The contribution of practical work to the science curriculum

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ABSTRACT Practical work is viewed by many as essential to the school science curriculum. It continues to be specified in many curriculum statements, with a wide range of claims being used to justify its inclusion. Currently, practical work is facing a number of challenges, including that it is not effective in promoting learning. An analysis of a specific activity shows the complexity of challenges faced by learners, with suggestions for making learning more effective.

Practical laboratory work is the essence of science and should be at the heart of science learning. (Council for Science and Technology, 2013)

This sentence is a view shared by many science teachers. It is taken from a letter to Michael Gove, the Secretary of State for Education, from the Council for Science and Technology, expressing concern that practical work is under threat in the school curriculum. In Part 1 of this article I will give a personal view on why practical work is essential, and what can be done to safeguard its place in the curriculum. In Part 2 I will 'dissect' a practical activity to suggest how learning could be made more effective.

Part 1: The place of practical work in the curriculum

What is practical work?

Teaching science often involves creating situations where students can experience things at first hand, whether this is an object, an event or a thought process. A key feature of such practical work is that the students themselves can make direct observations, and can manipulate equipment and materials.

The role of practical work

Practical science delivered with flair and knowledge can help pupils understand scientific concepts and ignite their interest in physics, chemistry and biology. Practical science is also an important part of scientific knowledge and teaches pupils about the empirical basis of scientific enquiry. (Department for Education, 2011)

This submission by the Department for Education to the House of Lords Science and Technology committee report on science teaching in 2011 shows strong support for the place of practical work in the curriculum. It also makes clear that there are several reasons why it is considered important:

- it supports learning about scientific concepts;
- it teaches students about the nature of science;
- it motivates students.

The justification for practical work as a means of 'igniting interest' in science is important but outside the scope of this article. There is some evidence that not all students find practical work motivating, and also other aspects of science can be motivating for students. From a teaching and learning perspective, therefore, practical work in the curriculum serves two key purposes:

- it is a component of scientific endeavour and students should be taught about the role of practical work in the generation of new scientific knowledge;
- it is a classroom strategy for enabling students to build their scientific understanding.

In summary, we can teach science through practical work and we can teach about practical work in science. The distinction between these two separate roles is sometimes overlooked and this can lead to confusion in discussions on effectiveness and on assessment. Identification of clear roles for practical work will be discussed further in Part 2 of this article.

Why is practical work essential?

Practical work – both in the classroom and outdoors – is an absolutely essential component of effective science teaching. (House of Lords, 2006)

Education and science communities share a view that practical work is an essential part of the curriculum, as exemplified above in the statement from the *Tenth Report* of the House of Lords Select Committee on Science and Technology. What is less clearly expressed is a reason why.

The Science Community Representing Education (SCORE) has a view that by age 16 students should have developed an understanding, through practical work, of 'what we know' in science, 'how we know' and 'how we find out' (SCORE, 2013a). It is the following three aspects that are justification for insisting that practical work is essential in the curriculum.

What we know

Without first-hand experience of phenomena, it is difficult to appreciate or understand many of the ideas and explanations in science. A certain amount can be learned from exposition, reading or even video material, but you really do need first-hand experience to appreciate some phenomena. Examples would include changes in temperature and smell as chemicals react, the texture and density of lung tissue compared with kidney or liver, and the push/pull of two magnets when the polarity of one of them is reversed.

How we know

The role of experiments and data can be taught in an abstract way but, to appreciate the tentative nature of scientific knowledge and that 'science does not have all the answers all the time', students need hands-on experience of having to collect and evaluate their own data. They also need to understand the 'messy' nature of certain types of data, including that collected during fieldwork, to recognise that specialist techniques, such as the use of statistics, are required to make sense of findings.

How we find out

The ability to measure accurately, assemble apparatus, follow instructions and control risk are all scientific skills that can be acquired through practical work. These skills, as well as being essential to any student going on to further study in the sciences, are valuable in any career and in life outside work.

Safeguarding practical work in the curriculum

The first quotation at the start of this article was written by the Council for Science and Technology to the Secretary of State in response to a perceived threat to the status and practice of practical work in the curriculum. The specific threat in this case was lack of curriculum time due to pressure on teachers to maximise the examination performance of their students. A number of other potential threats have been identified recently. As you read this section you might like to consider how the science teaching community could respond to the issues in order to safeguard the place of practical work.

Resources

The amount of resource (budget, laboratory space, outdoor space, technical support, storage) for practical work varies widely between different schools, between types of school and between phases of education (SCORE, 2013b). The low level of equipment available in some schools is of serious concern, as is the increasing proportion of science budgets spent on photocopying. Few schools have a budget specifically for practical work, and yet setting an annual budget can be a helpful first step in ensuring that there is planned provision of resources for practical work.

Assessment

Controlled assessments are due to be replaced by other forms of practical assessment in science GCSEs. Currently, there is little assessment of practical techniques such as assembling apparatus and measuring that require direct observation by the assessor, yet these skills are an essential part of practical work. We need to find better ways of assessing practical work to ensure that credit can be given for the acquisition of practical skill as well as scientific reasoning.

Expertise

Working with groups of teachers over a number of years has shown that increasing numbers of newly qualified teachers have graduated from courses, whether these were their degrees or their teacher training, that have not given them a wide experience of school-appropriate practical work. The role of Science Learning Centres and other continuing professional development (CPD) providers is becoming increasingly important in providing high-quality subject-specific professional development as local authority support is reduced.

The Association for Science Education (ASE) has recently been licensed to award suitably experienced technicians the status of Registered Science Technician (RSciTech). This is helping to safeguard professional knowledge on practical science. How can schools share expertise, to ensure that such professional knowledge about practical work can be safeguarded?

Effectiveness

Some practical work is not effective at promoting understanding and knowledge of science (Millar and Abrahams, 2009). To ensure that practical work engages the mind as well as the hands, there needs to be clarity about the purpose of a practical activity and an understanding of how to help students make links with existing and intended knowledge. This is the focus of Part 2.

Part 2: An analysis of the contribution of a practical activity

Recent curriculum documents have exemplified practical activities associated with particular parts of the curriculum. One such activity is the subject of the remainder of this article, which looks in some detail at the component parts, each of which needs to be completed successfully to achieve the intended learning outcomes.

Modelling how the surface area : volume ratio influences the rate of solute uptake in different-sized cells

Movement into and out of cells is a key idea in biology. It has applications in digestion, gas exchange, excretion, nerve impulses, drug treatment and many other areas. The cell membrane regulates the movement of material into and out of cells, and often a large surface area of membrane is associated with more rapid movement. However, the larger a cell, the more solute may need to be absorbed, and the distances travelled may be longer. Large volume is thus associated with slower movement.

The relationship between surface area and volume can be represented as a ratio (the surface area : volume ratio). Students at age 16 are expected to know that a large surface area : volume ratio results in faster uptake of solutes at cell level. They are also expected to understand that a larger surface area : volume ratio is associated with smaller cell size (providing the cells compared have similar shape). Consequently, students should be able to suggest why there is a limit imposed on cell size by the requirement for effective transport. Where cells exceed this size limit, they usually show modifications to their shape in order to increase the surface area : volume ratio. These are the intended learning outcomes of a specific practical activity.

It has been proposed in a recent GCSE curriculum content document from the Department for Education in England that students should carry out activities related to surface area : volume ratio, in the context of cell biology (‘*transport in cells – describe and explain how substances are transported into and out of cells through diffusion, osmosis and active transport*’):

- *calculate surface areas and volumes of simple shapes*
- *calculate surface area : volume ratios* (Department for Education, 2013).

Outline of the procedure

A suggested procedure for a modelling activity measuring diffusion rates in different-sized agar cubes is available from the *Practical Biology* website, www.nuffieldfoundation.org/practical-biology/effect-size-uptake-diffusion.

I have modified this procedure slightly and used it as a professional development activity with groups of biology teachers.

Procedure

- Cut three different-sized cubes of agar containing a pH indicator.
- Measure the lengths of the sides of the cubes and use these measurements to calculate the surface area : volume ratio for each size of cube.
- Immerse the cubes in a soaking solution and measure how long it takes for the indicator to completely change colour in each cube.
- Assess the correlation between time taken to completely change colour and different variables for the cubes (length, surface area, volume, surface area : volume ratio).
- Relate the findings in this model to developing understanding of cell size and shape in humans and plants.

Box 1 contains practical details for this activity.

Challenges to achieving intended outcomes

When using this activity with biology teachers, I have noticed the following:

- Cutting cubes of agar to a required size and shape is difficult. Some teachers do not have

BOX 1 Recommended method of making cubes for use in the diffusion experiment

The endpoint can be seen clearly if pink blocks are immersed in soaking solution that decolourises the blocks.

I have found the following recipe provides good results:

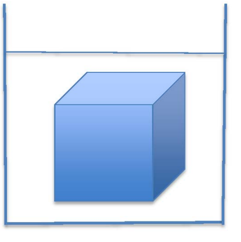
- Make pink agar by dissolving 2 g agar powder in 100 cm^3 of 0.01 mol dm^{-3} NaOH solution, and heat to boiling. Add a few drops of phenolphthalein solution.
- Pour the hot agar solution into a Petri dish to a depth of exactly 10 mm. Let it cool and set solid. Placing graph paper underneath the Petri dish, or drawing a grid on the base of the dish, helps students cut the edges of the cubes at right angles. They then need to use a ruler to ensure that all dimensions of their cubes are equal. Forceps are advised for holding cubes if further trimming is needed.
- Use 0.1 mol dm^{-3} HCl for soaking the cubes.

A 10 mm cube takes about 22 minutes to decolourise using these concentrations.

the manipulative skills to cut square sides to a cube and some find measuring lengths less than 5 mm difficult. I believe school students should develop the necessary skills to carry out this aspect of the activity successfully, but they will need practice. A number of steps can be taken to simplify this part of the activity (see Table 1).

- Cutting larger cubes is easier but these provide less useful data for this activity. Cubes with sides that are 10 mm long take over 20 minutes to change colour.
- Fixing the endpoint of a colour change is easier if the block is initially coloured and becomes colourless. (When does the last spot of colour disappear?) I have found pink blocks containing an alkali and phenolphthalein that are immersed in acid provide the best results. I have one reported case of a student stating that the colour 'leaches' out of the blocks when they are immersed in a solution, so students do need to be reminded of the reaction of indicators to changing pH, before the agar blocks are immersed in acid, if they are to make sense of this activity.
- Pupils often think that the accuracy of timing the endpoint for the colour change is more important than the cutting and measurement of the agar blocks, although it has less impact on the outcomes of the investigation. Teaching about the relative importance of different sources of error in this activity may be appropriate. An error of 1 mm when cutting a block intended to measure 5 mm × 5 mm × 5 mm is multiplied when calculating the volume and area of the block and consequently has a significant influence on the results obtained.
- Calculating surface area, volume and surface area : volume ratios can be challenging for some individuals. The challenge can be reduced by insisting that measurements are made in millimetres rather than centimetres, by providing appropriate formulae and by counting how many surfaces there are on a cube. I use a spreadsheet template containing

Diffusion into different-sized blocks



Length of side of block (mm)	Volume of block (mm^3)	Area of block (mm^2)	surface area : volume ratio (mm^{-1})	Time taken for complete diffusion, or estimate of time (s)

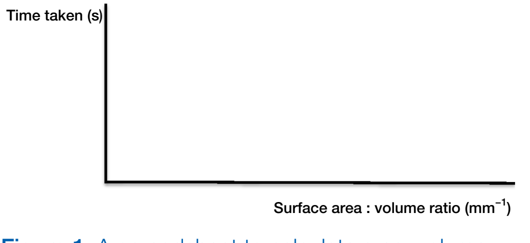


Figure 1 A spreadsheet to calculate area, volume and surface area : volume ratio when users input the length in column 1; columns 2, 3 and 4 contain the necessary formulae

the relevant formulae when doing this activity with pupils (see Figure 1). Teachers of mathematics assure me that students will be familiar with the necessary calculations but they may not previously have used them together in a single context.

- When plotting graphs of time taken against surface area : volume ratio, the ratio needs to be expressed as a single figure so that that it can be plotted on one axis of the graph. This step is not familiar to many people, but it is only a division of one figure by the other.

Relating the findings in the activity to 'real life' situations

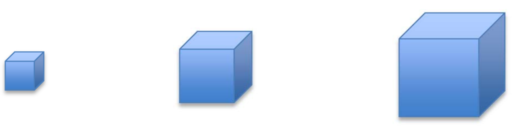
Many children only encounter human and plant cell types as two-dimensional images. They can struggle to understand that in fact cells are three-dimensional and so have volume. All cells are microscopic and children have a poorly developed sense of scale at the microscopic 'end of the spectrum'. It is difficult to relate the size of a red blood cell to the size of a palisade leaf cell when images in texts are often drawn to different scales. Figure 2 is an example of a sheet used to support discussion around some of these learning challenges.

What type of practical activity?

The ASE *Getting Practical* project (Millar and Abrahams, 2009) identified three learning objectives of practical work:

- to help students develop their knowledge of a scientific idea;
- to help students learn how to carry out a procedure;
- to help students develop an understanding of scientific enquiry.

Surface area to volume ratio calculator



Length of side (mm)	Surface area of one side (mm^2)	Surface area of cube (mm^2)	Volume of cube (mm^3)	Surface area : volume ratio (mm^{-1})
1	1	6	1	6.00
2	4	24	8	3.00
3	9	54	27	2.00
4	16	96	64	1.50
5	25	150	125	1.20
6	36	216	216	1.00
7	49	294	343	0.86
8	64	384	512	0.75
9	81	486	729	0.67
10	100	600	1000	0.60

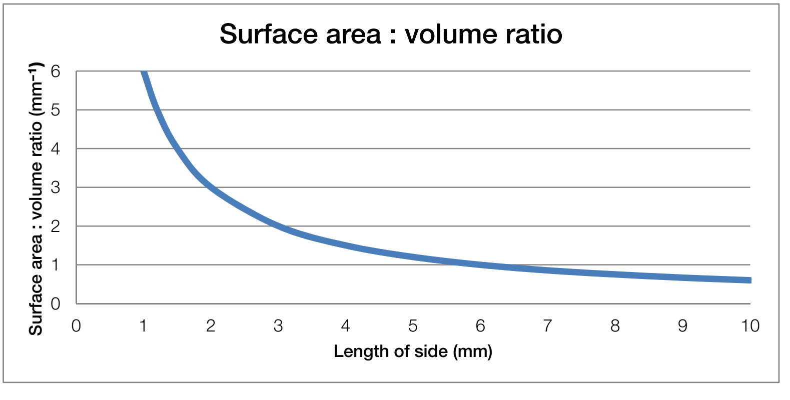


Figure 2 A spreadsheet used to support discussion around the relationship between size and surface area : volume ratio

Table 1 Breakdown of the activity into different aspects

Stage of the activity	Learning opportunity	Challenge to learners	Ways to reduce learning demand
Preparing different-sized blocks of agar	• cutting and measuring precisely • safe handling of sharp apparatus	• cutting blocks squarely • measuring blocks accurately	• provide pre-cut blocks • provide agar poured to a specified depth • provide a sheet of laminated graph paper as a cutting surface
Calculating surface area Calculating volume Calculating surface area : volume ratio	• application of mathematical formulae to a scientific context	• applying the correct formula • carrying out calculations	• prepare a spreadsheet with embedded formulae to calculate surface area and volume
Plotting a graph of surface area : volume ratio against length of side	• deciding on appropriate scale and orientation of graph • interpreting a complex graph • consideration of quality and quantity of data	• graph construction and fit of line	• provide prepared axes • provide spreadsheet template
Plotting graph of surface area : volume ratio against time taken for complete colour change	• deciding on appropriate scale and orientation of graph • interpreting a complex graph • consideration of quality and quantity of data	• understanding relative importance of sources of error when collecting data	• time lapse video recording of blocks soaking in acid next to stop clock
Applying the surface area : volume ratio model to living systems	• exploration of human and plant cell types	• many cells appear not to fit a surface area : volume ratio model; this requires students to have a clear understanding of cell roles and modifications	• illustrations of cell types with scale and functions • discuss gas exchange in mammals and plants and relate to the surface area : volume ratio model

A key message of the project is that to be effective it is helpful to clarify the learning objectives of the activity, in planning and in execution. Focusing on a single learning objective may be more successful than using one activity to promote learning in all three. However, in this specific practical activity, all three learning objectives are involved. It is possible to reduce the impact of one or more aspects of the activity as suggested in Table 1.

Other suggestions for improving learning

The previous section identified the complex nature of the activity. Removing some aspects of the activity can reduce the level of challenge for learners but there still remains the problem of making sense of what has been found out.

If students successfully measure time taken for cubes to change colour, and can draw a graph of the relationship between time taken and surface area : volume ratio, then they have been successful in making the intended observations. The next step is to make sense of these observations in terms of the intended learning outcomes. It is here that the real challenge to teachers arises – how to help students make links between their observations and the ideas that explain them.

At each stage of the activity it is important to help students to link what they are doing to previous knowledge, to be clear that they understand what they should have observed, and to understand how this builds into the bigger picture (the learning outcomes). As already noted, some students may not understand the role of colour change in the agar cubes. It can help to remind them of reactions between indicators and acids before they carry out this part of the activity. This allows them to focus their attention on explanations of why the colour change took different times in different-sized cubes, and then to clarify the implications of their observations in terms of size of cube and movement of solutes in living systems.

If this process of engaging students' thinking is carried out at different stages in the activity, there are considerable implications for planning and timing.

Summary

This particular example of a practical activity that is specified as part of the criteria for GCSE science is complex and challenging:

- it contains multiple aspects and each of these must be completed successfully to achieve the learning outcomes;
- it involves mathematical challenge;
- the outcome is counterintuitive (something has a larger ratio value if it is smaller);
- it uses a model to explain a phenomenon;
- it relates to objects that are not clearly visible.

Other practical activities are equally challenging. As a new National Curriculum in England, new arrangements for GCSE and changes to A-level come into effect, it is time to review the part practical work plays in the curriculum, and to ensure that any practical work included is effective in achieving specific learning outcomes.

Concluding remarks

Practical work has a central role in the curriculum and is viewed as essential for science learning. However, practical work faces several challenges, including how to ensure that it is effective in helping children learn science. More research into the teaching and assessment of practical work is needed, but already projects such as *Getting Practical* are showing the importance of analysis in the planning of activities and supporting a 'hands on, minds on' approach to teaching.

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SCORE (2013b) *Report: Resourcing Practical Science at Secondary Level*. London: SCORE. Available at: www.score-education.org/media/11805/score%20resourcing%20secondary.pdf.

Websites and support resources

Association for Science Education (ASE): www.ase.org.uk.

Centre of the Cell: www.centreofthecell.org/centre/index.php?page_id=28&ks=4.

Council for Science and Technology: www.gov.uk/government/organisations/council-for-science-and-technology.

Getting Practical: www.ase.org.uk/professional-development/getting-practical.

Practical Biology: www.nuffieldfoundation.org/practical-biology.

Science Community Representing Education (SCORE): www.score-education.org.

Science Learning Centres: www.sciencelearningcentres.org.uk.

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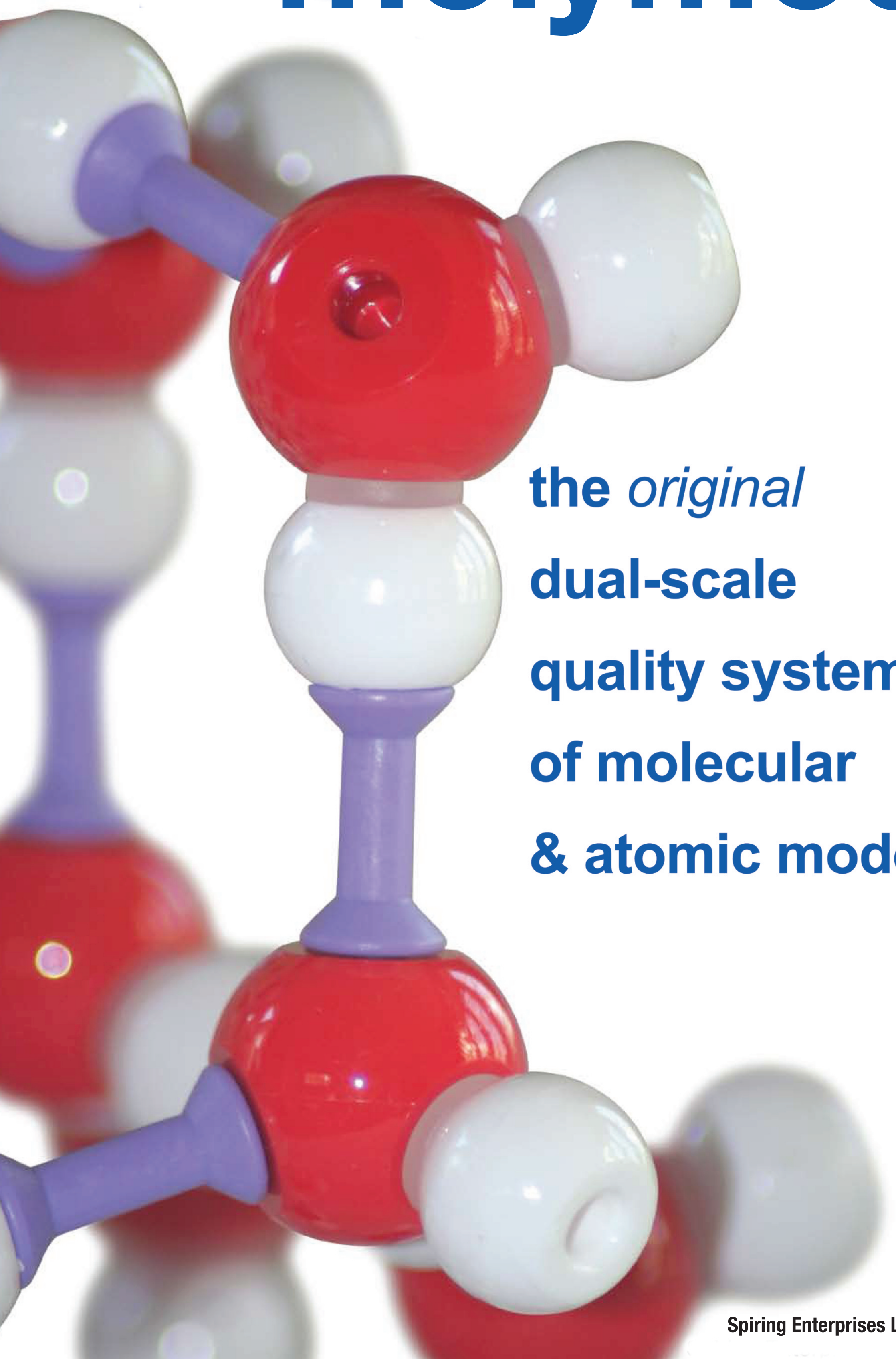

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