3D science – theoretical model or potential classroom reality?

PRICE, Gareth and BEVINS, Stuart <http://orcid.org/0000-0001-7139-1529>

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■ Gareth Price ■ Stuart Bevins

Abstract

This article offers an outline of 3D science that conceptualises science around three dimensions: domain knowledge, evidence-management procedures and psychological energy. We propose that this model could underpin a rigorous, effective and motivating approach to science education in schools. We show how self-determination theory offers useful insights into motivation in 3D science and discuss the benefits of this for teachers and students. As proof of concept we sketch out clear assessment objectives for a 3D-compliant science course and develop outline assessment criteria to show the possibility for progression.

Science is critical to human survival. It drives human development and provides for longer, safer, healthier lives. Science also explores some of the giant questions about the nature of the universe, its formation and, potentially, its collapse. Science is creative, collaborative and has a significant cultural impact.

Given science's importance it is perhaps surprising that science education in schools is not yet 200 years old and, as recently as 50 years ago, one in five girls in England did not study science beyond the age of 14. That changed with the introduction of the National Curriculum in 1988, which mandated that 20% of a student's timetable should be science. Since then there has been much heat, and some light, on what science education schools should provide, from three separate sciences, through broad and balanced double and single awards, to alternative qualifications based around GNVQs, BTECs and now T-levels.

The arguments about the nature of science and the best way to teach science have a history as long as science education itself. They typically crystallise around the debate on whether science is a process involving the strategic application of certain skills (hypothesising, observing, analysing data, etc.) or a body of knowledge (the facts and theories like photosynthesis, electropositivity or Newton's laws) (Barrow, 2006). We have discussed this dichotomy before (Bevins & Price, 2016) and have rejected both sides as inadequate, since they ignore the human presence of the scientist in science. We also suggest that detailed arguments about how much support is optimal for developing this knowledge or skills package (Kirshner, Sweller & Clark, 2006; Hmelo-Silver, Duncan & Chinn, 2007) miss the central point: science is more than a collection of facts and skills to be mastered. We suggest that including the human being as an active component of science would produce a more useful way forward and we have developed 3D science to formalise this insight.

3D science

Describing the theoretical basis for 3D science is beyond the scope of this article and is discussed in detail elsewhere (Bevins & Price, 2016), but we provide a summary here to aid discussion.
3D science conceptualises scientific activity as containing three related dimensions. These dimensions are:

- **D1 A body of knowledge**: informs scientists' thinking about phenomena and can generate questions and suggestions for inquiry.
- **D2 Evidence-management procedures**: ensures evidence is generated reliably, interpreted with reference to the underlying ideas and the observed data, and communicated appropriately.
- **D3 Psychological energy**: provides the energy to create and manage a scientific inquiry.

The three dimensions above have different natures, although they influence each other. D1 includes theories that are clearly recognised as 'science' (e.g. evolution or relativity) and a collection of facts

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(e.g. refractive index of crown glass or the structure of chlorophyll) normally associated with the discipline. A listing of the entire contents of this dimension is not possible given constant increases in, and continuous revision of, accepted 'scientific knowledge'.

D2 includes a range of skills and procedures, from simple mechanical ones (e.g. measuring the temperature of a body of water with an electronic probe) to more cognitively complex procedures (e.g. identifying and controlling variables, analysing data and hypothesis generation) that comprise the scientific method. Communication and networking skills relevant to the practice of science would also appear in D2, although they may be functionally identical to networking and communication skills used by a range of other subjects defined, in turn, by their particular D1 content and D2 procedures.

D3 describes where the motivation and the energy for scientific activity originates. This is where the 'scientist' appears in the 3D science model: to convert the lists of contents (D1) and the skills (D2) into a purposeful, engaging and personally relevant scientific inquiry. The 3D science model sees scientific inquiry as a temporary, purposeful activity built from relevant D1 knowledge and useful D2 procedures, driven along by the psychological energy generated by D3. This inquiry can create new insights or ideas that can then be integrated into D1.

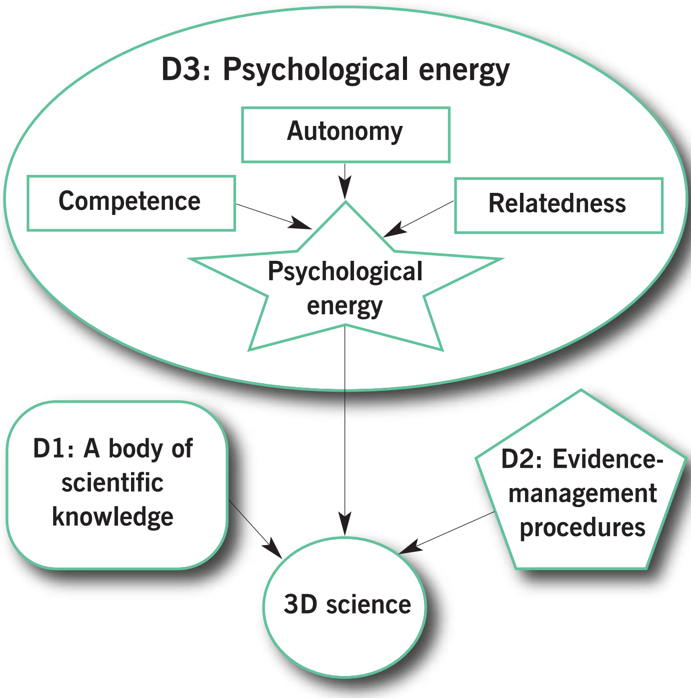

Figure 1. The 3D science model.

From theoretical model to classroom practice

Given the arguments about science education, adding yet another possible model to the discussion seems, at best, presumptive and, possibly, disruptive. However, we argue that the 3D science model offers some unique advantages to curriculum developers and course builders.

Any proposed model should be both valid, within the constraints of existing literature and evidence, and useful. Evidence to support the validity of the 3D science model will be published later this year – it includes observations of scientific activity and conversations with practising scientists and science educators. To assess the usefulness of 3D science we ask the following questions:

- Is it able to accommodate existing approaches without damage to the existing models or 3D science?
- Does it offer ways to improve motivation to study science and pursue scientific careers?
- Does it allow the development of improved curricula?

If the answer to these questions is 'yes', then the usefulness of the model has been demonstrated. The first two questions are theoretical issues, with the third revolving around classroom implementation.

3D science and backwards compatibility

The 3D science model requires that all science content belongs to a dimension (in the case of D1 they must be recognisable scientific theories) but the dimensions do not specify examples. D1 leaves open the discussion about exactly which theories should be included – D1 is effectively 'content agnostic' and can accommodate existing schemes. D2 is defined as the essential skills required to conduct scientific activity. Within this you will find a version of the 'scientific method' (Windschitl, Thompson & Braaten, 2008) and other useful or relevant skills. The particular skills included and exactly how they are described is not prescribed by the model itself. Again, D2 meets the needs of current curricula. Few, if any, existing curricula or models make explicit mention of what we call D3. This means that existing curricula can fit comfortably within the constraints imposed by 3D science.

3D science and motivation

Would a 3D-compliant curriculum be a restatement and repackaging of existing material? Does the 3D science model bring any new insights or suggestions? D3 is the key innovation and requires further discussion. Self-determination theory (SDT) (Deci & Ryan, 2008) is a useful way of looking at D3.

SDT has been used extensively to explore motivation. In education, motivation is often discussed in the context of encouraging students to engage with work that might not otherwise interest them. SDT considers motivation more widely as the force that drives any activity and supports the development of a healthy self (Lavigne, Vallerand & Miquelon, 2007). A detailed discussion of SDT can be found elsewhere (Deci & Ryan, 2012) but the insight into motivation as a driving factor for self-development supports D3.

SDT recognises a number of classes of motivation including intrinsic motivation, various types of extrinsic motivation, reward and punishment. See Table 1 for a brief overview.

Intrinsic motivation, or extrinsic motivation that is integrated or identified, tends to produce much greater commitment to a task than other forms of extrinsic motivation. This is particularly important when dealing with complex, high-level tasks requiring creativity and insight. It is not difficult to appreciate that scientists depend on this form of motivation to provide the energy to drive their thinking.

To generate this intrinsic motivation, SDT identifies three basic psychological needs:

- autonomy;
- a sense of competence; and
- relatedness to significant others.

Where these three needs are met, intrinsic motivation can develop, but where they are

Intrinsic motivation	Extrinsic motivation			
	Integrated	Identified	Introjected	External
The task is completed because it is seen as worth doing for its own sake.	The task is completed because it fits in with longer term, personal life goals. For example, studying science to become a doctor to help sick people.	The task is completed because the student can see the purpose of it. For example, studying science to make a career as a doctor possible.	The task is completed because it seems to be the 'right thing to do'. For example, a student attends a science class because otherwise they will feel guilty.	The task is completed to gain external rewards or avoid censure. For example, 'if you do not pass this examination you will not be able to graduate'.

Table 1: Intrinsic and extrinsic motivation.

thwarted, motivation is reduced or converted from the most useful intrinsic motivation into the less productive extrinsic motivation (Vansteenkiste *et al*, 2018).

Traditionally, teachers aim to motivate their students by seeking to make their work ‘interesting’. They demonstrate their own personal enthusiasm for a particular topic, use real-world contexts and promote a sense of relevance in the material. A range of meta-analyses (Minner, Levy & Century, 2010; Schroeder *et al*, 2007; Schwichow *et al*, 2016) have shown that emphasising the real-world context of science and allowing collaborative working increases motivation and improves performance. While work that is boring is inherently less motivating, words like ‘interesting’ and ‘boring’ conceal as much as they reveal. What is boring to a teacher may not be boring to a student.

Alternatively, teachers motivate by adopting a more utilitarian approach, suggesting, for example, ‘do this because it’s sure to come up in your exam’. Unfortunately, research shows that this strategy tends to offer a limited increase in motivation and the less effective form: external motivation.

How can you ‘teach’ students autonomy, competence or relatedness (the essential conditions identified by SDT for the development of intrinsic motivation)? These are not facts and theories or skills and capabilities; they cannot be taught. Maybe they are ‘caught’ by students as they work in classrooms that support student autonomy, allow working in collaborative groups and aim for mastery rather than performative goals of traditional public examinations. Researchers working in SDT have been looking at environments that affect student autonomy and other related D3 factors (Hyungshim, Reeve & Halusic, 2016) and have published excellent advice on these matters. Table 2 shows an example of strategies used with medical students (Kusurkar, Croiset & Ten Cate, 2011).

Table 2. Twelve tips to stimulate intrinsic motivation.

Box 1: Intrinsic motivation

- Identify and nurture what students need and want.
- Have students’ internal states guide their behaviour.
- Encourage active participation.
- Encourage students to accept more responsibility for their learning.
- Provide structured guidance.
- Provide optimal challenges.
- Give positive and constructive feedback.
- Give emotional support.
- Acknowledge students’ expressions of negative effect.
- Communicate value in uninteresting activities.
- Give choices.
- Direct with ‘can, may, could’ instead of ‘must, need, should’.

3D science and the development of new curricula

When we explore approaches to teaching science, we notice that much of it focuses on increasing learners’ knowledge (D1) and practising routines and skills described as scientific method (broad support of D2 but often in the form of over-detailed process scaffolding). Science, as presented by much of science education and most of the learning resources we have seen, appears to be merely the rigorous application of rules to ensure some extrinsic reward in the form of a higher grade. Both teachers and students can appear as operators with limited power, working in a machine designed by others for questionable purposes. How would 3D science be different and could it be different in the current D1-focused climate?

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Developing a new curriculum with supportive teaching, learning strategies and resources is not trivial. It requires input from academics, curriculum developers, practising teachers and, ideally, existing students, contributors from wider society and government.

In an attempt to stimulate this development, we offer two contributions:

- a set of assessment objectives; and
- a criterion-driven assessment model to reveal progression.

Creating assessment objectives

Table 3 converts our theoretical model into a set of assessment objectives for a 3D-compliant course. They have been described as skills but avoid the

D1	D2	D3	Activity area	Students should be able to:
			Managing domain knowledge	Identify and apply scientific domain knowledge relevant to a particular inquiry.
				Find and justify any deficiencies in their scientific domain knowledge and suggest strategies to collect this knowledge.
				Use data from inquiries (practical or theoretical) to develop their scientific understanding and/or apply it in new contexts.
			Initiating inquiries	Design inquiries to generate valid and relevant data showing awareness of the ethical dimensions of the proposed research strategy.
			Carrying out inquiries	Select and use equipment and techniques safely and effectively to generate reliable and relevant data with sufficient scope and scale.
				Reflect on an ongoing inquiry, progress and modify activity, and the activities of others, during it to ensure success of inquiry and maintenance of collaborative group.
			Managing and sharing data and insights	Record and manipulate raw data using mathematical techniques when appropriate. Use appropriate language and conventions to communicate inquiry and conclusions to specified audiences.
			Recognising purpose	Justify actions and strategies with reference to themselves, significant others and the wider world.
			Reflecting on performance	Recognise growth in their skills, understanding and competencies, and identify the activities that have helped to generate these improvements.

Table 3. Assessment objectives for a 3D-compliant science course.

atomistic skills of some schemes (e.g. can use a thermometer, can use mean and standard deviation with simple data sets) in favour of larger more integrated formulations. This is intentional and reflects 3D science's bias towards purposeful synthesis and holistic work. We have also kept the number of objectives as small as possible for ease of use, while still covering all dimensions. We are not suggesting at this stage that certain objectives should be weighted more highly than any others in any final assessment scheme, as is common with GCSE and A-level specifications in the UK.

A model for progression

Table 3 shows how 3D science can generate assessment objectives. A 3D-compliant course should provide opportunities for students to demonstrate proficiency in these areas. While accepting that 'weighing a pig does not fatten it', we accept that an open, manageable and rigorous assessment system would allow students and teachers to track their progress towards mastery of the key objectives.

This assessment system would need to be applied in more demanding circumstances than most of the existing GCSE practical assessments. Scoring pre-built and pre-programmed practical experiences would not allow assessment of certain aspects of 3D science. Since a key objective is that students will 'Design inquiries to generate valid and relevant data showing awareness of the ethical dimensions of the proposed research strategy', the assessment scheme must provide an almost impossible mix of rigour (to produce reliable results) and flexibility (to support student-developed activities). We suggest that a system based on generic assessment criteria, available at key levels, could help teachers and students to apply the system and track their own progress.

Table 4 offers a set of criteria for each assessment objective, at three levels, to demonstrate that progression is possible within each skill and that it can be described objectively. These criteria are provided as proof of concept at this stage and would need to be developed by a wider group with greater experience of this kind of work.

Table 4. Assessment criteria for a 3D-compliant science course.

Assessment objectives	Pass	Merit	Distinction
Identify and apply scientific domain knowledge relevant to a particular inquiry.	Uses simple scientific knowledge, typically supplied by the teacher, but fails to apply this consistently.	Identifies and applies relevant scientific knowledge from a list, sometimes supplied by the teacher in obvious contexts consistently.	Self-selects scientific knowledge across a range of topics and applies these in non-obvious and novel ways.
Find and justify any deficiencies in their scientific domain knowledge and suggest strategies to collect this knowledge.	Identifies obvious gaps in knowledge when supported but cannot always suggest ways to fill them.	Identifies relevant gaps in their knowledge and their significance for the activity. Suggests simple strategies to fill any gaps.	Identifies specific knowledge requirements related to the inquiry, explaining why it is significant, and suggests a well-formulated strategy to find this knowledge.

Table 4 cont. Assessment criteria for a 3D-compliant science course.

Assessment objectives	Pass	Merit	Distinction
Use data from inquiries (practical or theoretical) to develop their scientific understanding and/or apply it in new contexts.	Summarises results relevant to the specific inquiry but can fail to develop new domain understanding or apply it without help.	Generates new understanding linked to the specific inquiry. Justifies this new understanding in terms of the data produced by the inquiry.	Draws new insights and understanding from inquiry, abstracting these to other areas. Justifies all conclusions clearly and suggests areas for further exploration based on new understanding.
Design inquiries to generate valid and relevant data showing awareness of the ethical dimensions of the proposed research strategy.	Designs simple fair tests typically using qualitative values in simple contexts, often with teacher support. Considers the ethical dimension, usually when directed to by the teacher.	Designs inquiries relevant to the problem identified and focusing on simple variables (qualitative and quantitative) with confidence. Considers the ethical implications of the inquiry outcome for a single stakeholder.	Designs complex inquiries, potentially using quantitative variables, proxy variables and controls. Justifies how these develop understanding of the relevant issue. Considers ethical implications for the study and results for a range of stakeholders, suggesting sensible modifications.
Select and use equipment and techniques safely and effectively to generate reliable and relevant data with sufficient scope and scale.	Follows instructions for basic laboratory work. Produces data but they sometimes lack accuracy and/or essential steps (e.g. calibrating or zeroing instruments). Range and quantity of data points sometimes limited.	Consistently follows instructions showing good practical technique. Produces accurate data but sometimes the range and quantity of data points can be limited.	Implements instructions with understanding to produce safe, effective laboratory work with good technique. Modifies procedures when required.Produces accurate data consistently at an appropriate level of precision. Data have a good range and a sufficient number of data points.

Table 4 cont. Assessment criteria for a 3D-compliant science course.

Assessment objectives	Pass	Merit	Distinction
Reflect on an ongoing inquiry, progress and modify activity, and the activities of others, during it to ensure success of inquiry and maintenance of collaborative group.	Follows instructions without reflecting on the problems that might arise. Is prone to explain surprising results as a 'failure'. Tends to work without reference to others, not engaging in team discussions. Takes limited responsibility for task management beyond their own component.	Responds to unexpected changes and will modify the method as required (particularly when prompted). Initially agrees with other team members their relevant tasks but then tends to work in isolation with a clear focus on personal rather than team performance.	Reflects on the process and takes well-assessed risks to drive the inquiry forward by modifying methods or re-casting the inquiry to match insights generated by the process. Agrees tasks with other team members and checks regularly on progress – including offering an account of their own progress. Offers help to other team members as appropriate.
Record and manipulate raw data using mathematical techniques when appropriate. Use appropriate language and conventions to communicate inquiry and conclusions to specified audiences.	Data are collected but can be disorganised and some may be lost during process. Describes data using simple qualitative terms (e.g. bigger, hotter). Uses simple, single-step techniques (e.g. sum, mean) to summarise quantitative data when instructed. The experimental account, possibly incomplete, has limited technical language and poor compliance with established norms.	Data recorded appropriately in easy-to-process table or chart. Uses a range of mathematical techniques when prompted. A complete account of the procedure and results is provided with some scientific language used (particularly when prompted).	Selects and uses accurately, a range of multi-step techniques to summarise data, justifying choices in terms of eventual use of data set. Correct scientific terminology is routinely used without teacher prompting and in a way that demonstrates the limitations of the terms.

Table 4 cont. Assessment criteria for a 3D-compliant science course.

Assessment objectives	Pass	Merit	Distinction
Justify actions and strategies with reference to themselves, significant others and the wider world.	Explains reasons for pursuing a task purely in terms of 'interest' or to avoid censure. Offers limited justification beyond immediate context.	Explains reasons for pursuing a task as a long-term strategy to achieve significant life goals. These goals often couched in personal terms (e.g. to be a vet, to be a better soccer player).	Takes responsibility for decisions and justifies actions in terms of their personal values. Recognises and describes ethical issues in both technical ('this is contravened by ethical guidelines') and personal ('I think this is unfair') terms.
Recognise growth in their skills, understanding and competencies, and identify the activities that have helped to generate these improvements.	Recognises progress but the reason for these improvements often couched in general terms like 'working harder' or 'the topic was more interesting' with no specific examples.	Recognises growth in specific knowledge or skills but does not abstract these insights into a greater personal confidence. Can identify activities, and particular aspects of these, that they like and where they worked harder.	Recognises growth in terms of increased knowledge and understanding, relevant skills and greater appreciation of the social and economic context of the inquiry. Identifies processes that have driven these improvements and optimises approach for future activities, showing growth in personal confidence.

Next steps

The 3D science model uniquely involves the scientist and recognises that motivation and psychological energy are a part of science rather than bolt-on conditions to be fulfilled before students will engage with the science on offer in their lessons. We have found in conversations with practising scientists and science educators at the highest levels that the presence of D3 is clear and valued in their experience, which further convinces us of the validity of 3D science. Consequently, we are starting to explore how this theoretical model could be converted into a new classroom experience for our science students. We claim that 3D science can accommodate existing course demands in terms of domain knowledge and skills, although we would expect extra skills to be added to reflect D3.

We have also produced assessment objectives and assessment criteria for a proposed 3D science course and offer these as proof of concept for

discussion and development by others. They build our confidence that it is possible to go from the original theoretical model to a practical, recognisable science course for schools.

We propose that there needs to be further exploration of teaching and learning strategies that recognise the importance of, and promote, the development of D3. We should also stress that we are not seeking to reject 'interesting' topics in pursuit of 'boring' ones or to remove useful, open scaffolding in pursuit of autonomy. We anticipate that students will always struggle with science that they personally find boring and that structure can be useful as a bridge to more open, self-directed studies. We are seeking to bring a sense of D3 to the best of existing approaches and see how this would work out for teachers and learners in science classes. This is a long-term aim and we accept it is not a trivial task. Teachers regularly report the pressures on them to deliver large amounts of material in a limited time and that this prevents them doing investigative work (Bevins, Price & Booth, 2019). If the pressure to deliver an over-burdened curriculum already generates tension about the time needed to teach content (D1) and develop skills (D2), is the suggestion that we also allocate time for D3 another unwanted burden? If we are to help students to develop into citizens with a good understanding of science and an appreciation of its importance in decisions, both in wider society and in the research labs of professional scientists, we have to accept that D3 is not a desirable extra but an essential requirement.

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Gareth Price and **Stuart Bevins** are based in the Sheffield Institute of Education at Sheffield Hallam University.
E-mail: gareth2210@mac.com

This article first appeared in issue 380 of School Science Review.