Models, matter and truth in doing and learning science

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ABSTRACT Doing science involves the development and evaluation of models. These models are not objective truths but can be understood as explanations, which scientists use to explore and reason about an aspect of the world. Learning science involves students expressing and engaging with models in the classroom. However, this learning should not be seen as the growth of subjective understanding towards a correct scientific view. Students, like scientists, use myriad models to consider and explain the world. In this article, I will argue that recognising the role of models in both doing and learning science compels teachers to focus on the models that emerge in their classrooms.

In this article I will argue that models are integral to both doing and learning science but they can also be a source of confusion to students. Models emerge within specific contexts as scientists, students and teachers seek to explain phenomena in the world (and broader universe). It is through these models that scientists and students reason about the world.

To build this argument, I will firstly consider how scientists use models and, in so doing, suggest that models can be usefully framed as forms of explanation. This gives us a position from which to explore the relationship between scientific models and the phenomena they model. When it comes to learning science however, students encounter the models that are used by scientists but they also engage with words, gestures, pictures, videos, animations, physical models and symbolic representations. These are all models in themselves, which represent and explain aspects of the phenomenon being taught. The models that scientists use and the models through which students learn are connected: they are all explanations of the world, each embedded within the intentions and contexts of those who developed them. Through recognising this, I believe that teachers can frame science as a way of explaining the world that draws on empirical evidence but which is also bound to social processes and material context.

To develop this suggestion I will first of all consider how science itself relates models to the truth of the world. I will then consider how students learn science through the modelling that they encounter in the classroom.

Models and forms of truth

After 10 years of working with new science teachers, I am still struck by how many of them portray their scientific careers as a series of stages in which they found out that everything they had been told previously was wrong. A chemist might relate how, at the age of 14, they realised the world wasn't made up of particles and, at the age of 17, they were told that the idea of electrons in circular orbits is wrong. For every student that does pursue further study in science, there must be countless others who are put off by being treated like children who cannot yet understand 'real science'.

This view of learning science as slowly being told the truth is linked to the view that scientific models provide a true picture of the world 'as it is'. This caricature of science is embedded within our culture and, as with all caricatures, is an exaggeration of key features. The vast majority of scientists are *realists*, in that they believe that the universe exists independently of our observing it. However, *scientific realism* further attributes a relationship between the explanations developed by science and the world 'as it is'. A 'strong' view of realism is that models are very close to the reality of the world. This does not mean that someone advocating strong realism necessarily considers science to be infallible; it could be that explanations need revision or further detail. A 'weak' view of realism, though, is that models are developed for a specific purpose and that they represent reality only so far as they are useful.

As Bridges (1999) suggests, empirical science draws heavily on a correspondence version of truth: a criterion for accepting a scientific explanation is how well an explanation is structurally similar to the phenomenon in question. A strong realist position would be that this should be the main criterion for a model, that it is as close as possible to the phenomenon itself. Such a strong position might well lead to students seeing schooling as the progression of different models, each 'more true' than the other. However, strong realism is much critiqued in recent philosophy of science and is difficult to accept in the context of contemporary scientific practice.

Even if we take correspondence to the natural world as a key criterion for scientific models, we cannot see this as a one-way street from empirical evidence to explanation. Astronomer Royal, Frank Dyson, used Einstein's theory of relativity to model how light is bent by the Sun, which allowed Arthur Eddington to measure the position of stars in a solar eclipse of 1919. More recently, the $13 billion spent on finding the Higgs boson and the $620 million upgrade to the LIGO machine to detect gravitational waves have been bets placed (and thankfully won) on the assumption that models are generative in predicting and explaining things of which we have yet to see evidence. Kaldis (2013: 662) suggests that scientists perform 'surrogative reasoning' with models. That is, they infer things about a phenomenon based on manipulation and investigation of models, rather than the phenomenon itself. This accounts for how models explain features and processes about which we have yet to gather evidence.

Models, therefore, both explain and predict. However, this does not fully diminish the criteria of correspondence: if a model is closer to the phenomenon being modelled, then surely it will explain and/or predict more? In order to counter this view, I find it useful to draw on the growing interest in complex systems. Complex systems are characterised by their sensitivity to the minutiae of elements within them. The famous conjecture here is that the flapping of the wings of a butterfly may affect the formation of a storm on the other side of the world. Whether considering weather, earthquakes, ecosystems or social groups, a small difference may (or may not) have a big influence on the system. These systems pose a particular challenge to how we frame models, as the omission of even the slightest detail means that a model will potentially develop in a very different way to the modelled phenomenon. Complexity theory shows us that it does not make sense to talk of models that are 'more complex' being closer to reality. Whether complex systems are modelled through statistical relationships, network models or sophisticated agent-based models, there remains the issue that all models are reductions. This is not to say that resemblance to the phenomenon being investigated is not important but it does undermine discussion about making models 'more accurate'.

Scientists use models to reason, explain and predict but, when they are looking at how well a model reproduces the phenomenon being modelled, they are often focusing on a particular feature or aspect of that phenomenon. We might say that a photograph gives us a more accurate image of a landscape than a drawing, but a schematic map is likely to be of more use for orienteering. The judgement that takes place is actually about how well the model explains an aspect of the world, for a particular purpose, and this judgement is bound within the social processes of making models.

To develop this, we will consider an example: Hill *et al*. (2011) developed an agent-based model of the decision-making within a baboon population, with reference to empirical data on a troop of chacma baboons. By modelling range size, daily travel, energy and time budgets, Hill *et al*. describe how computational actors move within a grid of resources, after 'voting' whether they should move on. Research on primate behaviour, cognitive processes and social structures was employed and the model was run with a range of starting conditions to assess the influence of the model variables on the way in which the computer baboons behaved. The conclusion in the chapter by Hill *et al*. discusses how the coarse way in which the environment is presented, the sampling approach within the empirical data and difficulties in knowing how decisions are actually made led to the disparities found between the empirical data and modelling output. So, what is the model for and how might it be judged? There is certainly an aspect of the model being developed in order to refine modelling processes, forming the motivation for the involvement of a computer scientist. The authors also argue that the model adds to a 'growing body of evidence' about how decisions are made in primate societies, but there are no stronger arguments presented for what is actually learned about baboon behaviour, despite two of the authors being a biologist and an anthropologist. As Kohler (2000) suggests, models of this type are 'generative', in that they provide possible mechanisms for the phenomenon we see. So the way that baboons make decisions in the model of Hill *et al*. was tested as a hypothesis in that it did not produce the behaviour seen in baboon life. Here, we can see that models are useful for both developing and testing hypotheses, but their construction also helps in developing the tools for further modelling. Evaluating models therefore is not just about correspondence; models are not ways of getting to the universe 'as it is'.

As well as correspondence versions of truth, Bridges (1999) discusses coherence forms of truth, pragmatic forms of truth, consensus forms of truth and warranted belief: how well an explanation holds up to critical interrogation. All of these are relevant to how models are evaluated within scientific practice. Many scientific models are created that bear no relation to real phenomena at all, and this could be for a number of reasons: to teach others; to develop a method or approach; to make a theoretical point; to find a way of working; to attract a particular kind of funding; simply because the researchers are interested; and a whole host of other reasons. Within this, models are evaluated according to how well they fit existing understanding (coherence, consensus), how useful they are for particular purposes (pragmatic) or how far they can be justified to others (warranted belief), but also in terms of aesthetics (how 'elegant' the model is) or power relations (whether a renowned professor or a new student is proposing it). Correspondence is only one element of the criteria that scientists use to evaluate models and I will go so far as to suggest that the form of realism employed by much of science is very weak indeed. Models themselves form the focus of many scientists' attention, rather than the phenomenon being modelled.

Models as explanations in the classroom

If we wish to present an authentic view of science in the science classroom, then we cannot let students believe that science is the progression of increasingly accurate models, approaching the truth of the world. However, it may not be wise to fully expose young scientists to what Feyerabend (1975) calls the 'anarchy' of scientific method: scientists use whatever methods they need to advance science. As is evident from much of this edition of the journal, it falls to the teacher to decide how they will develop an understanding of the nature of science with their classes. Nevertheless, I suggest that we need to present a clear view of what science is and, given the prominence of models, this might be achieved by framing models as explanations. This suggestion draws on the work of a broad group of researchers who have been working on the presentation and use of models within science classrooms for over 30 years.

In framing models, Gilbert, Boulter and Rutherford (2000) helpfully delineate five different forms of explanation:

1. *Intentional* explanation. For example, in identifying the mode of operation of the AIDS virus with the intention of enabling prevention and cure.
2. *Descriptive* explanation. This is where measurements of a phenomenon are presented; for example, in considering variation in height between members of a class.
3. *Interpretive* explanation. Here we consider what a phenomenon is composed of; much of chemistry consists of these abstractions.
4. *Causal* explanation. A description of why a phenomenon behaves as it does; for example, why there is variation in the heights of class members.
5. *Predictive* explanation. Considering how the phenomenon will behave under specified conditions.

Models are thus simplified representations of phenomena that scientists use to explain, predict and reason about aspects of the world. This characterisation is still a rather idealised form of the nature of science and a cynic may claim that models are sometimes developed to attract funding, or to develop the tools of modelling itself. However, these might be seen as forms of 'intentional explanation', or a teacher might discuss the 'how science should be' vs 'how it is'.

What is also required, though, is an account of how models develop over time. Gilbert, Boulter and Elmer (2000) specify terms that are helpful here. They label *expressed* models as those representations placed within the public domain by an individual or group. Different social groups may then agree that a model is of value, at which point it may be labelled as a *consensus* model. If such a model is tested experimentally, peer reviewed and accepted by scientists, it may then become a *scientific* model. The exact nature of how scientific models develop and become replaced (thus becoming *historic* models) is contested within the philosophy and history of science. Nevertheless, clarifying the relationship between expressed, consensus and scientific models goes some way to providing a coherent account of the social and scientific processes involved in using models.

In my own practice, I have also found it useful to make a distinction between a model and a theory (you may have noticed above my claim that Dawson developed a 'model' based on Einstein's 'theory' of relativity). This is not something that scientists themselves provide a clear distinction between, with many using the terms interchangeably. However, I have found a distinction from mathematical *model theory* to be of assistance:

> *A theory admits a variety of models. The theory is not a theory of any one model in particular, but theorises an aspect of anything that happens to be a model for the theory.* (Holdsworth, 2006: 146)

That is, a model provides a description of a particular phenomenon, and multiple models support and develop a theory. For example, a particle model of matter provides us with an explanation of how a solid turns into a liquid when heated. A different particle model of matter can explain the relationship between pressure, volume and temperature in a gas. These might be seen as fitting particle theory. When we move on to explaining rates of reaction and surface area, then we may develop a model of interactions between particles to explain this. This framing goes some way to invoking the role of coherence and consensus in scientific modelling also: a model is informed by established theory at the time it is developed.

Drawing on the work of John Gilbert and colleagues, I have here presented models as explanations that serve specific purposes, and have claimed that those models gather evidence and support within communities of scientists as they are tested and discussed. This is undoubtedly a simplified account of the messy and often incoherent ways in which models are used by scientists. However, such a framing provides a coherent view of models, while still allowing for discussion of the multifaceted questions that models are developed to answer, and the social influences that affect communities of scientists. This allows the teacher to gauge just how much messiness to introduce into the discussion, and when!

Modelling-based teaching

So far I have presented a case for framing models as explanations and suggested that this links professional science and the science in classrooms. In many ways, though, teachers have a much more difficult job than scientists when it comes to models. Teachers engage with a huge variety of models every day and are concerned not just with how models relate to the phenomena being discussed but also how students will learn from those models.

Something as seemingly simple as introducing the heart may involve a plethora of models of different types (Boulter and Buckley, 2000): we might show a plastic heart (concrete representation), draw a diagram (visual), show a heart monitor display (mathematical), clench our fist and place it near our chest (gestural), or describe the heart as two pumps (verbal). What is more, these models might be static or dynamic, and often involve mixed modes of representation: for example, an animation with labels and commentary. Students learn from these models but they learn about both the consensus view of scientific understanding and the relation of models to scientific practice. Sadly, the latter is often ignored, despite being an important part of the curriculum

In England and Wales, the National Strategy Framework for Teaching Science (Department for Education and Skills, 2002) advocated 11- to 14-year-olds engaging with, developing and critically evaluating models in relation to different phenomena. In the 2007 version of the curriculum, this translated into models being a key part of the 'how science works' agenda, with progression through levels clearly mapped to the capacity of students to use, develop and critique models within explanations. We now know that the labelling of students as particular 'levels' often restricted their progress but, nevertheless, the development of modelling has been a key part of science curricula for some time. The latest National Curriculum for 11- to 14-year-olds in England (Department for Education, 2013: 3) states that students should '*use modelling and abstract ideas to develop and evaluate explanations*'. It goes on to explicitly mention models of pressure, chromosomes, DNA, the particle model, atomic model and light rays. It may surprise teachers in England to know that those who designed the latest curriculum intended the list of content to provide space for teachers to support the broader development of students' subject understandings (see Tim Oates talking about this: http://bit.ly/1xj893h). In most schools, this has simply not come to pass, with schemes of work focusing on content being delivered, rather than an understanding of the skills, processes and nature of science. Poor communication around the latest curriculum, pressures around tests for 16-year-olds (often leading to key stage 3 being compressed) and a lack of understanding in this area mean that students are simply not engaging with models explicitly, as an integral part of science education.

Gilbert and Justi (2016) have recently brought together decades of research in this area to outline and support an approach to 'modelling-based teaching'. Here I will draw on and develop one of their examples (Gilbert and Justi, 2016: 72–74) in order to exemplify an approach to engaging students with models, and also to explore how students learn through models. The creation, expression, testing and evaluation of a model does not take place in a simple and linear way, so the stages below should not be seen as prescription that ignores the constant interaction between thought, the expressed model and evaluation of it in relation to particular aims. To aid the reader, I will present the possible stages of engaging with a model:

- Firstly, students might research or conduct an experiment to understand a phenomenon: for example, the evaporation of water from a saltwater solution. The first stage of a modelling approach might be to pose a particular aim for a model, such as producing a model of the salt after evaporation. Gilbert and Justi say that students use their existing understanding to pose a mental *proto-model* through engaging their current understanding, information and experiences, in relation to the aims of the model. They may use an analogy or mathematical tools to do this.
- In the next stage, *expression* of the model, the students work in small groups to produce a model, a representation. Many students develop a NaCl molecule model, which could be expressed verbally or visually, or physically using two bound balls.
- The next stage is to *test* these models, for example by asking students why sodium chloride has such a high melting point. Some students respond to this by claiming that 'the' bond between sodium and chlorine ions is very strong (they see a single bond rather than considering a lattice of bonds). So, a second test might be to ask why salt crystals can be cleaved along specific planes. The teacher is here able to present the testing of models as part of scientific development, and also pose tests that introduce elements that are missing from student models. The balance between student autonomy and creativity and teacher interjection should develop over time.
- A further stage of the modelling process is to *evaluate* models. Here the teacher may ask groups to justify their models and the class may come up with a consensus model based on these discussions. If models are framed as explanations that serve specific purposes, as I have claimed above, then the limitations and scope of those models should be brought to the fore in relation to those purposes. However, this might be extended to see how far the model can be generalised, such as by seeing how far their model of NaCl is able to explain the properties of MgO (which has an even higher melting point but is not very soluble).
- Furthermore, a teacher may then add *further evidence* to guide the model towards scientific consensus. For example, lattices may have no distinct structure in student models, so evidence from X-ray spectra might be brought in to support lattice shapes, which students can integrate into their models.

Gilbert and Justi frame models as 'epistemic artefacts' in the classroom, from which students develop understanding of established scientific models as well as the process of modelling. From multiple studies across the world, they have established that teaching science in this way greatly enhances both student understanding of scientific content and their skills, and also provides a vehicle for developing an understanding of nature of science. However, the latter depends on teachers actively engaging students with this.

Learning through models – beyond concepts

Modelling-based teaching allows students to learn from the process of engaging with models in a way that approximates to the work of scientists, such that students learn both content and the processes of modelling. Here, I want to develop the stronger argument that students, like scientists, actually reason through the models with which they engage.

To develop this point, let us reconsider the different ways in which a heart may be modelled in the classroom. Imagine that a group of students build a model for the heart using plastic bottles and bits of tubing, and that they use it to discuss energy transfer from respiration and pressure in explaining how blood is pumped around the body. National curricula documents frame energy transfer, respiration and pressure as scientific *concepts* and therefore such a model may involve utilising and learning multiple concepts.

But how do students actually learn from these models and concepts? There is a tradition within science education of considering learning as the development of concepts within students' minds. This has its roots in constructivist learning theory and was developed in earnest in the 1980s and 1990s when a great deal of research focused on the misconceptions held by students and how these might be detected and addressed. Despite the wealth of research into the conceptual development of students, there still remain philosophical difficulties in defining where and what concepts actually are: how do they relate to brains, bodies and broader context? However, here I will focus on how constructivism has been interpreted in many science classrooms, namely as the development of mental concepts.

Focus on concepts often implies to teachers that students are somehow acquiring an understanding of the phenomenon itself through the activities with which they engage in classrooms. As someone who spends much of my time in other teachers' classrooms, I have lost count of the number of times that I have seen students use guesswork, whispers and the coaxing of answers out of a teacher to complete a worksheet labelling the parts of a cell, heart, atom or power station. Some teachers are then surprised that the students are not able to label a completely different diagram in the next lesson, or to explain the function of the components they have labelled. The point is that the students in such cases have interacted with a particular model and this does not entail the transmission of conceptual understanding about the phenomenon itself.

Gilbert and Justi are keen to move the terms *concepts* and *models* away from the sense of denoting mental representations of the world 'as it is' and instead consider them as 'artefacts' that have material presence in the classroom. As such, when laying out modelling-based teaching, they suggest that:

> … *mental models are epistemic creations, human-made artefacts, usually materialised in some way for sharing with others, that attempt to depict the world-as-experience by imagining what it is like.* (Gilbert and Justi, 2016: 83)

The models expressed in a classroom are not the manifestation of coherent mental representations but emerge from the brains, bodies and material circumstances involved in expressing them. While Gilbert and Justi see this as congruent with what they call 'the broad church of constructivism', I believe that the terminology and common interpretation of conceptual change research is a barrier to teachers. Despite a focus on learning from each other and the world around us, constructivism has been interpreted as being about the development of mental concepts towards consensus views of the world. This interpretation leads to teachers characterising learning as the intangible development of mental concepts/models and, in turn, to them not focusing on the specifics of what is being presented and developed within the classroom.

So how might teachers be helped to focus on models as integral to learning and reasoning in science classrooms? A first step is to recognise that learning is often evaluated on the basis of a student being able to respond to a question, problem or circumstance in a certain way. This is relatively easy to define with recall of information in response to a simple question: for example, how many ventricles does the heart have? Here, a student recognises the word 'ventricle' in relation to the word 'heart' and produces a very simple model, though stating that there are two, even if that is all they know about ventricles. If what is being evaluated is a student's capacity to explain how the heart evolved to pump blood around the body, then the student might use words, diagrams, hold their fist to their chest or make a model; they may do all of this. This involves a 'mental model' insofar as the brain of the student is able to utilise the resources available in the context (including their own body) to express models that explain how the heart pumps blood.

This is subtly different to framing learning as the development of intangible mental representations of phenomena: the shift in focus is towards expressed models, which emerge from the interplay of brains and material context. This framing allows us to consider the influence of the specifics of context, and this in turn will allow us to bring growing insights from educational neuroscience to bear on learning. Moreover, recognising that students both learn through and are assessed on their use of models in explaining phenomena promotes teachers considering carefully the models that emerge within classrooms. In this article, I have taken a broad definition of models as not only including the words, diagrams, physical models and animations that we use to explain things, but also the gestures that teachers deploy in the classroom. I have also argued that students learn through the models they see, express and evaluate. This means that, as students learn, they do so through the models that emerge in classrooms.

Models, truth and teaching science

In this section, I wish to bring together two threads within this article to argue that a great deal of what both professional scientists and students do is to engage with models, and this is what links learning and doing science. This link also gives us a perspective on what science is about and how the portrayal of 'truth' in science is bound up in how scientists develop and use models. Individual scientists have different roles, of course, and might be engaged in developing an experiment, gathering evidence or classifying information. All these processes involve the use and development of models however.

I have suggested that, although correspondence to empirical evidence should be a key criterion for how we evaluate our explanations of the world, we cannot use this criterion alone. The 'truth' of a model is bound up with coherence, pragmatism, consensus, warranted belief, aesthetics and power relations. Models, by which I mean all explanations in science, are not objective truths, despite what some students may think. I have also suggested that we need to move beyond characterising students' 'mental models' as coherent understandings that develop and have correspondence to the models that students express.

Putting these arguments together, we can see that models, manifest in the material of the world, cannot be perfect replications of a phenomenon. Models exist in a different space and time to the 'original' phenomenon, and they are usually made of very different stuff, as David Hay (2017) expounds in his article in this issue. In Hay's account, models are seen to take shape in relations between 'things' (non-human stuff) such as beetles, paper, plastic, plasticine, computer code or any other 'stuff', as well as in the human body, with its kinaesthetic sensitivities, feelings and thought. We use models to communicate, reason, predict, explain and do things in the world, but we also make and use models just to get to grips with stuff before we ever have words to talk about it. My advocating models as forms of explanation should not be seen as claiming that there is a progression from empirical experience of a phenomenon to explanation. Hay's article engages with the other side of the performative idiom in science and our two articles should be read as two sides of the same coin, which together give that coin due value in the matter of its weight.

I finish my account by emphasising two important issues. Firstly, the account that I provide ought to encourage science teachers to reconsider the models that they deploy in the classroom. Students learn through the models that they express and with which they engage, and this is not just about the concepts listed in curricula; it is also about how the process of doing science is modelled. Secondly, if we are to present science as a coherent and authentic subject, we must recognise that science is the process of explaining features of the world through the development and evaluation of models. This process is messy, as is the way that students learn in classrooms. However, relating how scientists learn about the world, and how students learn about science, encourages teachers to place modelling at the heart of the science classroom.

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