KEITH S. TABER

20. MODELS AND MODELLING IN SCIENCE AND SCIENCE EDUCATION

This chapter discusses the nature and roles of models in science, and in science education. It is argued that models and modelling are important in science teaching both because of the need to authentically reflect the importance of modelling in science itself, and because of the pedagogic role of models. It is suggested that effective teaching practice requires teachers to distinguish these two different roles of models in the science classroom. There are extensive literatures relating to the role of models in the practice of science, and to the use of models in science teaching, and the present chapter sets out to introduce readers to some key ideas about this important topic.

WHAT ARE MODELS?

A model can be understood as something that stands for something else, but which provides an affordance that goes beyond a simple representation, thus allowing the model to be a tool for some kind of action. Sometimes that may be a physical action, but often models used in science are primarily thinking tools. In particular, models are used to develop and test scientific explanations (Gilbert, 1998). It is in the nature of models then to be different from what they are modelling. One key feature is that models are often simpler. Many phenomena that scientists study are complex and models can offer carefully selected simplifications. One example would be Daisyworld which was used to explore an idea about the role of feedback cycles in natural ecosystems in maintaining stability despite perturbations. Daisyworld was designed to test an aspect of James Lovelock’s Gaia theory which suggested that the natural environment needs to be understood in terms of complex interactions between physical, geological and biological features. Lovelock argued that the evolution of life on earth involved the development of complex interactions that, within certain limits, worked to keep conditions stable.

One problem in understanding the Earth’s hospitality for life is how the planet has remained suitable for life despite significant changes in the Sun’s energy output (as a result of the gradual shifts in the Sun’s composition due to the nuclear reactions that cause the Sun to shine). All other things being equal, the Earth should have got a lot hotter – and so should either have been too cold for complex life when such lifeforms first appeared, or be too hot for complex life now. Yet the fossil record

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shows that the climate must have remained moderately stable over periods when the Sun's output has changed considerably. The geological record shows that there have certainly been many shifts in the Earth's climate but these have never been extreme enough to threaten life. Lovelock suspected there were feedback cycles that maintained conditions within certain bounds.

The biota on the model world, Daisyworld, comprised of just two varieties of daisies (black and white) which suited different conditions. Now such a simple biota would not be viable, and certainly does not reflect the complex range of organisms on earth. However, the idea of Daisyworld was to offer a very simple scenario that could test an idea. In the model the two types of daisy interacted with the environment differently (the black ones absorbing more radiation from the planet's sun, and re-emitting it at wavelengths that would heat the planet; the white ones reflecting more radiation back into space) and thrived in different conditions (the white daisies, less able to warm up by absorbing radiation, thrived better when the planet was warmer). This simple model showed that as the Daisyworld sun's radiation intensity increased, the balance of white and black daisies shifted in response, which changed the albedo of the planet sufficiently to counteract the increased incoming radiation, and so maintain a temperature viable for the daisies to survive. Whilst Daisyworld was far simpler than the real earth, it illustrated that in principle an ecosystem can include negative feedback cycles to maintain constant conditions in response to substantial (if not extreme) perturbations. Daisyworld was actually a simulation programmed into a computer, which allowed the evolution of the system to be speeded up massively compared with the rate at which a star's output actually changes.

Models then are usually simpler than what they model, but they may also be different in other ways that facilitate enquiry that would be difficult to undertake with the real system. So for example, a scale model of an aerofoil, such as an airplane wing, may be placed in a wind tunnel, and subjected to tests to see what happens to the flow of air over the model wing surface under different conditions (wind speed, the wing's 'angle of attack'). Building and testing models is a good deal more resource-effective than building and testing full size wings, and allows problematic designs to be rejected. Another example might be the use of cadavers as models of patients with medical problems requiring surgical treatment. A dead body that has been bequeathed to medical science can sometimes be modified to model a disease condition, allowing surgeons to develop new techniques (or novice surgeons to develop skills) without putting live patients at risk.

One of the most famous examples of a scientific model is the molecular model of the structure of DNA built by Francis Crick and James Watson at the Cavendish Laboratory in the 1950s (Watson, 1968/1980). Students seeing the photographs of that model now may think that it was intended simply as a model *to represent* a structure. However, Crick and Watson did not initially know what the structure was, and used modelling as a way of finding a structure that fitted with the parameters suggested by various laboratory measurements (such as the known ratios between base pairs, and the interpretation of Rosalind Franklin's X-ray diffraction images).

Building models to test against available data (that was difficult to interpret directly in terms of structural features) was a useful complement to the laboratory research.

Crick and Watson's approach was somewhat novel at the time (although it had been used by the Nobel laureate Linus Pauling). Nowadays it is very common for pharmaceutical researchers to model and test potential drug compounds within computer simulations. As synthesis of new drug compounds can be an expensive and slow process, the use of computer simulations allows researchers to explore likely properties of vast numbers of potential structures, to decide which compounds are likely to be most worth synthesising for testing in laboratory work and clinical studies.

Although it is suggested above that a model goes beyond a representation, the distinction may not always be obvious. For example the following equation represents a chemical reaction:

$$P_4 + 6Cl_2 \rightarrow 4PCl_3$$

We would normally think of this as a symbolic *representation* rather than a model, although the equation represents the reaction in such a way as to support calculations about the actual chemical system – such as how much chlorine reacts with a certain amount of phosphorus (see Chapter 24: '*Teaching and Learning Chemistry*'). This suggests it may not be productive to seek to be too definitive about what does or does not count as a model. Whether something is a model depends on how it is understood and used, rather than just its inherent properties.

Metaphors, Similes, and Analogies

Metaphors, similes and analogies are important model-related notions in science and science education. Similes and metaphors are figures of speech that are used to help communicate meaning. A metaphor suggests one thing is *the same as* another (although this is not intended to be literally so) and a simile suggests one thing is *like* another. A metaphor would be that the *cellular nucleus is the brain of the cell*. A cell nucleus is quite different from a brain, but someone using this metaphor would be suggesting that there is some similarity between a brain and a cell's nucleus. A person using this metaphor would not be trying to persuade the listener or reader that a nucleus and a brain *are* the same, but rather that it is helpful to think about brains when considering some aspects of the nature of a cell (for example, that the nucleus has a major role in controlling activity in the cell similar to the role the brain has in controlling bodily activity).

The astute reader may have noticed that terms like '*the* nucleus', '*the* cell', and '*the* brain' have just been used as if they refer to definite entities – particular cells and brains – when clearly the comparison is a quite general one. It is common in science to refer to '*the* cell', '*the* heart', '*the* atom', and so forth when making general statements that refer to classes of objects, for example '*the* [sic] heart pumps blood around *the* [sic] body'. There is a kind of modelling going on here in the way we use a mental construct of a generic example. Members of a general class of objects (hearts) are considered similar enough to be represented in scientific arguments by a generic representation of the class ('the heart…'). In everyday language the phrase "the athlete is strong" (rather than "athletes are strong") would normally be assumed to apply to a specific athlete, but in science when we say that "the kangaroo is a marsupial mammal" we generally mean "the kangaroo" to stand for the general class of all kangaroos. So the statement "the dog is a four-legged animal" refers to the conceptual model of the generic dog and stands even though (due to specific contingencies) there are some particular dogs that do not have four legs.

When metaphors come to be used habitually they can actually take on the meaning that was previously only *implied* by the metaphor. Such metaphors are said to be dead (!) metaphors (so here one metaphor is being used to describe the nature of another metaphor – the figurative power of the metaphor has 'died' as it no longer represents a juxtaposition of two distinct ideas). Examples of dead metaphors that arise in science teaching would be saying that *covalent bonding is electron sharing* or that *the electron has spin*. These ideas have come to be accepted as literately true because within the context of the scientific topic the metaphor has been adopted as part of the informal or formal technical language of the subject. Although chemists realise that atoms cannot share anything, they know what is implied by the commonly – if informally – used notion that electrons are 'shared' in covalent bonds. By contrast, we can say that electrons *do actually* have spin because they have angular momentum, but the meaning of 'spin' here has been formally extended beyond the usual everyday notions of something rotating. Clearly there is scope for such figures of speech and associated shifts in meaning to confuse science learners, and teachers need to be careful not to use such language without ensuring learners know precisely what is implied.

A simile has a very similar role to a metaphor, but is phrased in terms of explicitly referring to the similarity ('the nucleus of the cell *is like* the brain'). The difference between simile and metaphor is therefore in terms of the phrasing. To say that "an enzyme catalyses reactions because it fits substrate molecules *like* a lock and key" is to offer a simile. A lock is designed so that only the intended key will open it, and (in a somewhat similar way) enzymes have evolved so they interact with very particular substrate molecules in ways that catalyse specific reactions.

Metaphors and similes are used to help us think about how one thing is much like, or in some way like, another. We can see here something of the process of modelling (one thing stands for another, to support thinking about some system or other), but we would normally not consider these figures of speech to be fully developed models. That said, they might well act as starting points for modelling. An example here might be the notion of the 'liquid drop' model of the atomic nucleus. This idea was proposed by Lise Meitner and her nephew Otto Robert Frisch. Meitner had left her laboratory in Germany to escape Nazi persecution and had been sent details of experimental results obtained by her colleagues Otto Hahn and Fritz

Strassmann. These results did not make sense in terms of what was then understood about nuclear processes. Meitner and Frisch came up with the idea that if the nucleus was considered to be somewhat like a drop of liquid, then the absorption of a particle (that would initially lead to an increase in nuclear mass and nucleon number) could initiate excitations that might lead to the liquid drop (nucleus) breaking into smaller drops (nuclei). This comparison allowed people to visualise the process and understand how the absorption of a nucleon by a heavy nucleus could actually lead to lighter (less massive) products. Although the idea was initially little more than a metaphor or simile, it was developed by scientists into a sophisticated model. This process is referred to as nuclear fission, by analogy with the process of cellular fission, where one cell divides into two smaller ones.

Scientists often form visualisable mental models that help them simulate processes in their minds, and sometimes to run Gedankenexperiments (thought experiments). Einstein for example was well-known for running thought experiments in his mind in this way. A more contemporary example would be the engineer Temple Grandin who designs systems for humanely treating animals used in farming. She has described how she tests her designs by running simulations in her mind (for example imagining the experience of a cow being led into a slaughterhouse). Grandin, who is autistic (Sacks, 1995), considers visual imagery so important to her work that she sees verbal language as secondary by comparison.

Faraday visualised magnetic fields having field ‘lines’ as a way of making sense of magnetism. Although the lines of force used to visualise magnetic fields are only imaginary, this proved to be a very useful tool, and modern textbooks still use these kinds of diagrams. Indeed physicists calculate the flux of (imaginary) field lines as a measure of field strength, and explain high energy events on the surface of the Sun in terms of what is happening to these (non-existent) lines. In a similar way, rays of light are used in optics to model the paths of light through prisms, lenses and so forth. A ray of light can be considered as a light beam that is infinitesimally narrow (i.e. a conceptual model formed by abstraction from a real phenomenon). Light rays are – like magnetic field lines – imaginary, but useful, mental tools for modelling real physical systems.

Students also form their own mental models of natural processes in developing their understanding of scientific ideas. These mental models help learners visualise and explain scientific phenomena, in just the same way that scientists themselves use such mental models. Research suggests, however, that learners’ mental models may often be inconsistent with scientific models, as they often draw upon alternative conceptions (Taber, 2014). As an example, young children may explain the cycle of day and night in terms of the sun moving behind an obstruction such as a mountain – something based on their experience and observations of real events (Vosniadou & Brewer, 1994). Although the notion is not scientifically accurate, the model can be run in the head as a mental simulation that explains why it is sometimes daylight and sometimes dark. When mental models cannot be readily constructed to test some explanatory idea, it may be possible to fabricate models in the laboratory which do the job.

The Gaia theory referred to above in relation to the Daisyworld model was framed in terms of the analogy between the earth and a living organism. An organism, such as a person, relies for survival on the ability of the system to maintain the conditions needed by the component cells – not too hot or cold, not too acid or alkaline, enough oxygen and sugar, not too high a concentration of toxic waste products, etc. Keeping a wide range of variables close to optimal operating conditions relies on a series of feedback cycles that have evolved such that significant variations from optimal conditions are detected and action taken to counter the change (breathing more deeply, dilating some blood vessels, producing glucose from glycogen,…). Seeing the earth as a supra-organism suggested that the interactions within the ecosystem may also show something analogous to homeostasis, based on feedback cycles that had evolved to be part of the system.

An analogy can be the basis of a model by going beyond mere simile and offering an explicit mapping of the parallels between two systems. Consider the following two equations representing heat flow and current flow respectively:

$$^{\Delta Q}/_{\Delta t} = -K\,A\,^{\Delta T}/_{x}$$

$$I = -\sigma\,A\,^{V}/_{x}$$

These can be considered analogous by mapping between the two systems (see Table 1):

Table 1. Comparing two analogous system

Thermal system	*Electrical system*
$^{\Delta Q}/_{\Delta t}$ (rate of heat flow)	I (current – rate of charge flow)
– (heat flows from high to low temperature)	– (current flows from high to low potential)
K (coefficient of thermal conductivity)	σ (coefficient of electrical conductivity)
A (cross sectional area of material)	A (cross sectional area of material)
$^{\Delta T}/_{x}$ (temperature gradient across material)	$^{V}/_{x}$ ([electrical] potential gradient across material)

An analogy has negative features as well as positive features, in the sense that only some aspects of the analogy directly map onto the target system. Consider for example the idea (sometimes found in introductory science texts) that an atom is like a tiny solar system. The atom has been modelled in science through a complex series of models that have been developed over an extended period, but the simple orbital model of the atom (i.e., with electrons in orbits around the nucleus) has been considered to be like a planetary system. We might consider that in some ways a solar system acts as a good analogy to this model of the atom: but not all features of solar systems map across. Table 2 shows how in some ways the two systems are similar; how in other ways they are different; and how some features of the solar system simply do not have anything to map to (Taber, 2001).

Table 2. Mapping an analogy

Feature of analogy (solar system)	*Feature of target (atomic model)*	*Nature of mapping*
The star (sun) is the central body	The nucleus is the central body	positive
Most of the mass of the system is at the centre	Most of the mass of the system is at the centre	positive
A number of planets orbit the sun	A number of electrons orbit the nucleus	positive
A number of comets and asteroids also orbit the sun	[No parallel feature]	neutral – no relevant mapping
Planets are found at different distances from the sun	Electrons can occur in shells – so several are at the same distance from the nucleus	negative
Planets vary in size, composition etc.	Electrons are identical	negative
Planets may have their own satellites (moons)	[No parallel feature]	neutral – no relevant mapping
Centripetal force causes the planets to orbit (rather than leave the system)	Centripetal force causes the electrons to orbit (rather than leave the system)	positive
The centripetal forces are gravitational in nature	The centripetal forces are electrical in nature	negative
The orbiting bodies can interact through forces	The orbiting bodies can interact through forces	positive
Orbiting bodies (planets) attract each other	Orbiting bodies (electrons) repel each other	negative
Orbits may decay in time due to interactions	Orbits are indefinitely stable	negative

Analogical models make use of the analogy between two different systems to allow one system to be used to stand for the other. If exploration of the analogue is used to draw inferences about the target system, it is important to understand the limits of the analogy. It is not unusual for students to mistakenly assume electrons orbit the atomic nucleus because of gravitational attraction, by analogy with the solar system. Teachers using analogical models, as well as similes and metaphors, need to ensure students are clear about the nature of the comparison being made.

TEACHING ABOUT SCIENTIFIC MODELS

An important part of teaching science is teaching students about the nature of science (see Chapter 2: '*Reflecting the nature of science in science education*'). That is, not only should students learn about scientific ideas, but also about the nature of those ideas (as theories, or laws of nature, or models, for example) and how they are derived. Most of what we teach in science is theoretical, and much of it consists of, or heavily relies upon, models of one kind or another.

So when students learn about reaction mechanisms of nucleophilic substitution reactions, for example, they are taught about hypothetical changes at submicroscopic level, based on models of how matter is structured at that level. The S_N1 and S_N2 mechanisms that may be taught in upper secondary school chemistry are models designed to explain the products produced in nucleophilic reactions under different conditions. Students may assume that scientists know precisely what is happening to the molecules during these reactions as we can draw out the reaction mechanisms – but these schemes are inferences from what is necessarily indirect evidence, as no one has ever seen the interactions between the molecules (see Chapter 24: '*Teaching and Learning Chemistry*').

Scientific typologies are a kind of model. An important part of the work of scientists is to describe nature, and offer meaningful classifications of natural phenomena. Some of the typologies that scientists produce reflect features of nature well: for example the different chemical elements. In that case it is now fairly obvious to scientists how to distinguish one element from another, and so where to 'draw the line' between different elements. Historically this was not always the case.

Other classification systems may not reflect such obvious distinctions in nature. For example, classifying elements as metals and non-metals, or into metals, metalloids, and non-metals, requires some judgements about where to best put the boundaries between categories. Any periodic table which shows different groups of elements in these terms is a model that has involved some compromises in considering the different properties of some of the elements (where the same element has a range of properties which individually suggest distinct classifications). Similarly, deciding which acids should be considered strong and which weak is a matter of judgement as dissociation is always technically an equilibrium no matter how nearly completely an acid may be dissociated under some conditions. So in many chemistry laboratories bottles of mineral acids that are considered strong acids are provided as standard bench reagents: often hydrochloric acid, nitric acid (often both as 2M solutions) and sulphuric acid (often as 1M solution). Strong acids are often said to be those that dissociate 'completely' in solution, but nitric acid has also been described as an 'almost' strong acid, suggesting that even though a solution would contain very few undissociated HNO_3 molecules compared with the number of ionised products, dissociation is not 'complete'. Considering nitric acid as one of the strong acids is appropriate for most purposes, but this is based on a model that simplifies the complexity of nature.

Another example would be the use of the species concept. Scientists classify living organisms into types at the levels of kingdom, phylum, class, order, family, genus and species. The principle is that any example of a living organism can be classified according to this system, which is based on the assumption that natural types such as species are discrete. This then is a model of the way organisms fit into distinct categories. This system works well most of the time, but evolutionary theory tells us that over time species change, and sometimes split into separate populations that then evolve into separate species. This tends to be a very slow process so that at any time there is very little ambiguity in a system that assumes discrete species: the vast majority of specimens found can be considered to be clearly members of one species or another. However, there will always be some unclear cases, as the species model simplifies the complexity of the relationship between different organisms.

When it is known that students commonly hold mental models at odds with scientific models in a topic (see Chapter 9: '*The Nature of Student Conceptions in Science*') it is possible to develop activities that ask students to compare different models. One such activity asked students working in groups to explore how well two different models of ionic bonding (the model taught in the curriculum, and a model representing common alternative conceptions) explained a range of phenomena (Taber, 2007).

Student Understanding of Scientific Models

Research suggests that most school age students have quite naive notions of models – often thinking of them as scale replicas (Treagust, Chittleborough, & Mamiala, 2002). Of course in learning science students meet some models that are of that kind – such as scale models of the human torso containing removable organ systems. These are intended however as teaching models (see below) rather than as scientific models. A teacher would be aware of ways in which such a model is not just smaller than what it stands for, but is also a considerable simplification. For example the model does not reflect connective tissues which prevent the real organism from being so easily dismantled, or the fine networks of blood vessels and nerves that permeate through the body. The teacher may assume these omissions are obvious: but that may not be the case to many students.

As scientific models are simplifications, and often abstractions, students can have learning difficulties if they do not realise this. (An interesting question is whether students in many science classes realise that magnetic field lines and rays of light are not real objects.) It was suggested above that "whether something is a model depends on how it is understood and used, rather than just its inherent properties". A corollary of this statement is that when a teacher presents a model of some scientific system, it does not function as a model for learners unless they appreciate how it models the target system.

For example, the orbital atom model referred to above was once useful scientifically, and can still be used to explain some of the science taught in schools (it links to valencies, and patterns in ionisation energies for example), but has largely been superseded by more advanced and sophisticated models of the atom (Justi & Gilbert, 2000). As the orbital model is still taught, it is important that students know it is a model, and therefore a useful thinking tool, but also limited and not a precise description of reality. Where students instead form a realist understanding of the model (that it is a much larger version of what an atom is *actually* like) they may find real difficulties understanding the (incompatible) orbital concept needed for progression in learning chemistry (Taber, 2005).

This should not be seen as simply a limitation of weaker learners. Scientists themselves have been known to suffer learning blocks by putting too much reliance on their models. For example, for many years there was a widely accepted 'central dogma' in molecular biology based on a simple model of the relationship between proteins and nucleic acids. The model can be summarised as in Figure 1.

Figure 1. The so-called 'central dogma' of molecular biology suggested a one way process whereby information stored in DNA determined the structure of RNA and so indirectly the structure of proteins

The model proposed was actually more subtle than shown in Figure 1 (Crick, 1970), but came to be widely understood as suggesting information only flowed from DNA to RNA, and then to protein – with no exceptions. It is now known that some viruses (including the HIV virus associated with the disease condition AIDS) use an enzyme called reverse transcriptase to modify cellular DNA in host cells, so that they become factories (sic, notice the metaphor there) for producing the materials needed for the virus to reproduce. The viral RNA codes for new cellular DNA, so information can pass either way between DNA and RNA (see Figure 2). The central dogma – a model that was often assumed to be realistic – prevented some scientists looking for these kinds of effects for some years.

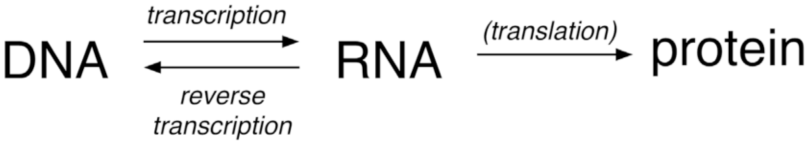

Figure 2. The model of information transfer in molecular biology has been amended now it is known that information in RNA can sometimes be transferred to, and so stored in DNA, before later being used in producing proteins

In is interesting to note in this context that one theory for the development of life on earth posits a time before DNA was produced when all genetic information was stored in RNA. Scientists developing the 'RNA world' theory try to model how simple life might have been based on RNA. If life on earth did pass through an RNA world phase then DNA was adopted at a later stage (as a more stable store of genetic information) at which point the information already represented in RNA must have been transferred to the first DNA molecules.

TEACHING STUDENTS ABOUT THE ROLE OF MODELLING IN SCIENCE

As models and modelling are so important in science, an authentic science education will emphasise models and modelling. This will mean that students will be taught about the status of scientific models *qua* models when they are presented in the curriculum. An authentic scientific education should also include opportunities for students to actually undertake modelling activities.

Curricular Models and Teaching Models

The role of models in teaching science is complicated by the existence of models which do not derive from scientific activity, but have been developed for educational purposes: curricular models that simplify scientific knowledge, and teaching models developed by educators to help teach science. Where scientific models have currency in science (or in some cases are superseded historical models that were once used by scientists) and so have been used as thinking tools to develop scientific explanations, pedagogic models are simplifications designed to help learners find out about the essence of some scientific idea or principle.

So curriculum authorities and designers may set out a simplified account of scientific knowledge as target knowledge considered suitable for learners. This is likely where the learning demand (Leach & Scott, 2002) of the scientific knowledge is considered too great for students – where the gap between students' starting points in terms of knowledge and understanding and the state of current scientific knowledge is considered too large to reasonably expect students to master the full complexity of the canonical scientific understanding. Such a curricular model can be considered authentic as long as it is true to the core of the scientific idea, and offers a suitable basis for later further learning that shows progression towards the full scientific account. Models that are oversimplifications can act as learning impediments (Taber, 2000).

There are also examples of teaching models that are designed to help students make sense of particular teaching points. Like scientific models, these teaching models may be of various kinds such as physical models, computer simulations or mathematical models. It was suggested above that children may often enter classrooms with alternative, scientifically questionable, mental models of the day-night cycle. It is common in teaching to illustrate the scientific model of this cycle (as well as seasonal changes) using a physical model with a globe rotating to show how the pattern of illumination from a light source (representing the Sun) changes over time. The model is a simplification, and not to scale, but offers a means of demonstrating the basic principle.

Another example of a physical model would be the model mine. This is basically a rectangular box, with a hole in the roof at each end, and a candle placed beneath one of the holes. When the candle is alight the smoke from a burning taper or splint will reveal air flow, and show that there is an air current passing through the channel between the two holes. (It is important to point out to students that the smoke is used simply to make the air flow visible.) This model is meant to demonstrate an application of convection, showing how mines were sometimes ventilated by a fire beneath one shaft. The model offers a considerable simplification of a real mine system but can help students visualise the convention process and understand the application of the principle.

Another common model used in teaching is the 'model lungs' composed of two balloons inside an open bottomed large glass jar fitted with a rubber sheet covering the bottom and sealing the apparatus. The rubber sheet acts as a diaphragm which can be manipulated to mimic the way a person's diaphragm moves during breathing. The balloons are attached to tubes passing through the bung sealing the top of the jar, into the air. When the rubber is pulled down, increasing the volume of the air inside the jar and so leading to a decrease in pressure, air flows through the tubes into the balloons due to the pressure difference (as it does into the lungs during inhalation). As the model can be manipulated it supports student visualisation and conceptualisation of aspects of how their own breathing occurs, although structurally it lacks superficial similarity to the actual system being modelled. For example, a negative aspect (cf. Table 2) is the way that even when inflated the balloons only occupy a small portion of the jar and are surrounded by air. A teacher can overcome this drawback by using a range of resources when making this teaching point – the physical model (three dimensional and dynamic, but not anatomically realistic) can be complemented by animations (dynamic, but two dimensional) and anatomically accurate models (lacking the dynamic features). Using a range of models and representations, and being explicit about their relative strengths and weaknesses, can help learners appreciate which features of particular models are (and which are not) meant to reflect the target learning, and also reinforce the nature of models as simplifications that represent only some aspects of the system being modelled.

Students can be asked to explicitly explore the strengths of teaching models used in the curriculum. For example, in an electricity module for lower secondary age classes (11–12 year olds) students were asked to use, and critique three different teaching models for representing current flow in circuits (Taber et al., 2015). The models were pedagogic models rather than scientific models, but students were told that the process of exploring models and testing them in relation to empirical evidence (experienced through making predictions using the models, and then building circuits) was an important part of science. The three models used (vans delivering bread to shops; a rope ring; and a physical simulation where students move around the room as if charge carriers in a circuit) are not used by scientists to model electrical circuits. It was important that students realised that these were simply tools used in teaching to help learners think about what was going on inside circuits. Yet it was also emphasised that the activity asked students to undertake a process (thinking with models) that was a common feature of scientific thinking.

Again, although it may be obvious to the science teacher which models presented in class are authentic scientific models (albeit perhaps simplified) and which are pedagogic tools, it is important not to assume students will always recognise the difference. If students are taught to appreciate the centrality of models and modelling in science, and how many historical scientific models now discarded were once at the cutting edge of science, then they should better appreciate why they are sometimes taught with teaching models that represent but do not match current scientific models.

Students Creating their Own Models

An authentic scientific education should also include opportunities for students to undertake modelling activities of different kinds. It is common in lower secondary science to ask students to build model cells, for example, using different objects (sometimes sweets of different shapes and sizes) to represent components in animal and plant cells. This can be a fun activity that allows students to be creative, whilst – if organised well – focusing their attention on the nature of the structures they are modelling. In this context the generic notion of 'the cell' referred to above may be an unhelpfully overgeneralised abstraction, but the teacher will likely refer to '*the* [sic] animal cell' and '*the* [sic] plant cell' as conceptual representations of two subclasses of the broader class of 'cells'.

However, the level of modelling activity included in science classes should not be limited to the building of scale replicas, when – as suggested above – scientific models tend to be more abstract and schematic. So students should also be given opportunities to build models that – like scientific models – are designed to offer explanatory accounts of patterns in data rather than just represent structures. Science is often seen as a subject which relies on logic and rational thought. This is certainly so, but the creative impulse is also important in science, and indeed the scientific process relies as much on scientists' creativity as their logic (Taber, 2011). Figure 3 offers a schematic suggesting how creative thinking is as important in scientific enquiry as logical thought.

Although creativity is central to science this is not always reflected in learners' experiences in the classroom, especially when most of curriculum time is used to teach students about scientific ideas that have already been tested and established. If students are to experience the excitement of science they need opportunities to be allowed to be creative – to suggest and explore their own ideas. Building,

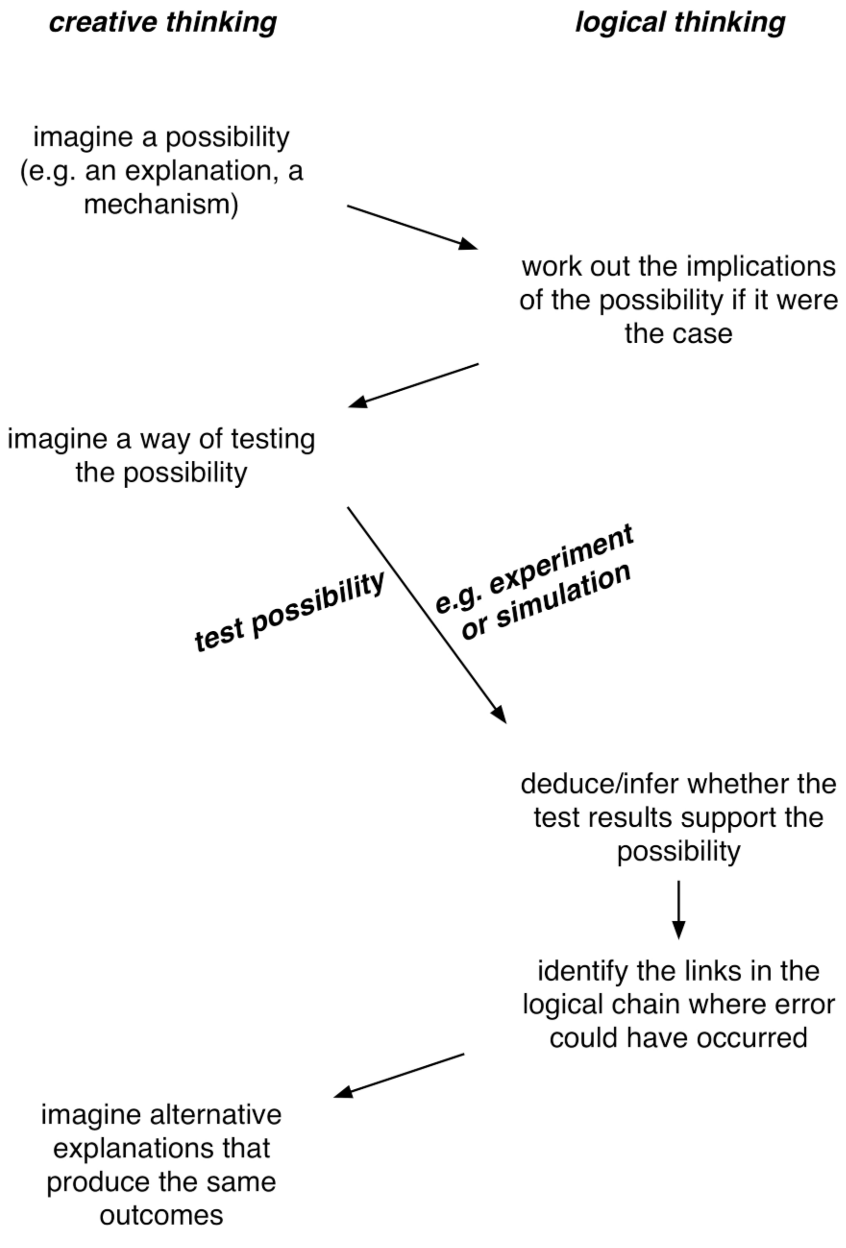

Figure 3. Scientific thinking requires an interplay of logical and creative thought. Whilst scientific enquiry relies upon rational thought, it just as much depends upon the use of imagination

developing, and testing models offers an authentic scientific activity that will engage learners and allow them to see the role of imagination in scientific work.

Teaching activities can be designed with suitable structure to support model building. An introductory activity could be to simply ask students to suggest, and justify, their own metaphors and similes for scientific concepts (Taber, 2016). Then students could be supported in building models based upon the scientific knowledge they are learning in curriculum topics. For example, one activity designed to be challenging for more able secondary students asked them to coordinate information from biology, from chemistry, and from physics, to build a holistic understanding of plant nutrition (Taber, 2007). As students gain experience in such activities and progress in their learning they can be set more advanced modelling tasks. For example, the 'Advancing Physics' course designed by the Institute of Physics in the UK for senior secondary students (16–18 year olds) incorporates software to support students in mathematical modelling (Ogborn, 1999).

CONCLUSIONS

This chapter has suggested that:

a. models and modelling are central to science
b. authentic scientific education should put an emphasis on models and modelling, so

i) that teachers should be explicit about the status of scientific models taught (i.e. that they are models);
ii) teachers and students should as a matter of course explore the strengths, and the limitations, of models met in the curriculum;
iii) science learning should involve opportunities to actively engage in creative modelling activities, not just to passively learn about existing models;
iv) progression in understanding the nature of models and modelling in science should be carefully supported as a long-term goal;

c. teaching science tends to draw heavily on pedagogic models, some – but not all – of which may reflect current or historical scientific models;
d. teaching models offer opportunities to explore the nature and affordances of models, but teachers should make it clear to students when teaching models have scientific currency, and when they are simply being used as pedagogic tools.

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