Towards an ideal chemistry curriculum

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Abstract This article discusses the development by the Royal Society of Chemistry of a framework to provide a relevant and coherent chemistry curriculum for all students. This work has been carried out by our Curriculum and Assessment Working Groups. The framework identifies three components that combine to give a rounded view of the discipline. Within the components, 'big questions' are used as a curriculum narrative and structure for progression. The big questions are used to select content, ensuring that it is relevant and can be linked to the narrative. We intend to develop this framework further in the light of feedback received, to ensure that it is supported by a wide range of stakeholders; readers are invited to respond to the author with any comments or questions. In due course, the proposals will inform the advice that the Royal Society of Chemistry provides to governments and other relevant agencies at times of curriculum development and reform.

One of the strategic priorities for the Royal Society of Chemistry is that all young people should receive a rich and inspiring chemistry education. There are many factors that contribute to this, one of which is to have in place an engaging and relevant curriculum. We hope that many young people will progress into careers in the chemical sciences, and one of the aims of the curriculum at all levels must be to lay suitable foundations for such progression. However, chemistry education must also be of value to students who make other choices, the majority. An appropriate curriculum will enable them to appreciate and understand some of the phenomena they see around them, give them skills that they will be able to use in other walks of life, and provide the scientific literacy they need to engage in informed debate about issues that affect their daily lives and wider society.

The term 'curriculum' is used in many different ways to refer to learning experiences at different levels, ranging from the selection of subjects available to a student to the fine mesh of teaching and learning activities experienced by a student on a day-to-day basis. In this article, we are thinking of 'curriculum' in terms of a core, specified curriculum set at a state level – for example a 'national' curriculum phrased in terms of a set of standards or a programme of study, or the core criteria for national qualifications. A student's experience is naturally much richer than this, but what happens in the classroom is ultimately influenced by high-level expectations, so these need to be right. After all, if the specified curriculum is not coherent or relevant, if it does not lend itself to being made engaging, this puts a lot of work onto schools and teachers to make something of it.

The Royal Society of Chemistry's Curriculum and Assessment Working Groups were convened to produce a vision for what the school chemistry curriculum from ages 5 to 19 should look like. In these groups, we have brought together teachers and other experts in chemistry education with representatives from our wider communities – such as in higher education and industry – as well as representatives from related disciplines. So far, our work has focused on the ages 11–19, but we also need to be able to extend our proposals into the 5–11 range in a way that still supports coherence and meaningful progression. We are not designing a curriculum for any specific nation or region, or for any particular existing qualification. We have tried to focus on what we think will give an 'ideal' experience, and that can be adapted to suit a range of systems, including both academic and technical pathways. This also means that our proposals will not amount to a complete curriculum ready for implementation. What we have produced can be thought of as a framework or set of guidelines that governments or other organisations can use as a basis for curriculum development. We have suggested content to be included in the curriculum framework, but these suggestions are not intended to be comprehensive. In particular, we want there to be space in any curriculum that allows teachers to apply their professionalism to ensure strong engagement with chemistry and its applications.

The following sections set out our curriculum framework.

The curriculum model

In framing the curriculum, it is worth defining what 'chemistry' as a discipline is actually about, and therefore how we want students to understand its aims and purpose.

We define chemistry as the study of the composition and properties of matter and how and why it undergoes change. The discipline of chemistry has built up, through centuries of observation, experiment and reasoning, a body of knowledge to explain the behaviour of matter and to rationalise the synthesis of new substances. Chemical scientists build on this knowledge to create new materials, measure the properties and composition of substances, and create models of behaviour. Our understanding of matter is continually developing, through ongoing empirical study and ways of reasoning. These findings help us to understand and improve our world.

This provides us with three core areas that a chemistry curriculum should cover, which we refer to as the components of the curriculum (Figure 1):

- **Chemistry as a science**: the practices of thought and enquiry that we use to develop new understanding.
- **Chemical concepts**: the body of knowledge and understanding about matter and its properties that the practice of chemistry has developed over time.
- **Chemistry and the world**: the way chemistry is used to understand and affect the world in which we live.

This starting point for the curriculum clearly represents the nature of the discipline. In line with our aims for the curriculum, we want learners to understand that chemistry is not a 'collection of facts': it is a dynamic endeavour, through which we continue to uncover new knowledge of the material world. We use this knowledge to solve the problems of our ever-growing and developing society. It is an endeavour that, hopefully, learners will envisage themselves contributing to in their future.

The three components are different lenses through which to view the discipline and each should be presented explicitly. However, true understanding of chemistry and appreciation of its relevance comes from understanding

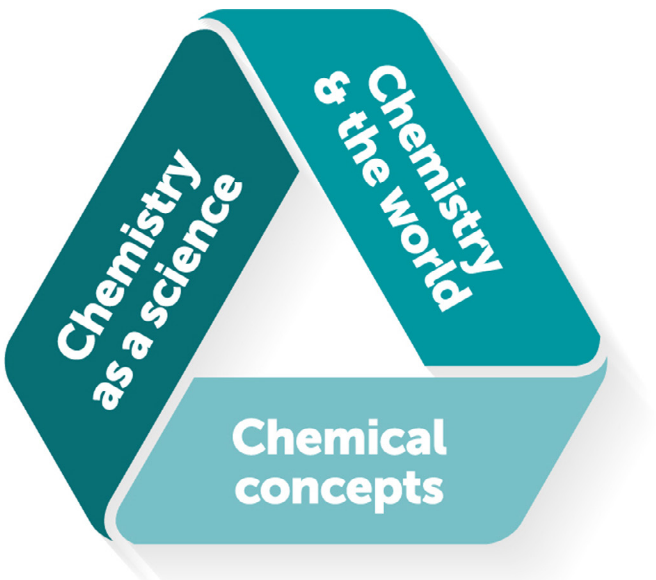

Figure 1 The curriculum model

how they combine. For example, students might examine some of the processes of inquiry, pattern-seeking and construction of conceptual models that have helped us make sense of the myriad organic reactions that exist. Then, they could study some specific reaction types and how these feature in the synthesis of pharmaceuticals, agrichemicals or smart materials that are used in the modern world. We do not specify any examples of applications that must be included, nor do we advocate either a context-led or concept-led approach, but embedding these links across the three components as a matter of course will be essential to students' appreciation of the discipline.

The big questions of chemistry

The next level of our framework is influenced by the work led by Wynne Harlen (2015), which presents strong arguments in favour of using the core ideas within a discipline as a framework for the curriculum: to build ideas into a coherent picture, to provide a basis for selection of content, and to provide a basis for progression in learning through the stages of education.

We have elected to use a framework consisting of 'big questions'. The use of questions mimics chemical scientists' interest in finding out about the world, inviting learners to do the same. It also allows the same framework to be used at all phases of education: the questions can be answered in age-appropriate terms from primary through to post-16, thus forming a continuous thread through students' learning. Our big questions sit within the components as follows:

Chemistry as a science

- How do we think about chemistry?
- How do we do chemistry?

Chemical concepts

- What are things made of?
- How do we find out what things are made of?
- How do we explain how substances behave?
- How can substances be made and changed?

Chemistry and the world

- What is the impact of chemistry?

Content and strands

Our working groups have developed proposed content that will serve to answer the big questions at the 11–16 and 16–19 stages. The content covers insights that will help students to answer the questions, as well as some of the skills that are used in the sciences (notably laboratory skills). The ideas and skills are grouped into strands, which help to visualise the key ideas and themes. We have ensured that all proposed content contributes to answering one or more of the big questions and that it can be linked to other areas of the framework. Facts and concepts are therefore not learned in isolation, but form a coherent whole.

We endeavour to keep the strands consistent across the age ranges in the interests of clarity and showing how ideas progress. However, there is inevitably some development in the strands as the ideas become more sophisticated over time. We anticipate that the 5–11 framework, once developed, will contain fewer strands than the 11–16 and 16–19 frameworks.

Table 1 depicts the curriculum framework for 11–16, showing the three components, the big questions, the strands and the key ideas and themes included in each

Table 1 The curriculum framework for the 11–16 stage

Big question	Strand	Key ideas and themes
Chemistry as a science		
How do we think about chemistry?	Developing and using models	The role of models in chemical reasoning. The particle model; collision theory; models for bonding.
	Using representations	The use and meaning of symbols, formulae, nomenclature, diagrams and equations.
	Using mathematics	The role of thinking mathematically, e.g. in the identification of trends.
	Classification, grouping and trends	The use of classification in chemistry as a tool to identify patterns. Grouping and trends in the periodic table.
How do we do chemistry?	Investigative processes	Development of investigative skills. The role of investigation in furthering understanding, by providing evidence to test ideas. Different types of investigative process.
	Experimental techniques	Development of basic laboratory skills such as careful measurement. Use of those skills in specific processes.
Chemical concepts		
What are things made of?	Substances	The nature of substances versus e.g. mixtures (including solutions). The particle model and how it explains a range of phenomena.
	Elements and compounds	The nature of elements and compounds. The periodic table: organisation and trends.
How do we find out what things are made of?	Chemical analysis	Understanding of different types of methods to analyse substances: based on physical properties, characteristic reactions and interaction with electromagnetic radiation.
How do we explain how substances behave?	Atoms and ions	Atomic models. Ionisation.
	Bonding and structure	Ionic, covalent and metallic bonding in terms of electrostatic interactions. Simple molecular versus giant structures. Linking bonding, structure and properties.
How can substances be made and changed?	Chemical reactions	The nature of chemical reactions and the meaning of reaction equations. Reactivity. Energy transfers in reactions.
	Rates and equilibrium	Collision theory, activation energy and rate. The nature of dynamic equilibrium.
	Synthesis	Design of reactions, including functional groups, reaction conditions and purification of product.
Chemistry and the world		
What is the impact of chemistry?	Investigating the world	The use of analytical chemistry to study the environment. The role of chemistry in understanding climate change. Using chemical concepts to explain real-life scenarios.
	Making things and developing processes	The use of industrial processes to make novel substances and materials. The use of chemistry to address global issues.
	Making decisions about chemistry	Ethical, moral, economic, political and environmental considerations feature in decision-making about chemistry.

strand. We emphasise that this is a framework for the development of a specified curriculum, and not a teaching structure. It is not the intention that the strands are taught as 'modules' or that the order in which they are presented implies a fixed sequence. There are legion ways in which connections can, and should, be made between strands, both within and across the components. Our proposed content does not list all possible connections, but some are visible. For example, at 11–16, several models are referenced in strands under the component *Chemical concepts*, such as the particle model and collision theory. These same models are referenced in *Chemistry as a science*. Both of these models can also be viewed through the *Chemistry and the world* lens, for example in discussing industrial reactions or the chemistry of the atmosphere.

What we want to achieve

A curriculum built on this framework should be able to avoid some of the pitfalls that are sometimes observed in chemistry education.

Too often we hear students describe chemistry as 'just a load of facts' that they have to learn, without seemingly any coherence. Countering this naturally requires the skill and expertise of good teachers, but must start from a curriculum that tells a story and puts the fundamental ideas of the discipline in the foreground (Harlen, 2015).

Our framework gives a strong message about what our discipline is about. Chemistry is an active endeavour, in which we ask questions about the material world and think about how to answer those questions. We also consider what we can do with our understanding. By allowing the detail of the content to flow directly from the components and big questions, all the content in the curriculum earns its place in the framework. Everything that is included contributes to a coherent understanding of the fundamental principles of chemistry.

We have carried this thinking about fundamental principles through in our proposed content. For example, we want learners to understand that 'All things are made of one or more chemical substance'. This is, in effect, another way of saying that students should learn about compounds, elements and mixtures, but, importantly, it puts the term 'substance', which has been identified as a unifying concept in chemistry (Johnson, 2014), at the core. Answering the question '*What are things made of?*' with the concept of substances creates bridges to particle theory, analytical chemistry, bonding and structure, and a world of investigative and applied work. The fact that 'all things' are made of chemical substances reminds us that everything, including living matter, answers to the same fundamental principles – creating a link to the biological sciences.

We also hope that our approach will reduce the inclusion of the type of content that appears to exist in syllabuses merely in order to be memorised. For example, the current combined science GCSE subject content (England) contains an isolated reference to tests for identifying a range of named gases (Department for Education, 2015). Content presented in this way risks a rote-learning approach and a lack of appreciation of why this knowledge is relevant. Better would be to focus on the principle of using unique chemical properties to identify a substance. Tests for gases are a fine way of illustrating this principle in the school laboratory, but there are many other examples and ideally a much wider range would be presented. We hope, in time, that agencies that use our proposals will explicitly link any specific examples included in a curriculum to the broader principles.

In our framework, we seek to put more emphasis on the practices of chemistry, in particular the thought processes that chemical scientists use in their quest to increase our understanding of the world. We would like to see the use of conceptual and mathematical models more explicitly discussed as approximations that allow us to explain and predict behaviour. In current curricula, treatment of models is often restricted to a succession of atomic models, with the implication that the older (more simple) ones are to be discarded and the most recent one is 'true'. In practice, scientists should aim always to apply the simplest model that will explain a given phenomenon, and may use different models in different situations. Bringing this thinking into the open would give students a more nuanced understanding of chemical thought and hopefully put a stop to teachers being accused of teaching things that were 'wrong' in previous years.

Chemistry as a science includes questions relating to both practices of thought and practical and investigative work. Our purpose there is to link the empirical more explicitly to the thought processes than is often currently the case. Existing curricula frequently refer to an investigative process that begins with asking questions and ends with drawing conclusions and potentially evaluating the investigative method. We would like to see more recognition of how scientists ask questions based on ideas they have formed by observing patterns and developing explanatory models, and that investigations serve to test those models. Empirical findings may then be used to further develop, or on occasion overturn, theories. This will require careful thinking about how practical work can be used to model these processes; see for example Kenrick (2017) for a superb idea for making learning about conceptual models more practical.

We have explicitly incorporated ideas about the impacts of chemistry partly because discussion of applications makes chemistry come alive for students, demonstrates its relevance and helps young people to become scientifically literate citizens. In addition, referring to a broad range of the ways in which chemistry is used – in laboratories, in industry, in the field – can help students to visualise what a career in chemistry might look like. The chemical sciences are vital to our being able to build sustainable societies, and are important economically. There is a huge range of rewarding careers that chemistry graduates can access, including in many areas outside the chemical sciences themselves. We know that extrinsic motivation, that is, an understanding of the potential benefits, is an important factor in students' subject choice, especially for those from lower socio-economic backgrounds (Mujtaba *et al.*, 2018). Good careers advice in all schools is essential, but the chemistry curriculum itself should also provide opportunities to demonstrate what futures the subject can offer.

Our ways of working

The Royal Society of Chemistry launched a Curriculum and Assessment Working Group in 2014, with the purpose of developing a comprehensive view of an appropriate school chemistry curriculum from primary to the end of formal education. Membership of the group consisted of representatives from higher education in chemistry and related disciplines, teacher education, secondary education (including FE), industry and other curriculum and assessment experts. This group soon agreed to focus, in the first instance, on post-16 level education, which was felt at the time to be more pressing.

The group discussed a range of approaches to a potential curriculum, taking inspiration from past and existing qualifications as well as literature studies. The big questions framework emerged and has since been refined, particularly with the requirements to fit all age ranges. It soon became apparent that working across the 5–19 age range was not feasible within a single group and so a separate group was set up to look at 11–16. The aims for this phase are different to those for the 16–19 phase, as most of the students studying chemistry up to the age of 16 are doing so because it is compulsory, often as part of a broader science subject. The curriculum at this lower level must therefore meet the needs of those who will use chemistry, at most, as informed citizens. This requires particular expertise in teaching for this age group, and so this group was constituted with a higher proportion of teachers and curriculum experts.

Some members sat on both the 11–16 and the 16–19 groups, allowing cross-fertilisation of ideas. Over the past year and a half, both groups have worked on refining the curriculum framework and proposing content. Work by the 11–16 group allowed the initial 16–19 proposals to be tested, notably influencing the development of the curriculum model and current division into big questions and strands. While there is still some work to do on aligning the outputs from the two groups, it is reassuring that we have been able to converge on a shared framework.

In practice, the development of our curriculum framework was highly iterative – and we think this is appropriate. While the idea of having a framework is to set the top-level expectations for the curriculum, the process of filling in the detail helps to sense-check that framework and to make sure that it is expressed in the best way. Since working across two groups, there have not been any major changes to the main aims for the curriculum or the core ideas that we want learners to come away with. However, refinements have been made to the big questions in terms of how they are phrased and changes have been made to the grouping of the strands and how certain ideas sit within them, to make sure that the structure as a whole is as coherent as it can be.

The future

We are planning a process of consultation on our proposals with a range of stakeholders, which will have taken place once this article is published. This will include sending our detailed frameworks to representatives from our subject communities, to experts in chemistry education, to our sister societies and other interested organisations, and so on. We are also organising focus groups with teachers and other educationists. Our priority at the moment is to get feedback on whether our framework makes sense. Are the big questions the correct ones? Is the right sort of content included in each of the strands? Can this framework indeed be used to construct meaningful curricula for chemistry?

This feedback will help us set priorities for the next steps of our development process. We will bring our 11–16 and 16–19 work together and make sure that the one feeds smoothly into the other. We need to make sure that there are no 'dead ends' – ideas in the earlier phase that do not lead into anything – and that all the required foundation for the post-16 ideas is laid pre-16. We will also start work on the 5–11 age range. In effect, this will give us another round of sense-checking of our framework, as we discover whether it works to support the first introduction of ideas about matter.

Alongside this, we are having increasing discussions with our colleagues from the Royal Society of Biology and the Institute of Physics. We need to make sure we are talking about crosscutting themes such as energy in compatible ways and that core concepts introduced in one science but used in another appear at the appropriate stage. We also need to consider themes that stretch beyond our disciplines, such as environmental science, climate science and earth science.

As this more detailed work progresses, we will want to get further feedback, such as about the realities of implementing our proposals. What support would teachers, technicians and school leaders need in order to effectively provide a curriculum based on our framework? What barriers exist at a school or whole-system level to making these plans work? We are well aware that the answers to these questions might well be different depending on which educational system you are in.

So, there is potentially a lot more work ahead. We hope, though, that at this point we have the core of a solid idea. With a consensus of support for our framework, we will already be able to use it to influence discussions about how the chemistry curriculum should be structured. The power of a simple narrative, a small number of big questions, to get to the heart of what we want learners to appreciate about chemistry, is something we can put across to policy makers and teachers alike. We hope you agree – please do get in touch if you would like to find out more, by writing to the author at the email address below.

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