher said so' may not motivate all students. A task that will be presented to an audience may seem to have more rationale. This might be a presentation to the class (with different groups given different parts of a topic to research), a letter to an authority or company (perhaps advocating for some environment-friendly change), a display for parents to see on an open day, a poster for the corridor . . . .

That is a general notion. The teacher of a subject will develop expertise in knowing which topics best lend themselves to (or benefit from) such an approach and which particular teaching objectives are suitable for addressing in this way, and which forms of product will work with different types of classes at different curriculum levels . . . and so forth. Some of that development is ‘theory’ work, that is, using knowledge of the subject and curriculum aims to conjecture where it might be sensible to use such a pedagogic approach in a chemistry course; and some of the development is ‘empirical’ in that it comes from evaluating those conjectures in classroom teaching.

PCK is then a form of synthetic knowledge that is built through the interaction of SK and general PK. We might consider that these three knowledge bases are part of an interacting system within a teacher’s mind (see Figure 1.1). Teachers often learn theoretical ideas to inform PK in their preparation for teaching, but (as is generally true of formal abstract knowledge) it evolves and strengthens when it is applied in practice. PK itself develops as the principles become better understood through

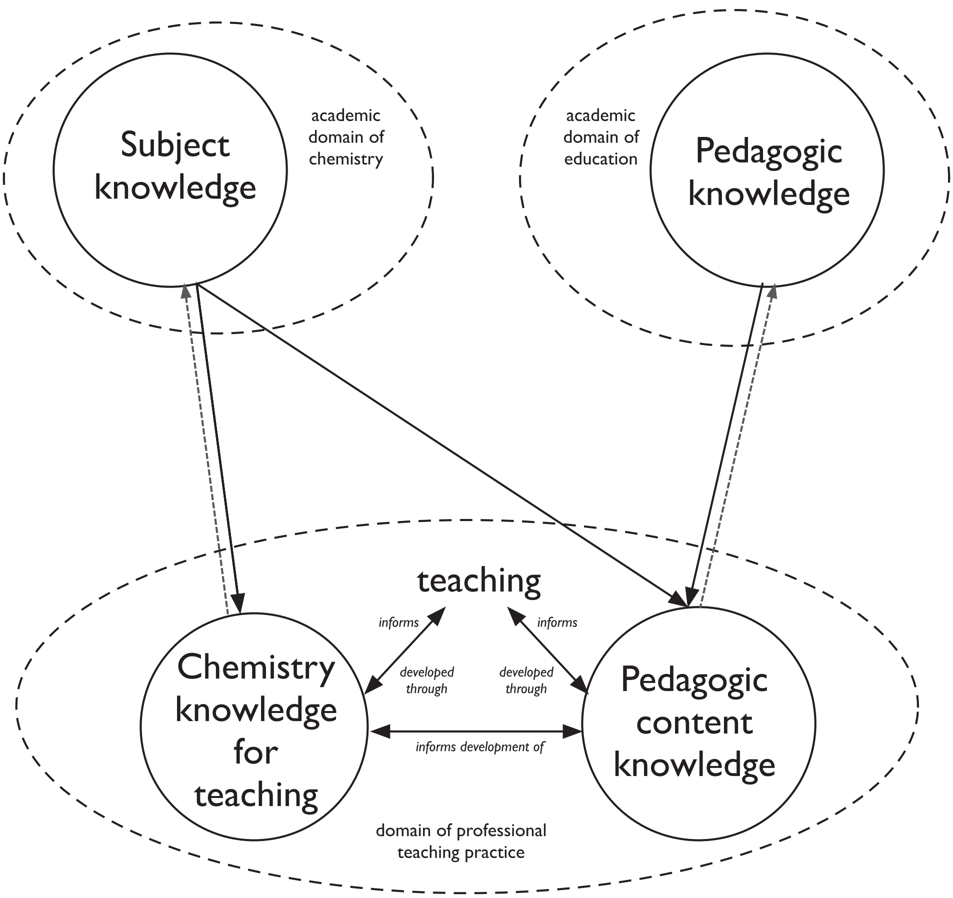

Figure 1.1 The teacher’s professional knowledge draws upon several knowledge domains, and forms a dynamic system which develops through the application and evaluation of knowledge in teaching

practice, and what is initially a unitary theoretical idea becomes more nuanced as its power and range of application are tested in teaching (Taber, 2018a).

Useful concepts meld theory and experience

Some readers may recognise how this reflects somewhat the ideas of the educational theorist Lev Vygotsky (1934/1986), who discussed how conceptual development involved an interaction between concepts we learn as formal abstract ideas (e.g., from lectures or reading) and those we instinctively develop to make sense of experience. Spontaneous concepts lacking formalisation may be context-bound and not open to direct introspection, whereas academic concepts that are not grounded in any personally relevant experience may only be learnt by rote and applied in an algorithmic manner without invoking personal meaning. Chemistry offers a good many potential sources for the latter experience for our learners: imagine a student applying the idea that electronegativity difference influences bond type – without having any feeling for what ‘electronegativity’ is. The concepts we can use effectively and with fluency are *melded* concepts (Taber, 2013b) – concepts where we have a feeling for their meaning as well as a formal language for expressing and thinking about them.

In a similar way, PCK is a melding of SK and PK. The effective professional is using ‘hybrid’ concepts with roots in both theory and practical experience. Teachers are taught about the nature of human learning because this helps us think about how our students learn, so to inform us when we teach. However, such principles apply to our own professional learning as well.

Consider the simple idea, used as an example earlier, of setting work to develop some kind of public product. This will be found to be more useful in some teaching situations than others. It may motivate students in some groups (but perhaps not all) to write to politicians or companies about their policies or practices relating to pollution or recycling, but there are many topics in chemistry where producing such letters would be rather pointless. There are places in a chemistry course where it may make sense to set different research tasks to small groups, leading to a session where each group reports to the class. However, with most classes, it does not make sense to divide up an abstract theoretical topic in this way, especially a topic that requires a sequential building of ideas. This is likely to be confusing, demotivating, and to require the teacher to subsequently reteach the material. However, there may be other topics where it makes sense to teach some basic ideas and have students then apply these ideas researching different examples of applications, so that the ideas are reinforced in the group presentations. Both SK and PK are needed to identify suitable topics and themes and to assess the effectiveness of the approach in practice.

The refinement of the teacher’s PK requires experience of trying out the technique in a range of contexts. Two distinct things will be happening when using PK in teaching contexts: the PK will become more sophisticated, and content-specific PCK will be developing through applying PK in teaching subject matter.

Somewhat less attention has been given to a related but distinct theme – that of subject knowledge itself being seen through a pedagogic lens. This is not about how one's knowledge of a subject such as chemistry informs pedagogic decisions made in planning and carrying out teaching but how knowledge and experience of teaching informs one's conceptualisation and organisation of subject knowledge. We might call this – chemistry as conceptualised from a teaching perspective – *chemical knowledge for teaching* (CKfT).

Chemical knowledge for teaching

An immediate response to this suggestion might be that chemistry is chemistry; that chemical knowledge develops through chemical research; and that chemical knowledge should not be changed by being a teacher. Either manganese is an element or it is not. Being a teacher rather than an industrial chemist, or a biochemical engineer, or whatever, will not change that. Ditto, the acidic nature of sulphur dioxide or the molecular mass of bromine, etcetera. Of course, this is true: the reader can be reassured that this book is not going to seek to undermine disciplinary knowledge. Part of the rationale for this book is the view that if we are going to teach chemistry in school, and thus require students to study the subject, we should get the chemistry right.

What is implied by CKfT is that effective teaching can modify the *organisation* of one's subject knowledge. A teacher needs good canonical subject knowledge, but just knowing the chemistry is not enough. A good teacher needs to think about the subject matter in ways that best support teaching for student learning. Perhaps there are some chemistry specialists entering chemistry teaching with chemistry knowledge across all curriculum topics that is so comprehensive, so deep, so sophisticated, and so free of errors that teaching chemistry will not impact upon their disciplinary knowledge itself. Perhaps such paragons of chemical knowledge and understanding exist – although I do not think I have yet met one.

There is a saying attributed to teachers along the lines that you never fully understand an idea or topic until you have to teach it to someone else. That is phrased quite starkly, but even if it may be an exaggeration, it reflects a common experience. Understanding is not best considered a binary property as if someone simply either does or does not understand something. Even if we feel we already understand rates of reaction or homologous series or the properties of transition elements, this does not mean we might not be able to develop deeper understandings. Usually the processes of thinking about how to approach teaching a topic, and then actually engaging in explaining the topic to young learners and responding to their questions, changes one's own understanding. Sometimes in researching and teaching a topic you correct some errors or oversimplifications in your knowledge, and sometimes you add new elements (so to speak), but even when this does not happen you will almost certainly find your knowledge of the topic becomes better integrated, and your appreciation of the limits of its application becomes more nuanced, and your fluency in using the ideas improves. As a teacher you will become more aware of the nature of approximations, models, and theories as useful but partial accounts of the natural world.

Almost certainly, then, in teaching chemistry to students you will inevitably be teaching yourself as well – at least in the sense of increasing the sophistication of your own knowledge. The processes of preparing for and engaging with teaching (which includes assessing student learning, and reviewing your own teaching) will therefore:

1 allow you to develop PCK in the specific topics areas you teach;

2 and in doing so

   a develop your understanding of general pedagogic principles (i.e., PK); and

   b develop CKfT; which

   c also develops your own SK, your understanding of the chemistry itself.

This system of knowledge domains also has some built-in feedback cycles (e.g., if developing PCK feeds back to develop PK, then the more sophisticated PK can better support the future application – and so further development – of PCK, which in turn . . .).

An example: scaffolding learning

As one example, a key pedagogic principle is that of scaffolding student learning (Taber, 2018c). You may have learnt that effective scaffolding involves pitching learning challenges beyond the students' current competences in what is sometimes known as the student's 'zone of proximal (or next) development', or ZPD (Vygotsky, 1978), but then offering a kind support that both enables student success in a task and, in so doing, models the competencies to be acquired. This allows the learner to internalise those new competences as the scaffolding is faded.

If you have not met these ideas before, then that description may seem fairly meaningless. Even if you have been taught this theory, but you have never had a chance to apply it, then perhaps you have abstract notions of what is meant by the terms 'scaffolding', 'ZPD', and 'fading' but may be less sure how well you can operationalise these ideas in the classroom. Perhaps you decide this perspective could be useful in teaching the topic of the reactivity series, or kinetics, or organic reaction mechanisms . . . .

In seeking to apply the pedagogic principle to a teaching topic you will think about the subject content in a particular way (so potentially developing your understanding of the science), as well as beginning to develop a grounding for the pedagogy in a real teaching context. If you go ahead and teach this topic according to this principle you will experience the principle in action (so further grounding the abstract idea in experience) and get feedback from the learners' responses in class that will inform you about your application of the pedagogy, as well as about your success in communicating the chemistry content. At the end of the process you will likely find your teaching was not optimal (teaching is complex, and most of us find we hone our teaching with more experience), but you will be a little wiser. Your knowledge and understanding of the particular pedagogic approach will have developed, as will possibly your understanding of the chemistry itself. Certainly, your CKfT will likely have grown, as well as your subject-specific PCK.

Applying a broad repertoire of pedagogic principles

Probably, you will not only be looking to implement scaffolding but a range of other pedagogic ideas and principles. You will be aware of the limited concentration span of learners, especially younger ones. You will know about limited working memory and so the need to break up the material to be taught into manageable learning quanta. You will know it is important to diagnose and to take into account the alternative conceptions that students often have about a topic before planning teaching. You will be aware of the different levels of educational objectives – so recall of some specific material is important, but higher-level skills such as application of ideas and critical evaluation and synthesis of material are more challenging to students and are important for deep understanding. You will know that to make the unfamiliar (what the students do not yet know about, but you have to teach them) familiar may involve employing not only everyday examples and applications but often also analogy, metaphor, simile, modelling, narrative – but you will also be aware that analogies and such work best (to mix some metaphors) as temporary crutches or training wheels that should be carefully discarded once the students master the target ideas (Taber, 2018a).

You may be doing all of this and much more (e.g., ensuring you allow thinking time when you ask questions), and if you manage to be successful at your first attempt at teaching a topic at a particular year/grade level, that will be very impressive. More likely, you will have partial success: but you will learn an enormous amount in the process. You will slowly develop competence in applying these types of principles, and, through the wealth of experience you are building up, much of it will even start to become 'second nature', so you begin to intuitively respond to classroom challenges. You will be developing a repertoire of PCK through seeing how these ideas can be applied in relation to specific topics, particular concepts, and the teaching resources you can access.

You will also be thinking about the subject matter you are to teach as a teacher of chemistry rather than as a scientist. Nothing is lost here – you do not cease to be able to think like a scientist, but you become so much better at (also) seeing the chemistry from the perspective of your novice learners and thinking about the material you are teaching as subject matter – in relation to classes of students, in relation to curriculum programmes and examination specifications, in relation to specific lessons located within teaching sequences, in relation to specific teaching and learning activities that make up lessons, and to the repertoire of teaching moves you can employ in the classroom (Taber, 2018a).

How to make best use of this book

This book, then, explores chemistry from the perspective of CKfT. A range of key topics and chemical ideas are considered. However, there is no attempt to simply reiterate all the chemistry likely to be found in a school chemistry course – there are plenty of textbooks that will provide this information, sometimes tailored to specific teaching schemes or examination specifications. Rather, the book sets out to offer teachers, and especially those relatively new to chemistry teaching, a treatment of key chemical ideas understood as subject matter to be taught.

It is assumed that readers know some chemistry – but clearly different readers will have different breadths and depths of chemical knowledge. In some places subject matter is presented in detail to explore issues related to how it can be taught. In many places, however, other chemical concepts are simply referred to as if the reader (being an actual or intending teacher of chemistry) will know about them. It is not assumed that all readers will already have detailed knowledge of all these ideas (though some will) – but it is assumed that a reader will use this book alongside resources such as chemistry texts intended for learners and so will be able to access materials to supplement their existing chemistry knowledge as needed. A good teacher never assumes they know it all and is always open to learning more about their subject. Much of this book explores fundamental topics in chemistry, but where it is useful to make particular points, some more advanced topics are also discussed. Some readers who may only be teaching introductory chemistry topics may choose to skip over these sections, but arguably all teachers of chemistry will benefit from expanding their subject knowledge, and one factor that can be important in thinking about how to teach chemistry to any class is what other related, more advanced topics those students will progress to learn about later in the school.

Chemistry is a science where models are ubiquitous

A keen-eyed reader may notice recurring themes that inform the account of chemical knowledge for teaching in this book. One relates to the nature of chemistry as a science (which has its own chapter as well as being infused through the book as a whole). It has increasingly been recognised that teaching science authentically has to mean teaching about science (as a set of processes or practices) as well as teaching some science (that is, specific topics such as acids or the periodic table). The extent to which the chemistry curriculum has been reformed to incorporate such a perspective varies from country to country – and indeed in England this has been the subject of continuing debate (Taber, 2018b). Generally, it is now considered that modern chemistry courses need to include some material on the nature of chemistry itself, and so this becomes part of the subject matter – therefore, students should have some understanding of what kinds of things models and theories are and their role in the science of chemistry.

Even if the curriculum does not specify that, for example, students should be taught about the nature of models and their role in chemistry, there is a strong argument that you have not effectively taught students about, say, a shells-based model of atomic structure unless the students know that it is a model and appreciate something of what that means. If students learn that atoms have concentric shells of electrons that orbit the nucleus and think that is a realistic representation of how atoms actually are, then that learning is seriously flawed.

Even in the absence of being asked to explicitly teach 'nature of science' (NOS) content there is a strong argument that the teacher needs a good grasp of the nature of the scientific ideas that they are to teach – for example what is meant by 'law' in terms such as 'periodic law' or 'Raoult's law'. So, going beyond the NOS aspects, this book more widely considers the nature of chemical concepts themselves. In effect, teaching chemistry is often about teaching concepts – the concepts of acid, oxidising agent, element, period, surface area, molecular mass – the list can be extended considerably. It is not suggested that students should be asked to ponder the nature of these concepts as concepts – but the teacher of such a highly conceptual subject needs to think about the nature of the concepts that are to be taught (see Chapter 6). This book is therefore informed by and draws upon an examination of the different kinds of concepts presented as target knowledge when teaching chemistry (Taber, 2019b).

Curriculum, scheme of work, lessons, activities, moves

That notion of 'target knowledge' deserves some explanation. The remainder of this chapter discusses the ways in which chemical knowledge needs to be considered in relation to curriculum requirements and the practicalities of teaching in schools that schedule teacher and student work according to timetables with discrete lessons (be they 35, 50, 70, or whatever minutes in duration).

The curriculum sets out target knowledge

As a teacher you will be asked to teach according to a curriculum – something which sets out what learners are expected to learn. This does not usually set out a teaching order. For example, in English schools there is a National Curriculum that sets out the chemistry to be taught to secondary-age students. This is split between the content that should be taught to 11- to 14-year-olds and the content that 14- to 16-year-olds are expected to learn. That leaves a great deal of flexibility in deciding how to sequence the material – although governments may offer guidance on this (Taber, 2018b).

Typically, school departments take responsibility for making those decisions and have schemes of work (SOW) which sequence the curriculum. Sometimes these SOW are quite detailed and go beyond sequencing content to specify activities or learning materials (perhaps specifying particular laboratory work), and they may be presented on a lesson-by-lesson basis. One would expect that professional teachers have a high level of responsibility for planning their own classes, and so even very specific schemes may be intended as *guidance* to teachers rather than something prescriptive that they must follow.

In some teaching contexts, the science disciplines may be taught by non-specialists or specialists in a different science, in which case departmental schemes may in part be designed to support the teacher with a background in, say, astrophysics or ecology when teaching chemistry topics. Very precise and detailed schemes may be very useful as starting points for thinking about lessons for new teachers, student teachers, and temporary teachers but should not be used to undermine the responsibility and creativity of teachers. For inexperienced teachers of a subject, the prescribed SOW can be considered a form of useful ‘scaffolding’ to be ‘faded’ (as mentioned previously) as the developing teacher is ready to take on more responsibility for strategic planning of their teaching. For, as suggested earlier, there is an important thinking process in planning lessons that engages the teacher in considering the particular nexus of a specific class, pedagogy, and subject matter.

Lesson activities

Ideally, then, the SOW is a useful starting point for developing lesson plans rather than an algorithm for the lesson. The lesson usually consists of teaching and learning activities. Some of these activities will involve the teacher talking to the class – telling, explaining, questioning, leading discussions. However, with most school-age learners, lessons that are largely this kind of activity or have long periods of this kind of activity are not ideal. So there will also be other types of activity ‘glued’ together by these teacher-led segments. These other activities may sometimes require students to work individually, but often it is more productive to ask students to work in pairs or small groups where students will have to present and justify their thinking and will have their ideas open to challenge (Mercer, Dawes, Wegerif, & Sams, 2004).

In chemistry lessons, an activity for students might be:

- observe the teacher undertake a practical demonstration;
- carry out a standard laboratory practical;
- undertake laboratory enquiry;
- undertake a series of observations of some natural phenomenon, either in laboratory conditions, or in the field.

I have avoided using the term ‘experiment’ here. Experiments are tests of specific hypotheses undertaken to see *whether or not* some prediction will be accurate. Enquiry lessons may include experiments, but so-called ‘demonstration experiments’ are seldom genuine experiments as, when they work as intended, they produce outcomes the teacher is relying upon to make particular teaching points. Indeed, ‘demonstration experiment’ is something of an oxymoron – they are demonstrations of well-established effects intended to have a known outcome. They only seem to be experiments if they go wrong!

There was a time when school science lessons shifted between ‘theory’ and ‘practical’, where students were active in the practical sessions and the ‘theory’ was usually teacher exposition supplemented with student reading, the occasional ‘video’, and students working quietly on completing exercises to apply and consolidate what they had been taught. Arguably, in some national contexts, pedagogy in science developed slowly compared with some other curriculum areas. Teachers of some other subjects recognised the need to base their lessons on various kinds of student activities, normally collaborative activities requiring discussion of ideas, to maintain student concentration and engagement. Science had lab work, which most science teachers feel ‘trumps’ other kinds of group work (we have Bunsen burners, after all), but the so-called ‘theory’ sections of lessons seldom involved other kinds of group work.

State-of-the-art pedagogy today is strongly influenced by ideas about cognition (such as limited working memory capacity) and constructivist ideas about the nature of learning – that students build new knowledge on the foundations of their existing (canonical or non-canonical alternative) conceptions, in a process that is interpretative (making sense of the new in terms of the familiar), incremental (building in modest ‘learning quanta’), and therefore iterative (Taber, 2014). It is realised, therefore, that meaningful learning relates teaching experiences to what is already familiar, and effective teaching actively seeks to help learners make such links. The need for ‘active’ learning (Devetak & Glažar, 2014), where students’ minds are fully engaged, means that for most students, most of the time, listening to teacher presentations is only effective in short-duration chunks – and often, at least with younger learners, this means just a few minutes at a time. Moreover, sitting silently working on a task that is meant to help students understand and apply ideas the teacher has presented is often not very effective for many students – and activities that require them to talk their ideas over with others are usually much more productive.

There are many other activities that can be included in classes to supplement and reinforce teacher presentations, such as modelling, P-O-E (predict-observe-explain), concept cartoons, various DARTS (directed activities related to text – such as labelling a diagram using a provided text); jigsaw learning (where different groups research different aspects of a topic and then present to the other groups and answer their questions); writing newspaper articles; making a video; etcetera.

Successful activities tend to be those where there is some kind of product or outcome beyond the students' own notes and where individuals engage in meaningful conversations that are genuinely dialogic (Mortimer & Scott, 2003) – that is where different views or suggestions are compared and explored (rather than reaching instant decisions, or each group member taking a different view and pressing for it without engaging with the arguments of their peers).

Such activities are likely to be educative, that is of genuine value in supporting student learning and development, when students are given tasks that are challenging (rather than simple 'drill and practice' exercises) but which they are able to succeed in with the support provided. That support will often be a mixture of teacher hints and help, resource materials, and the contributions of the peers that they are working with. This assumes a level of scaffolding (mentioned previously) – matching support in the form of temporary structures to allow student success. As all classes are heterogeneous to some extent, this also implies planning different levels of support for different students in the class.

All of this is very general (i.e., PK), and is certainly not limited to chemistry or science teaching. The skill of the subject teacher is working out how to select and operationalise such activities in teaching particular subject content (developing PCK). The lesson plan, then, is based around a sequence of activities, some of which will involve teacher-as-explainer led episodes, but others will require the teacher to take different roles whilst students work on activities: as resource allocator, as moderator of group discussion; as critical friend in supporting decision making; as helper or hint-giver; as evaluator or moral cheerleader; and so on (as well, sometimes, with some classes, as police officer and peacekeeper).

The limit to lesson planning

Lesson activities can be planned in some detail, and instructions certainly need to be clear, and resources engaging, accurate, and well-presented. However, there is a limit to how well lessons can be choreographed. All teaching involves working to a mental model of what students already know and understand; applying this in anticipating how these particular students will (i) understand new teaching and (ii) respond to the lesson activities. Yet every class, every learner, is to some degree unique – so the teacher's internal mental model is never going to allow a perfect simulation of how a lesson will actually develop. The better the teacher knows the class and the more diagnostic assessment is carried out (Taber, 2002), the better the teacher can envisage the lesson in advance. But teachers have to see a lesson plan as being somewhat pliable. It is less like a musical score to be followed note for note and a little more like the sports coach's strategy and tactical plan ahead of a team match – which has to be employed in the context of how the other team play the game on the day. Keeping to the musical allusion, teaching is akin to improvisation on a theme: something which has elements of going with 'the moment' but also depends for success on extensive preparation and a deep understanding of the rules or structures within which the improvisation will be developed.

Making your moves – teaching as an intellectual dance

No matter how well planned a lesson is, it cannot be scripted completely in advance – or it becomes a lecture: which is seldom an effective approach with typical school-age learners. Teaching is an interactive process where the teacher seeks to move the class towards a predetermined objective and has to rethink the route in the light of the impediments that may appear in the path during the journey. Although the lesson plan can be understood as a sequence of episodes, of discrete but linked activities, the teacher has to work to maintain the overall process. The work of teaching may be analysed as a sequence of specific moves. These moves occur at a much finer grain size than the lesson activities. This can be illustrated through a few examples.

Whether to interrupt the practical

Consider a class undertaking a laboratory practical activity. The process of getting the class to undertake the practical, monitoring their work, and bringing the activity to a close will require both advanced planning and the teacher undertaking a range of – what I am referring to as – moves throughout the process. These might include reminding students of some safely rules before starting the practical – such as that safely goggles should be worn at all points during the activity. That would be planned in advance by the teacher.

Now, imagine that at one point during the activity the teacher spots one student pull off her goggles and rub her face. This was not specifically anticipated in the lesson, and thus there is no specific response in the lesson plan ("at 11.04 admonish Alicia for removing her goggles . . .") – but of course that does not mean the teacher should ignore this because it was not planned for. There is a decision to be made here.

One possible move the teacher might make is to gently walk across to this student, and to have a quiet word with her, and reminder her why it is important both that she keeps her goggles on, and to avoid touching her face without first going to wash hands that have been handling the materials being used in the practical. An alternative move would be to loudly instruct the class as a whole to stop what they are doing for a moment, and, once all are silent and paying attention, then to talk to the whole class about the safety point. We might ask: which of these moves is more sensible?

A teacher is likely to take a version of one of these alternatives in some situations, and a version of the other option at other times. That need not reflect arbitrary inconsistency. The decision will depend upon a range of factors: does this teacher know this class well? Is this student a 'repeat offender'; and how would she respond to being called out in the class? Is this a useful opportunity to review an important safety rule with a class where such reiteration would be valuable? Or is this a generally a class that knows and follows procedures well, and little would be gained by interrupting their ongoing work? What is the atmosphere in the laboratory like today – is there a sense of quiet, well-organised industry, or a sense of students just going through the actions with limited focus on the work?

The choice of move depends on contextual factors, some of which would be known by the teacher on entering the particular classroom but some of which relate to the variability found in any class from day-to-day. Even the most studious class occasionally has a lazy or distracted day; even the most boisterous class is more amenable to getting down to work on some days than others. If it is a Thursday afternoon just after a windy lunch break, the same class will likely be louder and more agitated than if it is a rainy Monday morning. Teachers cannot always anticipate the weather when planning their lessons!

Monitoring and adjusting classroom activities

Consider a different type of activity – say a class of 11- to 12-year-old students working in small groups on discussing concept cartoons (Naylor & Keogh, 2000). Concept cartoons offer several imaginary characters (e.g. 'Ahmed', 'Sally') voicing realistic suggestions for the science involved in some scenario (e.g., a character might be saying 'I think the magnet will pick up the aluminium foil because aluminium is a metal'). The group task is to examine the options presented and decide which of the characters they agree with, and to give reasons for their choices. The teacher may have planned that this activity will last 15 minutes. Once the activity is underway (groups organised, materials distributed, instructions given – all requiring specific 'teaching moves') the teacher *could* sink into a much-needed reverie or get on with some marking, or do some web-searching for materials to use in another class.

However, that implies that once students are active, the teaching can be suspended. The teacher will actually want to monitor the work that is going on. With some classes this might well be in part to check for and stop off-task behaviour. However, the teacher also needs to know that the activity is proving productive. Perhaps one group has not mastered the ground rules for effective group-work, and the members are talking across each other rather than engaging in genuine dialogue that responds to and builds upon each other's contributions. Some teacher intervention is needed to shift a good deal of repeating of views ("well I agree with Sally"; "no, I agree with Ahmed"; "no, Sally's right"; and so forth) into something more akin to a scientific discussion.

Perhaps another group of students have very quickly worked through the statements they have been asked to consider and have come to agreed positions on each and are now discussing last night's television programmes. The teacher has to be alert for all kinds of possible developments and be prepared to stop an activity, change group composition, give hints, offer extension work, and so forth. If all groups seem to have made faster or slower progress than anticipated, then should the scheduled 15 minutes be cut to 10 minutes or extended to 20 minutes, with possible consequences for the rest of the planned lesson? Again, the teacher reaches a decision within the wider context of knowing the class, the 'atmosphere' in the class that day, the wider lesson plan, and so forth. As a reader will appreciate, there are no 'right' or 'wrong' answers in absolute terms, without regard to the context as it appears to the teacher at that moment.

Similar considerations apply when the teacher is explaining the science to the class. Have students appreciated some example or analogy, or should it be followed-up with an alternative? Is this a sensible point to pause and ask some questions to check students are following what has been said so far? If something is taking longer than expected, as students have been slower to understand than anticipated, then is it sensible to stop at this point and move to an activity, and then resume the explanation later, starting with a recap? Or, alternatively, is it necessary to extend this teacher exposition activity to complete what was (according to the lesson plan) to be covered now, before students can productively move on to the next activity?

There are many such issues that may arise. Is it sensible to be diverted by a student question which is not centrally about the core issues being discussed, and risk some in the class getting confused or losing track of the 'thread' of the lesson, but which raises an interesting point and reflects genuine curiosity and interest? Or would it be better to avoid a potential diversion and have a private conversation with that particular student a little later in the lesson, with the risk that the spontaneity is lost or even that a suitable opportunity may not arise?

There are no absolute answers to these questions, as what is the right thing to do in one particular lesson may not be the best move in another, and only someone with knowledge of the context itself (and especially the students concerned) can make an informed decision. None of this seems to be about the subject matter itself – but that is also part of the context. In many cases where teachers need to improvise teaching moves as classes proceed, a key part of the knowledge base that is relevant to making choices is the subject matter itself. The remainder of this book focuses more on some of the specific chemistry to be taught and learnt. However, a reader should keep in mind throughout that understanding the chemistry is just a starting point for thinking about how that subject matter will be represented within classroom activities in timetabled lessons following a scheme of work intended to meet the requirements of a chemistry curriculum.

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