Making Meaning with Models

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Making Meaning with Models

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Abstract: Narrow interpretations of Piagetian theory have led to assumptions that children are unable to grasp complex concepts, yet Bruner contended that any subject could be taught to any child in some intellectually honest way. Our work with separate groups of primary-aged children, in different scientific fields, indicates that children can attain understandings of complex concepts, particularly with the aid of tangible models. Children aged 7 and 10 years used a simple model made of wool to understand aspects of DNA, genes and inheritance, and children aged 9 years used models of atomic orbitals and magnetic atoms of elements to understand aspects of atomic-molecular theory.

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Introduction

Inhelder and Piaget (1958) suggested that children pass through four defined stages of cognitive development. From infancy to age 2 years, children are in the sensorimotor stage, and from ages 2 to 7 years, children are in the pre-operational stage, during which they cannot conserve quantity nor think logically. The concrete operational stage occurs between the ages of 7 to 11 years, in which children begin to think logically but only with practical aids. From ages 11 to 16 years and onwards, children transition to the formal operational stage with the development of abstract thinking. On the basis of Piagetian theory, curriculum writers often delay the introduction of abstract concepts such as DNA and atoms until children are in the middle of the proposed transition to the formal operational stage.

In contrast with narrow interpretations of Piagetian theory, Bruner (1960) suggested that no content should be off limits for school-age children. He said

> We begin with the hypothesis that any subject can be taught effectively in some intellectually honest form to any child at any stage of development. It is a bold hypothesis and an essential one in thinking about the nature of the curriculum. No evidence exists to contradict it; considerable evidence is being amassed that supports it. (Bruner, 1960, p. 33)

Bruner went on to suggest that children are able to get an intuitive grasp of a complex concept before they have the background and maturity to deal with the same topic in a formal manner. More recently, Lehrer and Schauble's (2000) research showed that revisiting science ideas enables students to understand and apply concepts that they would not typically understand until several years later.

The work reported here results in the integration of theory from Piaget and Bruner. We acknowledge the need for concrete or tangible examples to engage children at the ages of Piaget's concrete stage. We also concur with Bruner that any topic can be taught to children in some way. With appropriate models and sound pedagogy, the children we studied came to higher order understandings that appear to surpass their concrete stage as delineated by Piaget.

Theoretical Framework

The word "model" has a wide range of meanings, from miniature replica (such as a model airplane or car), visual representation (such as an animation of cell division) to a conceptual structure (such as using the analogy of a life cycle when discussing the future of the Sun). Stewart, Cartier, and Passmore (2005) adopted a narrow definition of a scientific model as a conceptual structure that describes natural processes or relationships. In their schema, physical entities are *representations* of models but are not models themselves. They pointed out that whilst students think of models as physical entities, scientists readily think of models as theoretical constructs. They contended that if we want students to emulate scientists, we should give them regular opportunities to engage in devising and refining scientific models. We assert that it is important to have children engage with theoretical models, but in this paper, we adopt the broader concept of model, as espoused by Harrison and Treagust (1998, 2000) and more recently by Krajcik and Merritt (2012), that includes mental, physical, and visual representations. In particular, we focus on the strategic use of physical models as a way of helping students attain conceptual understandings.

Harrison and Treagust (1998, 2000) and the National Research Council [NRC] (2005) explained that students may have difficulty in understanding such different interpretations of models and so this should be addressed from the outset, clarifying the specific meaning(s) to be applied. In both cases to be discussed, this was a deliberate aspect of the pedagogical approach to the use of the tangible models.

Harrison and Treagust (2000) presented a full typology of models, but at the simplest level, models can represent objects or events. This includes objects that are too small (e.g. atoms) or too big to see or bring into the classroom (e.g. a planet), that no longer exist (e.g. a dinosaur) or are yet to be invented (e.g. a new product). Events include those that occur too slowly (e.g. evolution) or too quickly to see (e.g. a chemical reaction), events that happened long ago (e.g. the Big Bang) or are yet to occur (e.g. the end of the Sun).

Using models can have many benefits for students. They:

- give students think time to grapple with ideas and challenges,
- help organise thinking,
- can assist students to devise an appropriate series of steps in a process,
- help students develop a modelling language and understanding of conventions (such as showing a zoomed-in view),
- are particularly helpful for understanding connections and cause-and-effect, and
- show that rival explanations are possible (Harvard, 2008).

However, some issues have been identified concerning the use of models. These issues are, in many cases, similar to those identified with the use of metaphors and analogies in teaching. According to Quay and Frangos (2010), these include being an approximation and therefore inherently inexact, reflecting our incomplete understanding of a process, and containing uncertainties with regard to parameters, especially the starting points or boundaries of the real process being modelled. The model is also only as good as the data that went into creating it, and models are generally a simplification to achieve a particular purpose. Like analogies (Harrison & Treagust, 2006), all models break down at some point in their depiction of 'reality', and it is important that students understand this breakdown. It is beneficial to have children discuss the reasons why models are useful and the limitations of models for themselves (Harrison & Treagust, 1998, 2000).

There has also been considerable debate in the literature about the efficacy of models for different ages and stages of development. The two sides of this debate fully outlined in Venville and Donovan (2008) is summarised below:

1. Children who have not reached formal operational thinking lack the capacity to draw comparisons between a model/analog and the target, therefore using models is contra-indicated before the age of 11 years
2. Younger children who are still in the concrete stage of thinking can benefit from concrete models, and the use of these helps them to visualise and achieve complex understandings of non-tangible phenomena and processes.

One of the aims of the larger study, of which Case Study 1 is a subset, was to attempt to shed light on these opposing points of view.

Our Research

Participants and Methods

Case Study 1 is based on research conducted from 2004-2006 in metropolitan Perth, Western Australia by the first and third authors (Jenny and Grady). Part of a larger study, the focus here is on two groups, one consisting of 14 (out of 17) Year 2 students (average age 7 years 3 months) from non-English-speaking backgrounds at an Islamic school and the other consisting of 12 Year 5 students (average age 10 yrs 1 month) from a state primary school. This study sought to examine the development of children's theories of biology, kinship, and inheritance. To expose the children to the physical relationships between DNA, genes, alleles, and chromosomes, the first author (Jenny) devised a simple model made of wool. This model was used to explore the similarity of parents and offspring in terms of inheritance. Publications previously based on this work include Donovan and Venville (2005) and Venville and Donovan (2007, 2008) where details of the methodologies and findings are provided.

Case Study 2 is based on research conducted in 2013 in a Catholic school in metropolitan Brisbane, Queensland by the first and second authors (Jenny and Carole). The participants were a single class of 26 Year 4 children (average age 9 years 9 months) and one Year 1 child (Marcia, aged 6 years who was present by the request of the parent). It was a diverse class. Three children (Kensei, Oliwia and Nadine) had English as their second language (ESL), with the latter two arriving late into the program from a holiday in their home country. Joel, another ESL student, had Speech-Language Impairment (SLI). Edward had been designated as SLI and Intellectually Impaired (II), and required an individualised learning program. Loughlin had been diagnosed with Autism Spectrum Disorder (ASD) and Danisha was Hearing Impaired. This research sought to verify claims of success made by a science teacher, Ian Stuart, who had developed a program of lessons to introduce atomic-molecular theory to young children. Models of atomic orbitals and magnetic atoms of elements devised by Ian are the focus of this paper. Some of this work has been published in Donovan and Haeusler (2014) where details of the methodology and the findings of the pre and post-interviews are provided.

In both cases, ethical permission was sought and obtained from the Universities and education systems, and informed consent obtained from school principals, teachers, parents, and children to conduct the research. Semi-structured interviews (Creswell, 2005) was the technique of choice for these age groups, allowing the interviewers (the authors) to expand on set questions with further explanation as necessary, and with probing questions to elicit more information. Interview response sheets to note answers and facial expressions supported audio recordings. Pre-interviews were conducted prior to exposure to the pedagogy and the models. The intervention in Case Study 1 was just one lesson, so the follow-up interviews (post-interviews) occurred some two weeks later. The intervention in Case Study 2 comprised a program of 10 x 1 hour lessons given over a school term. Consequently, a post-interview was conducted immediately after the program ended, and further interviews (retention interviews) were conducted some eight weeks later to ascertain how much information the children had retained over time. Reflective field notes written by those applying the interventions were a useful secondary data source. Children's names used in this paper are pseudonyms from an appropriate ethnic background.

Relevant Data

Case Study 1

Previous work (Donovan & Venville, 2004; Venville, Gribble, & Donovan, 2005) indicated that children in upper primary school thought that genes and DNA were two completely separate entities, both structurally and functionally. Genes were perceived as something that makes you resemble your family, whereas DNA made you uniquely identifiable. This finding has been repeated with every group of children we (Jenny and Grady) have studied over the past decade, with 25% of the most recent group of 62 children aged 10-12 years, stating this belief (Donovan & Venville, 2014). We have also published on the difficulty of the gene concept (Venville & Donovan, 2005), and considered many models and analogies for genes and DNA (Venville & Donovan, 2006; Venville, Gribble, & Donovan, 2006). The decision was taken to work with younger children who had not yet developed this conception of difference, to see if it was possible to establish a scientifically accurate foundational understanding that genes are made of DNA.

In the research reported here, the first author (Jenny) conducted all interviews, then devised the model and delivered the intervention in collaboration with the class teacher, so any reference to "I/my" in the following account refers to Jenny. One of my roles was to introduce the model to the class to maintain consistency in that process. Initial interviews consolidated student readiness for these new concepts, in terms of their understandings of living things and the presence of some mechanism of inheritance. Class teachers testified to their prior use of models; there were already models in the classrooms that the children had used or made. The first and third authors (Jenny and Grady) collaborated on the data analysis.

Complex analogies or models with links in a chain or beads would not be suitable for 7 year olds, so I devised a new tangible model to demonstrate that genes are made of DNA. The model needed to be inexpensive, readily available, easy to make, easily handled, safe, yet as accurate as possible in terms of the target understanding. It would be an added benefit if it would allow for expansion of thinking across several years of schooling. For these reasons, I made a simple model out of wool (see Donovan & Venville, 2005, for details).

In brief, the substance of the wool represents DNA. Different colours represent genes, linked end to end. Shades of the same colour represent alleles, and some of the longest genes had multiple shades. Having more than two alternative alleles for some genes was more complex than necessarily needed at this stage, but in devising the model, I felt it was important not to introduce a misconception that there are only two alternatives for each gene. Each student received two lengths of DNA, each with six genes, but the variety of shades allowed for every student to have different alleles for the genes. One DNA strand was preassembled; they had to knot the other strand together to match. In the Year 2 class, there were identical twin girls, so they were the only students who received the same DNA; everyone else's was different. There were no twins in the Year 5 class, but the children raised this scenario during discussion. This simple wool model can easily make enough different DNA for a class of 28 students.

By agreement with the teachers, no further consolidation of these ideas occurred prior to the post-interviews two weeks later. Questions about DNA, gene, allele, and chromosome were deliberately asked in a different sequence from that presented in class. This did trip up some children in both Years 2 and 5, but overall the level of understanding was high. Detailed results are published in Venville & Donovan (2007, 2008). Table 1 summarises this research process and its findings. Some data has been abstracted from previously published results but additional insights arose from revisiting the raw data, particularly the reflective field notes written immediately after the lessons.

Table 1: The use of the wool model to represent DNA and the resultant learning in students from Years 2 and 5

	Year 2	**Year 5**
How participants were selected	Ongoing professional relationship with teacher	Referral from another researcher
Number of participants for whom full data obtained	14	12
Academic background of participants	Considered remedial due to difficulties in Year 1 and all from non-English speaking backgrounds.	An average group of children from mixed backgrounds and a range of attainment in science.
Prior learning established in pre-interview	They had explored ocean animals and land plants, and had good understandings of living and non-living things for their age. They knew the difference between biologically inherited characteristics and culturally acquired characteristics and that offspring resembled their parents, but none knew why or how this occurred.	All knew that biological traits are passed from parents to offspring, and half of them mentioned genes/DNA as responsible for this. None knew the mechanism by which this occurred. Eight children had some ideas about genes/DNA including it is in blood and used to solve crime. Four children thought genes/DNA are two separate entities.
Prior learning about models	Models already in classroom – a globe, and children had made *papier-maché* models of ocean animals.	Models already in classroom – some animal skeletons in cases, plastic model of a torso and some paper planes made by the children were suspended from the ceiling.
How the model was introduced	Referral to offspring resembling parents and what is it that makes this happen. It's DNA and it's so small we can't see it even with a hand lens to look at skin. So we will use a model to help us imagine what it looks like. The wool is not really DNA but it *represents* DNA.	Referral to offspring resembling parents and what is it that makes this happen. Some of you know it's DNA, but not what that actually is. DNA is so small we can't see it even with a hand lens to look at skin. Not even with a microscope like this. So we will use a model to help us imagine what it looks like. The wool is not really DNA but it *represents* DNA.
Lesson duration and participants' response	45 minutes: Interest level was very high. They were on task for the whole lesson. They asked some surprisingly deep questions and listened intently to the answers.	60 minutes: Interest level was extremely high. They were on task for the whole lesson despite being end of day. They asked more questions than I could answer in the time; one followed me to the car park still asking more.
Participants' capability of handling the model	Had difficulty knotting the second strand but persisted with help from teachers. Easily matched the strands, and saw that everyone's DNA was different except that of the identical twins. Immediately connected that the sameness of their DNA had to do with their being identical twins. Showed they understood the	Some had difficulty knotting the second strand but learned quickly. Treated the model very seriously and quickly saw everyone had different DNA. They quickly caught on to genes, alleles, some genes having more alleles but each person only having two alleles for each gene. They came up with the idea of

	model represented something in our bodies that makes us look the way we do. With the explanation of genes and alleles, the children quickly grasped the idea that some genes have several alleles but each of them only has two alleles for each gene.	individuals being homozygous or heterozygous for particular genes though didn't know those terms. They seemed to understand chromosome more clearly than the Year 2 students.
Participants' contribution to the discussion (student questions in **bold**)	**How does the DNA actually make us look like Mum or Dad?** I said that it controls what chemicals can be made in different parts of the body and it's these chemicals that end up making us look the way we do. **Where does the DNA came from?** I said one strand came from Mum and the other from Dad, and reiterated that we have a lot more DNA than represented by this model. Each strand is much longer and when it coils up it makes a chromosome and we have 23 pairs of those. **How can DNA help us solve crime?** I said that the DNA would be more similar in each of your families than with different families but each of you has your own unique combination of alleles from Mum and Dad, so you could be identified if your DNA was collected at the crime scene. **What about the identical twins – they have the same DNA so we wouldn't know which of them did the crime?** I said there might be very small differences but yes, the fact that they are identical twins would make it difficult to be sure.	**Does it make a difference if some people have the same two alleles for a gene while others have two different ones?** I said yes, it can make a difference in inheritance as some alleles are more likely to show up in the offspring than others are (the idea of dominant/recessive alleles). I related this to human features such as tongue rolling and ear lobe attachments, pointing out these features are rare in possibly being controlled by one gene each. **What about Viking genes? Irish genes?** Led to ideas that traits are due to many genes working together, and that individuals in populations may have similar alleles for some of these genes. This produces national similarities but there are no such things as Viking or Irish genes. Used example that Irish populations may have lots of genes for red hair and green eyes while Scandinavian populations may have lots of genes for blond hair and blue eyes but it's not true for every Irish or Scandinavian individual. **Genes cause disease like breast cancer?** I explained this was a lazy way that mass media mentions genes – the gene exists because it has a biological function and disease is usually the result of something being wrong with the gene. They were familiar with cystic fibrosis (CF) so I explained this was a very large gene with 100s of different alleles (not just five like the green gene on the model). Its job is to help transport chloride (part of salt) between fluids but when it goes wrong, the fluids get thick and sticky. This is why people with CF need to have mucus drained from their lungs and take pills to help them digest food. They gained an appreciation that one gene's function could affect different parts of the body. They realised that depending on the specific alleles inherited, the disease could look different in different people. **Is each feature, like a big nose, caused by a gene?** No, most features are due to several genes working together. People's noses aren't just two sizes, big or small, there's a range of sizes and that's because of the alleles a person has on several different genes. **What about identical twins? Wouldn't they have the same DNA?** Yes, they would. **Non-identical twins wouldn't have the same DNA? Definitely not if one boy and one girl, but not if they're both the same sex either?** I confirmed their deductions.
Lesson closure	The nature of the model was reiterated – the wool is a way of helping us imagine what DNA is like, it is not actually DNA. The model represents only a small piece of DNA, we have much more.	The nature of the model was reiterated – the wool is a way of helping us imagine what DNA is like, it is not actually DNA. The model represents only a small piece of DNA, we have much more.
Evidence of fundamental learning established in post-interview 2 weeks later	More than half knew that the wool represented DNA (other answers being chromosome and gene), all could count the genes on the DNA molecule, and most knew that the coloured sections represented genes or alleles (some confusion between these terms). All but one of those without a twin realised that no one would have exactly the same DNA as them, and the twins correctly answered that only their twin sister had the same DNA. When asked who might have *similar* DNA to them, all but one correctly named family members such as Mum, Dad, sister, brother, aunt or just "family".	Ten out of 12 spontaneously mentioned DNA/genes as making offspring resemble parents, and knew the wool represented DNA. Eleven could count the genes and more than half correctly identified all of DNA, genes, alleles, and chromosomes. All suggested that parents and siblings would have similar but not exactly the same DNA as themselves. When specifically asked what genes do, seven referred to family relationships and resemblance, four referred to genes doing lots of different things, working to form body parts and features, with one further clarifying that lots of genes have to work together to do this. Only one had no idea what genes do.
Evidence of higher order learning in post-interview (given that the	All but one student had made the conceptual link that living things would contain DNA, and four further realised that once-	All had made the conceptual link that living things would contain DNA and 11 had further realised that once-living things

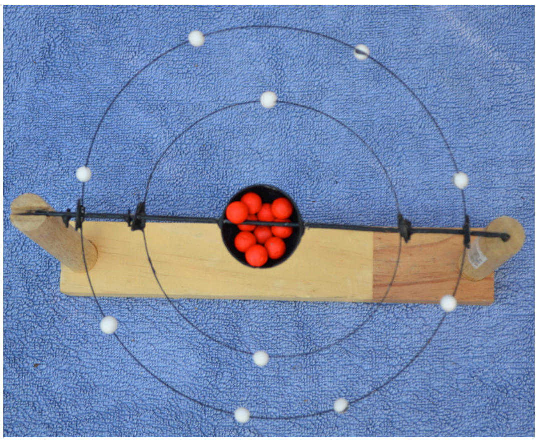
in post-interview (given that the lesson had focused on DNA in humans)	things would contain DNA, and four further realised that once-living things may still contain DNA. All but one student had transferred their understanding of DNA to cats, realising that cats and kittens with the same physical traits were probably related and would have similar DNA. Two students further generalised their ideas by adding "Has DNA" to their list of characteristics of living things.	contain DNA and 11 had further realised that once-living things could still contain DNA. Ten out of 12 had transferred their understanding of DNA to cats, realising that cats and kittens with the same physical traits were probably related and would have similar DNA. Two students further generalised their ideas by adding "Has DNA" to their list of characteristics of all living things.
Types of learning seen	• Acquisition of genetics language. • Understanding of the model and what the model represents in our bodies. • Concrete visualisation of a mechanism to explain the process of inheritance. • Integration of new knowledge into their existing conceptual framework about living things. • Capacity to generalise their understandings to other organisms.	• Acquisition of genetics language. • Understanding of the model and what the model represents in our bodies. • Concrete visualisation of a mechanism to explain the process of inheritance. • Coalescence of DNA/genes from separate entities into related entities. • Recognition that genes/DNA have a biological purpose. • Integration of new knowledge into their existing conceptual framework about living things. • Capacity to generalise their understandings to other organisms.

It is acknowledged here and to the children that the model conveys a simplistic view of genes that does not reflect the complexity of the 'real thing' but it was felt that this complexity could be added later. This is especially likely if a strong foundational understanding has already been achieved as indicated by these findings.

Case Study 2

This research was sparked by media attention and subsequent contact with a science teacher, Ian Stuart, who had devised a program for teaching atomic-molecular theory to students in Years 3 and 4. His claims of success had not been verified by independent research so we (first and second authors, Jenny and Carole), chose to conduct a pilot study with him in a new school. In this study, Jenny and Carole shared in the design of the research, and conducted half of the interviews each, so in this section, use of the word "we" refers to Jenny and Carole. The initial data analysis was done by Carole. Ian is referred to by name. The classroom teacher opted to maintain a background role, seeing herself as an "expert learner" in this project.

Ian had already designed and built his own classroom sets of models to suit his program. These include atomic models with shells for building concepts of atomic structure, the octet rule and valency (an example of which is shown in Figure 1), and magnetic atoms with which to assemble molecules (an example of which is shown in Figure 2). Figure 1 shows an overhead view of an atomic model completed by a student to show the proton and electron configuration of neon (neutrons are omitted for simplicity) and Figure 2 shows an assembled model of methane.



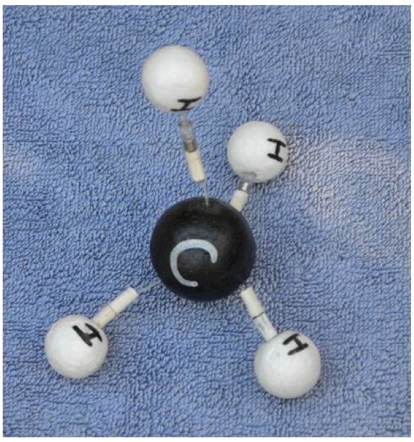


Figure 2: Molecular model of methane / Both types of models designed and constructed by Ian Stuart.

In this study, we used pre-interviews to ascertain students' initial understandings (if any) of atoms, molecules, elements, protons and electrons, and their attitudes towards science. Post-interviews were conducted after the conclusion of the program, and retention interviews eight weeks later. Table 2 summarises the research process and findings for Case Study 2 in line with that shown in Table 1 for Case Study 1.

Table 2: The use of atomic and molecular models and the resultant learning in students from 26 students in Year 4 and 1 student in Year 1

	Year 4 Students and one Year 1 Student
How participants selected	Parent of one Year 4 student and the Year 1 student campaigned to have the program in the school following media attention
Number of participants for whom full data obtained	26 Year 4s and one Year 1
Academic background of participants	Highly diverse as explained in methods, seven children with special needs
Prior learning established in pre-interview	Only two (those whose parent had campaigned for the program) had significant pre-knowledge of atoms and molecules. One other had moderate prior knowledge. Half the children claimed to have heard of molecules but had no further information.
Prior learning about models	Uncertain, so Ian introduced them by using two different models of the same thing i.e. a model skeleton and a whole-animal model of the same dinosaur. Children quickly realised that models are not the real thing but represent the real thing, that models only give part of the story and that different models can show particular aspects of what something is like.
How the models were introduced	Children were introduced to the Periodic Table. From this, the concepts of increasing atomic weight due to increasing numbers of protons and electrons were established, using the atomic shell model to build the first 10 elements. Finally, the magnetic models were introduced as representing a condensed view of the atoms. The magnets represent valence electrons that could be shared with those of other atoms to form bonds, thus combining atoms to form molecules.
Lesson duration and participants' response	This was a 10-week program with each lesson lasting about 60 minutes. Children enjoyed the lessons but as the classroom teacher rarely talks to the whole class as one, they were unaccustomed to this style of delivery used by Ian. They enjoyed the activities, including the models and testing metals for electrical conductivity. Children were proud of their learning 'high school science'.
Participants' capability of handling the models	The small Styrofoam beads simulating electrons became a bit battered with use, but the heavy red balls for protons were no problem. The children readily used the magnetic models.

Key points of the program with comments regarding participants' attainment (in **bold**)	Lesson 2: Nathan declared **he was going to be a scientist and solve the world's problems**. Edward (who has intellectual impairment - II) was **able to read the Periodic Table and locate atomic numbers.** A student made an **"I love science"** drawing for Ian. Lesson 4: students loved **learning about electric force** by bending streams of water and other similar activities. Questions showed **students were already familiar** with such forces but **lacked the language** to articulate this. Lesson 5: **students used magnets to consolidate the rules** learned when considering electric forces. **Most understood the rule** but only about 1/3 could translate it to mathematical language (inverse). Lesson 6: students **used the atomic shell models to understand protons and electrons. Wide-ranging maths abilities** (from Hanadi being unable to work out 13-(8+2), to Nathan understanding that $10^0=1$) made this challenging to teach to the class as a whole. Lesson 7: students used the atomic shell models to **construct and learn the first ten elements.** After doing the first three together, they were readily able to build the next seven. Edward (II) **managed the proton arrangements but had more difficulty with the maths involved with the electrons.** A standout question: **If an electron leaves an atom, doesn't it stop being an atom?** This led to an unexpected discussion of ions. Lesson 8: after an **initial chaotic phase with the magnetic models,** they were able to **discover the valency of H, O, N, and C** before constructing a range of specific molecules. A student asked, **Hydrogen is on the left side of the Periodic Table – is it a metal?** Ian pointed out the uniqueness of hydrogen but that frozen hydrogen is very like a metal in conducting electricity. Much **social learning and correction** occurred whilst making the molecules. Lesson 9: students **constructed small alkanes, ethene,** and then **polyethylene, an "aha" moment.** They then **made up their own molecules, writing formulae.**
Lesson closure	Each lesson recapped the key concepts introduced in that lesson. These were further supported with worksheets and videos designed by Ian.
Evidence of fundamental learning about atoms and molecules established in post-interview	***Atoms:*** All but one knew atoms were very small and most offered extra information; 18 said that they make up everything. Ten children drew external views of atoms as small circles, 12 drew increasingly sophisticated internal versions of the atomic shell model, with five adding correct charges and the element name (see Figure 3 by Seb). Further questioning revealed that all knew about protons and electrons though some got the locations or charges the wrong way round. Seventeen explicitly explained the octet rule, yet when asked to use the Periodic Table and the model to make neon, all but Edward could do so correctly. ***Molecules***: All but two knew molecules, 16 said they were larger than atoms, with seven saying they were atoms joined together and eight others supplying that information via drawing a molecular or structural formula. Eleven children named molecules such as water, CO_2, H_2, methane, ethane, and acids. The 17 drawings ranged in complexity from simple ball-and-stick representations to Loughlin (with ASD) who showed how H and O share electrons to make water (Figure 4). Some complex molecules were also correctly drawn including CH_3CH_2OH, CH_6ON_2, C_2H_5ON, and $CH_3CH(OH)CH(OH)NH_2$ (see Figure 5). .

Evidence of higher order learning about atoms and molecules in post-interview	***Atoms:*** Following the activity in which children were asked to build a neon atom using the model, they were asked if neon would combine easily with other atoms. Out of the 15 students who answered in the negative, eight clearly reasoned that neon's full outer shell of eight electrons prevented neon from sharing or accepting electrons from another atom, whilst another five recognised that neon's electron configuration was relevant. ***Molecules***: After building a methane molecule, the children were asked to work out how many bonds silicon could form. Five students were able to state that silicon would form four bonds. Without prompting, Christian and Loughlin worked this out from the electron configuration of silicon (2,8,4) whilst Nathan stated that Group IV elements formed four bonds.
Evidence of robust learning about atoms and molecules from retention interview	***Atoms:*** Despite an eight week gap, those children who had demonstrated significant understanding of the sub-atomic structure of the atom retained their understanding. For example, Seb who drew oxygen in the post-interview (see Figure 3) was able to draw the electron shell arrangement of beryllium and Ellen drew the lithium atom correctly both times. A few students (e.g. Emilia and Oliwia) drew representations of atoms that were *more* accurate in the retention interview. Understanding of the limitation of the physical model (it had only the first two shells) was tested when they were asked to build a sodium atom. Only three students were unable to respond, but 21 stated a third shell was needed for the extra electron of sodium and a further two just stated that there was not enough space. ***Molecules***: The same retention and clarification of children's understanding was demonstrated for molecules. Seven students were able to draw correct molecules at the post interview and drew different ones eight weeks later. Two students drew the same molecule both times, whilst Nathan and Danisha drew more complex molecules at the retention interview. To test whether students' capacity to build molecules was dependent on the kit designed by Ian, children were asked to build methane using a previously unseen molymod kit. They were supplied with a key showing the symbols and colours of different atoms and a brief explanation about how to use the connectors to join the spheres. After some pauses to think, almost all students were able to manipulate the molymod kit to build methane and write its molecular formula. Only two students had forgotten how to build molecules whilst one student (Mark) built ethane instead of methane. A further opportunity to observe children's problem solving skills and understanding of molecular formula was included in the retention test. Children were asked to build carbon dioxide and write its molecular formula. Eighteen students were successful. Some required no hints. The rest explored various linear and ring combinations of O and C, and after a prompt that only suggested the long connectors could bend, were able to build a carbon dioxide molecule.

Figure 3: Seb's oxygen atom

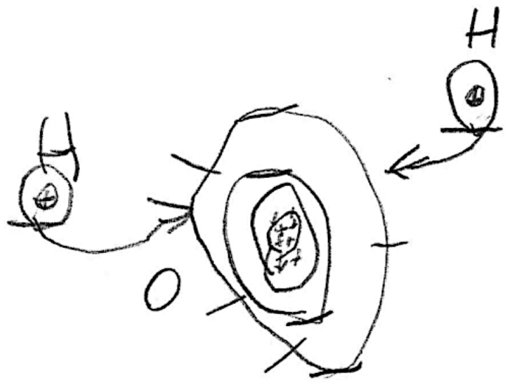


Figure 4: Loughlin's formation of a water molecule

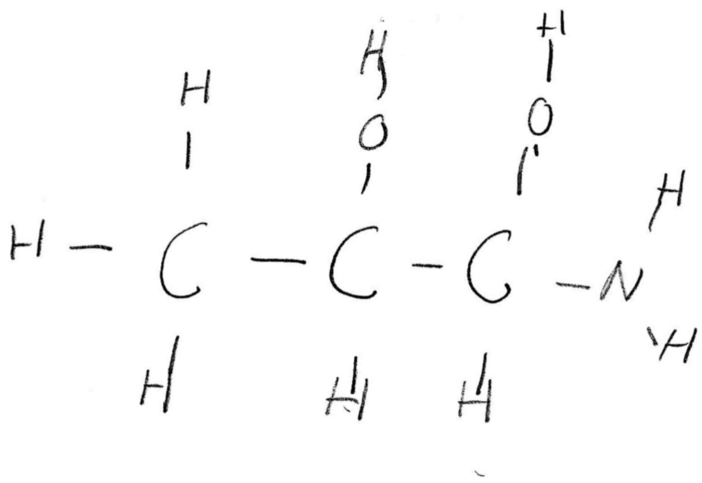


Figure 5: Oliwia (ESL) drew a complex made-up molecule correctly

Data analysis further highlighted the positive influence of the models. Children could clearly express more understandings about atoms when manipulating the model than by verbal or drawn means and very little learning was lost two months later as shown by Figure 6.

Figure 6: Children's understandings of atoms in different modes in post and retention interviews

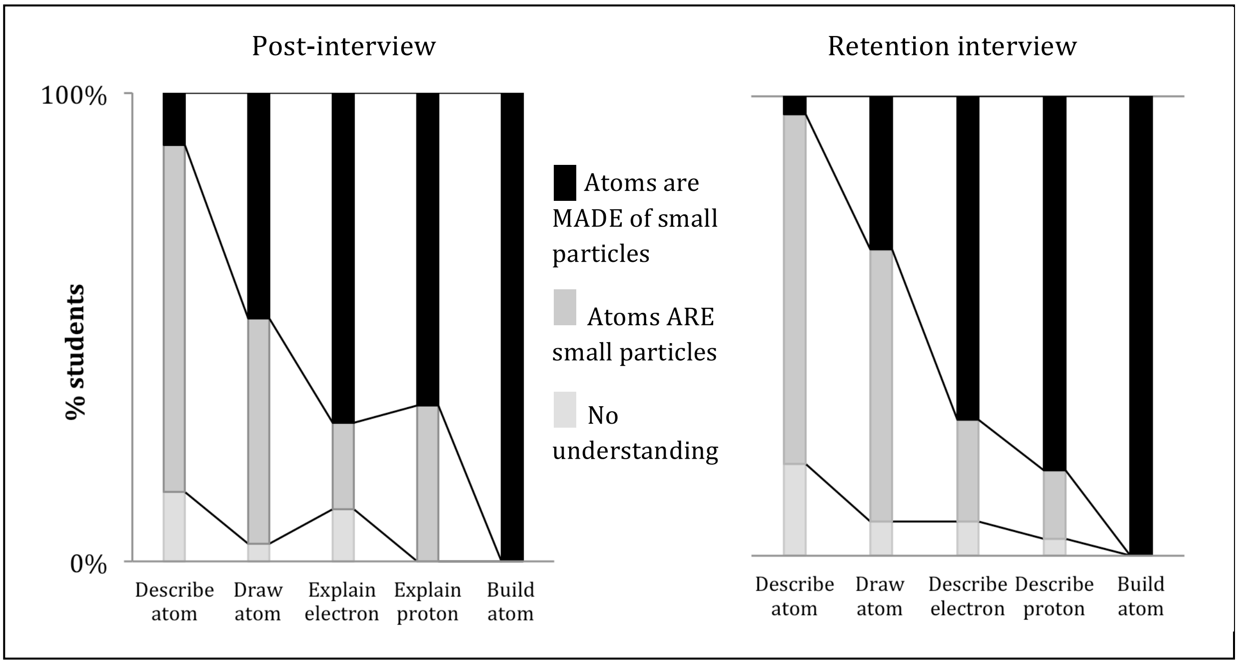


Figure 6 shows that drawings allowed children to express more understanding than they could accomplish verbally, but all could use a model to build an atom. Given the diversity in this participant group, this indicates that models were accessible to all children, despite language, sensory, or intellectual impairment. Similar improvements were noted in the children's capacity to express their understandings of molecules as shown in Figure 7.

Figure 7: Children's understandings of molecules in different modes in post and retention interviews

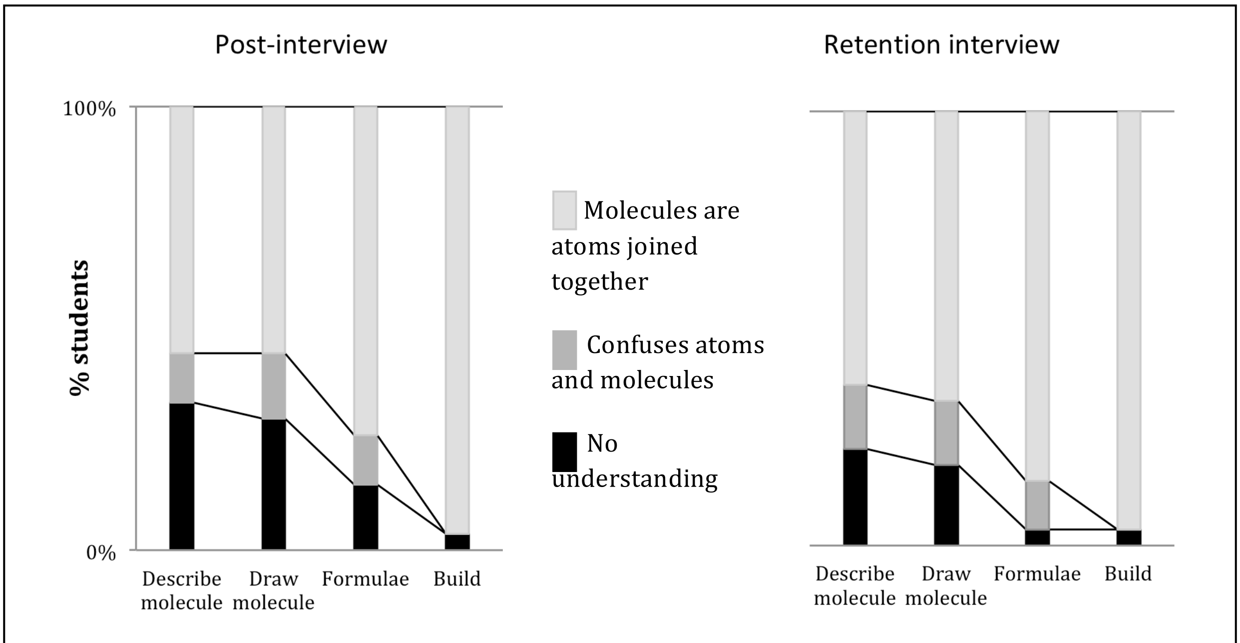


Figure 7 shows that confusion, evident when speaking or drawing molecules, disappeared when the model was used to build molecules, and that nearly all children could build a molecule with the model. There was improvement over time. Collectively, Figures 6 and 7 indicate that models are a powerful way for young children to express their understandings about concepts that are generally considered too abstract and intangible for them to grasp.

Discussion

The findings from Case Study 1 indicate the power of a tangible model to help young children imagine something as complex as genes and DNA, resulting in understanding not only of the model as presented, but understandings that were generalised beyond the model. By carefully introducing the model at the start, then revisiting the same ideas at the close of the lesson, the children realised and could later articulate that the model represented DNA; it was not actually DNA. In education, research has to do no harm, so it was not feasible to find similar Year 2 and Year 5 classes and attempt to teach them about DNA in a theoretical manner, without recourse to the model. This could have left students with misconceptions, confusion, and/or feelings that genetics will always be too difficult for them. However, our experiences as teachers led us to the strong intuition that a theory-only approach would not have resulted in such robust learning.

Also striking was the capacity of such young children to engage with these concepts, and their excitement and interest in doing so. The children were on task throughout the lesson and the depth of their questions enabled exploration of all the fundamental understandings anticipated, and more. Having formerly battled to engage high school students with these concepts, this experience permanently changed the first author (Jenny)'s thinking about science in primary school. I could see that this is when students are eager for this knowledge; to use an analogy, they were drinking it in eagerly instead of my having to force it down their throats. This made engaging with these ideas a far more pleasant experience for all. This experience fired my ongoing drive to find out more about what primary children are capable of grasping with appropriate support, and to press for more engagement with these ideas in primary schools.

As an aside, Case Study 1 also demonstrates the value in revisiting old data with the benefit of fresh eyes and hindsight. The discrimination between fundamental understandings and higher order thinking seen in the data and articulated here is novel. This sheds further light on the power of the model to assist in developing children's understandings of complex concepts, indicating that it has the capacity to promote higher order conceptualisation and generalisation, even when used in only one lesson.

The findings from Case Study 2 show that a very diverse group of young children can substantially engage with atomic-molecular concepts when introduced with thoughtful pedagogy involving as much hands-on activity as possible. To that end, models were purpose-designed and used extensively during the lessons to illustrate key concepts about the structure of atoms and molecules. All the children, even Edward with intellectual and speech-language impairment, acquired some fundamental understandings of atoms and molecules. Most were able to acquire a considerable amount of knowledge of these topics, and this knowledge was generally robust, as seen in the retention interviews. Higher order thinking is evidenced in questions which required application of knowledge and understanding in new situations and examination of the limitations of a physical model.

Figures 6 and 7 graphically indicate the power of the model not only in the active learning phase but also as a particularly effective means of expression of understandings gained. As reported fully in Donovan and Haeusler (2014), the children's attitudes towards science, already positive, were only enhanced further by their engagement with the program.

Taken collectively, Case Studies 1 and 2 demonstrate that children are capable of using physical models, adhering to Harrison and Treagust's (1998, 2000) and Krajcik and Merritt's (2012) definition of models, to arrive at some level of conceptual or theoretical model, such as promulgated by Stewart, Cartier, and Passmore (2005). Children in Case Study 1 made important generalisations from the model to their existing conceptual frameworks about living things and inheritance. In Case Study 2 children were able to use their knowledge acquired from their use of the models to attain higher order thinking such as predicting the bonding capacity of atoms not previously studied and building complex molecules.

In both cases, the models represented something too small to be seen, and made invisible and intangible objects and processes visible and tangible to the students. The models were carefully introduced in ways that made it clear that the models were only physical representations of a thing, not the thing itself. Children subsequently showed that they are capable of grasping this understanding. No harm to children's understandings from using the model was evident in the data. To the contrary, extant misconceptions such as the separation of DNA and gene were largely mitigated by exposure to the models.

In keeping with the findings from Harvard (2008), the models apparently gave children time to think and grapple with the concepts, assisted students in Case Study 1 to understand a process, and helped some children to develop modelling language, as some children in Case Study 2 drew distant and close up views of the atom. Further, the models appeared to help children develop considerable technical language, but also provided an alternative way of expressing understandings when such language failed them.

The three of us contend that models not only help children to make meaning, but also provide them with a powerful and effective means of conveying that meaning to others.

Conclusion

Both case studies support the use of physical models in the science classroom. Their successful use is contingent upon the crucial step of establishing what type of model is being used, and the reason for its use. It is also important to emphasise that the model is a representation, not the real thing, and in concert with that, to point out limitations of the model. Combined with thoughtful pedagogies, models provide hands-on experiences that children value and that are valuable for them.

Models can enable young children in primary school to grapple with complex and intangible concepts usually considered too advanced for them, and restricted to high school. Children use models to acquire technical language and some advanced understandings. Models are not just for students with average or above average intellects and favourable prior educational experiences; in Case Studies 1 and 2 they were effective for students from non-English speaking backgrounds, and in Case Study 2 they assisted children with Autism Spectrum Disorder, sensory impairment, speech-language impairment and intellectual impairment to attain some level of understanding. Children enjoyed the lessons, the models, and the intellectual challenges, and were proud of being able to learn ‘high school science’.

The findings from these case studies support Bruner’s (1960) contention that it is possible to teach any topic to children in an intellectually honest way with appropriate pedagogy. These findings relate to science, but many other disciplines employ models of various types. Concrete models appear to enable children considered to be in Piaget’s concrete stage of development to attain understandings more consistent with Piaget’s formal operational stage years prior to their expected transition to this stage. Models not only allowed the children to make meaning, they provided an effective means for the children to express their understandings and convey meaning to others.

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