

# Developing scientific literacy: introducing primary aged children to Atomic–molecular Theory

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## EXECUTIVE SUMMARY

This chapter challenges existing school science curricula modes for teaching atomic-molecular structure and describes a current research project designed to provide supporting evidence for reviewing school science curricula. Using evidence from this project and other research studies, the chapter argues for the introduction of atomic-molecular structure in the curriculum at Year 3 or 4 and proposes that consideration be given to devising a spiral curriculum in which the macroscopic and microscopic properties of matter are taught concurrently rather than sequentially.

## KEY TERMS AND DEFINITIONS

**Affective domain:** The field of study concerning perceptions, beliefs, and attitudes about a topic.

**Atomic-molecular theory:** One of the ‘Big Ideas’ of science; all matter is made of atoms, many of which are joined to make molecules.

**Cognitive domain:** The field of study concerning knowledge held about a topic.

**Learning progressions:** Sequences of concepts increasing in sophistication designed to be taught each year so that learning progresses over time; such progressions are integral components of a spiral curriculum.

**National science curriculum:** Detailed plans for learning and teaching of science developed for implementation across a nation, including such curricula for Australia, the USA and the UK.

**Piagetian model of developmental stages:** This idea, developed by Jean Piaget and other psychologists, contends that children experience distinct phases of development in terms of their cognitive capacities.

**Primary children:** Children who attend primary school: in Australia, this includes children from ages 6 to 11 years.

**Scientific literacy:** The capacity of people to understand science sufficiently to make informed decisions about scientific issues.

**Spiral curriculum:** An idea developed by Bruner and others, that concepts are best presented early to create foundational knowledge, and then revisited often and built upon over successive years.

## ORGANIZATION BACKGROUND

Three years ago, a former high school teacher responded to questions about matter and atoms from his young son. His son's interest and apparent capacity to grasp the concepts led to the teacher offering to teach the rest of his son's primary class. The apparent success of this early venture led to further development of the teaching and learning program and the backyard development of innovative hands-on models to better facilitate the learning. We are two science teachers, now University educators of preservice primary teachers, who became interested in this program. Our study seeks to verify whether the teacher's claims of success can be supported by research. Consequently, the research participants in this case are a diverse class of Year 4 children in a school new to the specialist science teacher. Our research examines the development in these children's understanding of atomic-molecular theory from their learning experiences with the specialist science teacher following 10 hours of instruction on atoms, molecules, and elements (1 hour per week over a 10-week period).

## SETTING THE STAGE

Commonly, the teaching of atomic-molecular structure begins in high school. For example, in the new Australian Curriculum: Science (Australian Curriculum, Assessment and Reporting Authority [ACARA], 2013) the first mention of 'atoms' is in Year 9, when most students are 14 years old. The new K-12 Next Generation Science Standards from USA (National Research Council [NRC], 2013) are based on disciplinary core ideas from their earlier framework (NRC, 2012). This K-12 Framework introduces particles at Grade 5, and then elaborates these as atoms at middle school level, Grade 6. By the end of Grade 8 students should know there are approximately 100 different types of atoms, but even in this bold new curriculum which aims to introduce core ideas in science, technology and engineering from students' earliest schooldays, the details of atomic-molecular structure and the Periodic Table are still not tackled until Grade 9. However, at least this progression attempts a spiral curriculum (pioneered by Bruner, 1960) by introducing the scientific language of atoms earlier and building upon this baseline. The new national science curriculum to be introduced in the United Kingdom from September 2014 appears at first glance to be conservative, but introduces the particle model and atoms from Key Stage 3, i.e. Year 7 and onwards (Department of Education, 2013). However, this is classed as high school and part of the secondary science curriculum; there is no mention of atoms in the primary science curriculum.

Yet an Australian researcher (Jakab, 2013) found that most of her participants aged 8 years or older could state some everyday knowledge of molecules when first asked, and some 11 year olds had sophisticated knowledge, one expressing the aspiration to become a particle physicist. This chapter will report on an independent innovative attempt to teach children of equivalent age about atoms, atomic-molecular theory and the Periodic Table.

This practice of leaving atomic-molecular structure to high school seems to be the consequence of the developmental stage theory of Piaget and others (Inhelder & Piaget, 1958). Interestingly, in the Australian context, this approach also seems to coincide with broad student resistance to, and lack of enthusiasm for, the learning of science. This is evidenced by measureable decline in the number of Australian secondary students who continue with the study of science, particularly the physical sciences, into the final years of high school and university (Goodrum, Druhan, & Abbs, 2011). Yet research reported by Tytler and Osborne (2012) has shown that students are highly interested in science at 10 years of age, and form their career aspirations by age 13 or 14. The importance of engaging students early in science education is supported by other studies: grade 8 students who expected to have a career in science are more likely to graduate with a science degree (Maltese & Tai, 2010; Tai, Lui, Maltese, & Fan, 2006) and 65% of a sample of scientists and graduate students had developed their interest in science before middle school (Maltese & Tai, 2010). Leaving the 'Big Ideas' of science until high school may be too late.

## **The problem with Piaget**

The Piagetian model of developmental stages (Inhelder & Piaget, 1958) holds that children pass through four defined stages of cognitive development. Infants to age 2 years are in the sensorimotor stage, and from ages 2 to 7, children are in the pre-operational stage, during which they cannot conserve quantity nor think logically. Children aged 7 to 11 years are in the concrete operational stage in which they begin to think logically but only with practical aids, and from ages 11 to 16 years and onwards, children transition to the formal operational stage with the development of abstract thinking. It is on this basis that abstract concepts such as atoms are delayed in curricula until children are in the middle of the proposed transition to the formal operational stage.

Curiously, some curricula are inconsistent, in that some abstract concepts such as atoms and DNA are delayed, whereas other abstract concepts, such as energy, are not. For example, energy is introduced in Year 6 in the Australian curriculum (ACARA, 2013) and in Grade 4 in the new USA standards (NRC, 2013). However, the forthcoming UK curriculum is more consistent in that neither atoms nor energy concepts are mentioned in the primary curriculum (Department of Education, 2013).

Piaget's theory has been challenged by developmental psychology (Bidell & Fischer, 1992). Children's cognitive development is highly variable, and variability exists at all ages, in all areas of learning and at all points in learning (Siegler, 2007). Not only does variability exist between different people, it is also evident within an individual solving the same problem at two points close in time, or even within a performance on a single problem. Variability in thought and actions occurs in infants (Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997), toddlers (Chen & Siegler, 2000), pre-school children (Flynn, O'Malley, & Wood, 2004), older children, and adults. In a study of the development of scientific reasoning (Schauble, 1996), grade 5-6 children and non-science adults demonstrated significant variability in understanding of content and experimental strategies. The way people think is constructive, dynamic and culturally embedded, as are the organisation and pattern of their psychological structures (Fischer & Bidell, 2006). Rather than following distinct hierarchical stages, children's cognitive development shows variability in the age, synchronicity and sequence of acquisition of specific skills (Bidell & Fischer, 1992), and this variability is dependent upon factors such as the area of learning, cultural background, learning history and learning style.

Siegler's overlapping waves theory (Siegler, 1996, 1998, 2006) also recognises the variability in cognitive development. For example, in solving problems, children choose adaptively among strategies, with some strategies becoming less frequent, others becoming more frequent; new strategies are discovered and others abandoned. A similar pattern of variability has been found in the age, synchronicity, and sequence of children's understanding of the concept of matter. Applying Fischers' dynamic skill theory (Bidell & Fischer, 1992) and Siegler's overlapping waves theory (Siegler, 1996, 1998) to the US sample from Third International Mathematics and Science Study (TIMSS) data set, Liu and Lesniak (2005) proposed a model of student matter concept development from elementary to high school which comprised a series of multiple successive and overlapping waves. A subsequent phenomenographic study by the same authors (Liu & Lesniak, 2006) of grade 1 to grade 10 students' conceptual progression patterns on matter confirmed that there was no clear conceptual leap between different grade levels.

## **Children's curiosity and innate capabilities**

Piaget's theory underestimates children's capabilities. Many young children display uninhibited curiosity that has an affinity with the scientific method and philosophy itself. As the following examples will show, they are more than simplistic thinkers and are able to engage in quite sophisticated reasoning processes that are the foundations for scientific thinking (Fleer, 2009). Elementary aged children used the intuitive rule "everything comes to an end" when asked to consider the continual subdivision of both material and mathematical objects (Smith, Solomon, & Carey, 2005; Yair & Yair, 2004). In discussions about the process of evaporation (Tytler & Peterson, 2000), 5 year-old children used elementary conceptions of substance. Prior to instruction, children aged 7-10 were able to express naïve ideas of the particulate nature and behaviour of matter (Nakhleh &

Samarapungavan, 1999). Similarly, Jakab (2013) describes how 6-11 year-old children were able to articulate ideas about the molecular nature of matter when offered the use of molecular artefacts such as symbols, diagrams, models and a website with interactive models.

## **The importance of background knowledge and the quality of instruction**

The conclusions of cognitive psychology (Hirsch, 2006; Willingham, 2008) reveal that learning history and learning style are important factors in the conceptual development of children. Background knowledge is critical in providing contextual information enabling children to make sense of what they read, view and absorb from the world around them. Therefore, both Willingham and Hirsch consider it integral to practice to expose children to background knowledge that may appear to be beyond their immediate full understanding but which helps to provide contextual information for future learning. In this, they follow in the footsteps of Bruner, who in 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.

Murphy (2012) supports Vygotsky's contention that learning leads development, so teachers should always be challenging students rather than waiting for them to reach a predetermined developmental stage. Unfortunately, curricula do not always reflect these insights, and rarely give children the opportunity to engage with concepts beyond their current level of thinking or to revisit them periodically. Willingham (2008) points out

For children and adults, understanding of any new concept is inevitably incomplete. . . . If you wait until you are certain that the children will understand every nuance of a lesson, you will likely wait too long to present it. If they understand every nuance, you're probably presenting content that they've already learned elsewhere. (p. 39)

It is the thinking of researchers such as Bruner, Willingham, and Vygotsky that encourages the earlier introduction of concepts, with concrete aids where possible. This aims to facilitate the transition of children through development in their cognition, whether or not such development occurs in set Piagetian stages or more gradually.

The conceptual understanding of children may be limited more by the quality of instruction than by any developmental process. In the 2007 National Academies report (Duschl, Schweingruber, & Shouse, 2007), *Taking Science to School : Learning and Teaching science in Grade K-8*, the authors reviewed the extant literature on cognitive and developmental psychology and science education. The conclusion from this review was that what young children are capable of is largely dependent on their prior opportunities to learn, and is not determined primarily by some fixed sequence of developmental stages. A student (or even a whole class) not understanding something does not mean that the task was developmentally inappropriate. Lack of understanding may indicate a lack of prerequisite knowledge or an ineffective way of presenting the material to make it easier to understand.

We note that the concept of teaching the 'Big Ideas' of science to younger children is not new. Other researchers have worked on ways of doing so; but thus far, curriculum policy has kept its distance from the outputs of such research. Effective teaching interventions can allow children to learn about atoms and molecules. Using role-play and building molecules with ball and stick molecular models can assist grade 5 students to learn about important molecules and their properties (Brown, Rushton,

& Bencomo, 2008). Third grade students, exposed to a one-hour digital presentation of molecular models, were able to describe and draw accurate representations of molecules (Halpine, 2004). In 1993, Lee, Eichinger, Anderson, Berkheimer, and Blakeslee showed that addressing common misconceptions about matter and molecules improved Grade 6 students' understanding and application of the kinetic theory of matter to states of matter, changes of state, thermal expansion and dissolving. The use of scientific modelling and argumentation in instruction is important in developing primary aged children's understanding of the atomic nature of matter (Schwarz et al., 2009). Acher, Arcà, and Sanmartí (2007) describe how 7-8 year old children used a "model of imaginary parts" (p. 401) built from their idea about the discrete materials to explain the behaviour of different materials. Extensive research by Nussbaum (1998) has demonstrated that in order to build students' understanding of atomic-molecular theory, they need to be engaged in cycles of model building and deep discussions about alternative theories and essential metaphysical and epistemological issues.

The recent development of learning progressions acknowledges that there are multiple pathways of conceptual change possible for student understanding of matter (Johnson & Tymms, 2011; Merritt, Krajcik, & Shwartz, 2008; Stevens, Delgado, & Krajcik, 2010; Wiser & Smith, 2008). However, most of these studies were based on existing curriculum models in which the macroscopic nature of matter is located in the primary curriculum and particulate models introduced in lower secondary years. Yet a longitudinal study of junior high school students in Grades 9 and 10 (Margel, Eylon, & Scherz, 2008) suggested that a long-term development of the particulate model requires building a strong foundation of knowledge about the microscopic structure of materials through a process of spiral instruction. In science, the judicious use of models, with clear explanations as to how they do and do not resemble the actual thing they are modeling, can be helpful in presenting abstract concepts to young children.

In earlier research (Donovan & Venville, 2004; Venville & Donovan, 2005), one of the authors and her colleague consulted expert geneticists for their opinions on essential genetics concepts students should acquire for everyday life, and on ways to teach these concepts. They recommended early introduction to vocabulary and use of pictorial and spatial models wherever possible. These findings led to the development of a simple wool model successfully used to introduce the essential vocabulary of DNA, gene, allele, and chromosome at a variety of age levels, the youngest being Year 2 students (aged 7 years). These students (Donovan & Venville 2005; Venville & Donovan, 2007, 2008) happened to be at an Islamic school and were all English-second-language students identified in Year 1 as requiring remedial assistance. At a subsequent post-test, these students demonstrated clear understanding that genes are made of DNA; that these molecules are responsible for our appearance being similar to that of our parents; and that identical twins would have the same DNA as each other. The model enabled them to learn some valuable genetics vocabulary and to link it with concepts of family identity. Consistent with Carey (2010), there is no claim that this fast mapping of the words 'genes' and 'DNA' enabled these students to develop full understanding of the words with all nuances of meaning. However, in current non-spiral curricula, which do not afford further exposure and opportunities for discussion and instruction, the extended mapping of these concepts, which Carey (2010) describes so clearly in the context of her research, will not occur. Opportunity has been lost. Thus we concur with Willingham's (2008, p. 39) notion that, "Without trivializing them, complex ideas can be introduced by making them concrete and through reference to children's experience."

Finally, support also comes from the field of neuroscience. It is now accepted that the brain is not fully developed early in life as was once thought. Instead, it has plasticity – structural and functional changes are possible throughout life. However, development is not linear. In very early life, the main plasticity involves the formation of new synapses, from 2,500 per cortical neuron at birth to 15,000 synapses per cortical neuron by age 3 (Gopnik, Meltzoff, & Kuhl, 1999). Adults have about half that number, so further development involves synaptic pruning. Neurons that are frequently used develop stronger connections; those rarely or never used eventually die. Learning may be defined as the ability to acquire new knowledge or skills through instruction or experience, memory as the process by which that knowledge is retained over time, and plasticity as the capacity of the brain to change with

learning (Sousa, 2001). Information is initially placed into short-term memory, but over time is transferred into long-term memory, involving physical changes in the brain (Sousa, 2001). Drubach (2000) identified two types of such physical changes: a change in the internal structure of neurons, especially in the area of synapses; and an increase in the number of synapses between neurons. Further, recent neuroscience research suggests that ages 5-10 are years of heightened brain plasticity (Abdeldayem, 2012), during which the acquisition of science's 'Big Ideas' could be perfectly timed.

## **Children's prior knowledge: The influence of media on children's view of science**

The changing structure of the brain involved with learning results from the input of data. Children of today are surrounded by the mass media. A recent study conducted by one of the authors and her colleague (Donovan & Venville, 2012a, 2012b) of 141 children aged 10-12 years in four non-metropolitan areas in three Australian states reported an average level of exposure of 5 hours and 10 minutes per day. This averages 2 hours and 30 minutes per day less than for children in the USA (Rideout, Foehr, & Roberts, 2010). Television (TV) was the main contributor to this usage, averaging 800 hours per year. Children are thus exposed to considerable input of information.

Surprisingly, the study revealed very little research into the influence of this exposure to the mass media on children's academically relevant knowledge. Much is known of its influence on opinions, beliefs, attitudes and behaviours such as body image, risk-taking, and violence, but only a few studies had exposed children to specific TV programs or movies and probed how concepts presented were taken up by children. By contrast, the author's study considered the totality of children's voluntary exposure to entertainment mass media, and followed up these named examples for mentions of genes and DNA. These were cross-referenced to the understandings about genes and DNA expressed by 62 of the children in face-to-face interviews.

Although the study design cannot demonstrate causality, nonetheless, the evidence did indicate the likelihood that the participants' knowledge of genes and DNA (which, like atomic theory, is not taught in schools until children are aged 14 or 15) has been derived from their exposure to the mass media. The same genetics themes arose from the children, particularly DNA being used to solve crime and to resolve family relationships, as appeared prominently in the media examples they mentioned (Donovan & Venville, 2012a). Specifically, words used by children to describe how DNA is used to solve crime paralleled the way it is presented in crime shows that 79% of them reported viewing, despite these shows being rated for ages 15 years and older. For example, 12-year-old Annette (a pseudonym) said, "They use a special machine, and the machine will determine if it knows the DNA or if it's used that DNA before, and it will also show what the DNA looks like so you can compare it with other DNAs and find a culprit" (Donovan & Venville, 2012a, p. 25). Further evidence came from their relative lack of knowledge about the biological structure and function of DNA, which also paralleled the relative lack of this information in the mass media (Donovan & Venville, 2012a, 2012b). With 89% of the children knowing about DNA and 60% of them knowing about genes, this finding relates to the greater exposure of DNA compared with genes in the media. Collectively, this evidence indicates that, without formal teaching, primary children are capable of understanding more about genes and DNA than previously imagined and that the mass media are the most likely source of their information.

The children themselves (80% of them) acknowledged that TV was their major source of information, and were remarkably perceptive about which specific programs provided more information about DNA and genes (Donovan & Venville, 2012a). Furthermore, 27% of the participants had conducted their own research into genes and DNA and achieved sophisticated understandings. For example, 11-year-old Willis viewed few crime shows but had become interested in DNA from documentaries. He was able to describe in detail how DNA databases work, how to take a biopsy to test for cancerous cells, and knew that animals, humans and plants all have DNA. Thus, the participants in this study support Tytler & Osborne's (2012) findings that primary children are highly interested in science.

The favourite TV show nominated by participants in this study was *The Simpsons* (Donovan & Venville, 2012b). Searching *The Simpsons* wiki ([http://simpsons.wikia.com/wiki/Simpsons\\_Wiki](http://simpsons.wikia.com/wiki/Simpsons_Wiki)) indicates the show often mentions words related to atoms and atomic theory, with character Homer working in a nuclear power plant, outside of which is Nuclear Lake where waste is dumped. The local football team is The Springfield Atoms and the baseball team is The Springfield Isotopes. Many plotlines involve science and the show is far-reaching – even the eminent journal *Nature* was moved to select the staff's 10 favourite science moments in *The Simpsons* (Hopkin, 2007). However, it is not the only TV show to contain references to science. From classics such as *Dr Who* to the meteoric rise in popularity of *The Big Bang Theory*, today's children are bombarded with science as part of their daily entertainment.

Science is also found in other mass media. For example, 11-year-old John, one of Jakab's study children (Jakab, 2013) is very knowledgeable about molecules because he loves fantasy and science fiction books. He knew about methane from the plotline of a book that he has read. It would benefit primary school teachers to consider the sources of scientific vocabulary and concepts in the everyday worlds of the children they teach and 'add the science' to such encounters. At the very least, teachers should acknowledge that their children bring prior knowledge to the classroom, some of which may have been derived from their encounters with the mass media.

## Challenging the paradigm

Science educators continue to express concern over the failure of traditional science curricula and traditional science pedagogy to engage students' interest in science (Tytler, Symington, & Smith, 2009). Wisner and Smith observe

... science curricula treat knowledge as unproblematic facts; few students have any appreciation of the coherent nature of scientific theories or the role of ideas, models, and symbolisation, and cycles of hypothesis testing in their creation. (Wisner & Smith, 2008, p. 226)

Margel, Eylon, and Scherz (2008) acknowledge that, despite the considerable time spent on instruction, existing traditional science curricula do not lead to robust particulate conceptions by the end of high school. Students' lack of understanding of matter and atomic-molecular theory continues to be reflected in many common misunderstandings (Özmen, 2004; Özmen & Ayas, 2003; Stein, Larrabee, & Barman, 2008; Vosniadou, 2012) even amongst senior high school students and college students of chemistry. Consequently, the argument that atomic-molecular theory should be introduced when students are 'developmentally' ready is flawed.

Johnson and Papageorgiou (2010) suggest that students' poor understanding of the particle theory of matter is a result of the 'solid, liquids, gases' context in which it is taught. Their work found that 9-10 year old children demonstrated greater understanding of the particle model when it was taught within the framework of a concept of substance. Wisner and Smith (2008) argue that atomic-molecular theory should be taught before students have a complete scientific theory of matter at the macroscopic level. How this is to be done has not been extensively explored. Our contention is that the elements of atomic-molecular theory should be introduced early in primary school, and continued within a spiral curriculum, revisited each year.

## CASE DESCRIPTION

### Research Participants

This pilot research project aims to verify claims made by a specialist high school science teacher that Year 3 and 4 children can learn atomic-molecular theory. Owing to mass media coverage of this teacher's innovative program, other schools have become interested in its uptake. Specifically, our research is being conducted in a metropolitan Catholic primary school in Queensland, Australia,

because a parent of children at the school suggested to the Principal that their school could become involved. This made it an apparently ideal candidate to host the pilot research, as the specialist teacher has had no previous contact with the school that could confound the results. It is envisaged that future studies would expand the number of schools, contexts and regions in which this program is offered to seek information about its generalisability to the Australian primary school population. Such broader research would also be more generalisable to the international scene. This chapter presents only preliminary results from the pilot study, in the hope of stimulating interest from potential collaborators to further this research.

Prior to commencing the research, ethics permission from both the Catholic education sector and our University was obtained, and the agreement of the Principal and classroom teacher. All participation in the research was with the written permission of parents and the continued willingness of the children to be involved, ascertained by asking them if they were happy to be interviewed each time. All names used in this chapter are pseudonyms from an appropriate cultural background.

The participants are thus a single class of 26 Year 4 children (average age 9 years 9 months) and one Year 1 child (Marcia, aged 6 years and present by the request of the parent). It is a diverse class. Three children (Kensei, Oliwia and Nadine) have English as their second language (ESL), with the latter two arriving late into the program from a holiday in their home country. Joel is another ESL student who also has Speech-Language Impairment (SLI). Edward has been designated as SLI and Intellectually Impaired (II), and requires an individualised learning program. Loughlin has Autism Spectrum Disorder (ASD) and Danisha is Hearing Impaired. The regular class teacher has welcomed the program as a professional development opportunity for herself as well as an extra learning opportunity for her students. At various times, a teacher aide and interested parents have joined the class to assist the children.

## **Research Questions**

Specifically, this pilot study sought to answer the following four research questions:

1. What do children aged 9 years believe science is, and what is their attitude towards science?
2. What prior knowledge about atoms, molecules, elements, and sub-atomic particles do children aged 9 years possess?
3. What knowledge about atoms, molecules, elements, and sub-atomic particles can children aged 9 years gain through an intervention designed by a specialist high school science teacher?
4. How can data obtained in this study inform the future development of the intervention?

## **Research Methodology**

The pilot project employs qualitative methodology involving the triangulation of three sources of data. The primary data set consists of the information gained from semi-structured interviews with individual children; this constitutes the main data presented here. Prior research experience with children of these ages yielded an expectation that repeating and paraphrasing questions in response to direct queries or body language would be necessary to achieve negotiated understanding of the questions. Consequently, a semi-structured interview protocol (Creswell, 2005) was the most appropriate method to yield rich qualitative data about children's conceptions about atoms. A secondary data set comprises the children's responses to classroom assessment tasks and the third data set is derived from teacher reflective journals.

The participant interviews are being conducted at three intervals – Stage 1: pre-instruction, Stage 2: post-instruction and Stage 3: approximately two months after post-instruction to assess children's retention of understanding. During the audio-recorded interviews, the children are able to draw or sketch how they visualise aspects of their thinking. In Stages 2 and 3, children have access to the models they have used in class in order to support their attempts to explain their understandings to the



interviewer. At the time of writing, only Stages 1 and 2 interviews have been conducted. The authors (the researchers), without input from the specialist teacher, are conducting all interviews with the children to maintain appropriate distance and lack of bias.

The triangulation of data allows us to substantiate learning by matching the children's responses in interviews to responses on teacher devised assessment tasks (e.g., short response test items, investigation reports), and to teacher reflections on the learning processes. The children's responses to the interviews and assessment tasks are being analysed using a coding schema derived from Stevens, Delgado, and Krajcik (2010). The teacher reflective journals are analysed for teaching objectives, pedagogical strategies, and teachers' perceptions of student learning.

## **What was taught during the 10 hours of instruction**

In brief, the learning and teaching program covered the atomic nature of matter, properties of metals and non-metals, including conductivity, the structure of atoms, and the relationship of atomic-molecular structure to the properties of elements and their position on the Periodic Table. The children were taught how to read and interpret the Periodic Table in terms of the related properties of groups of elements such as the noble gases, the halogens, and the alkali metals. Valence electrons, covalent bonding, and the law of conservation of mass in simple chemical changes through conservation of atoms were also covered. The interview questions were drawn from the learning and teaching program but utilised different specific examples where possible. Consequently, a greater appreciation of what was covered in the teaching and learning program can be ascertained from the interview questions, and the marking scheme for scoring these questions, supplied in an appendix to this chapter.

In particular, the specialist teacher believes that the sequence of introduction of the concepts is critical, and this has been the subject of deep consideration in his development of the program. Also unique are samples and models that he has developed to support the learning. The samples include a set of 12 metals and 7 non-metals that the children can handle, including hydrogen and helium in balloons. The models include an atomic shell model to which children can add protons and electrons to build up the first 10 elements, and magnetic molecular models that accurately simulate the shapes of molecules, valency, and the sense of the involvement of energy in the making and breaking of bonds. Learning was also supported by worksheets and videos created by the specialist science teacher.

## **Findings**

In this chapter, we will present only the results of the comparison of the preliminary analysis of the repeated questions in the pre and post interviews. Analysis of the extra questions asked at the post-interview is still ongoing. The analysis is presented within two domains, the affective and cognitive domains.

### **The affective domain**

Asking the children if they liked science in the pre-interview showed this class was already very switched on to science, with 24 out of the 27 children reporting liking the subject. This was not necessarily an expectation of the researchers, as studies have shown that the teaching of primary science in Australia is patchy (Goodrum, Hackling, & Rennie, 2001). The remaining children were unsure. In the post-interviews, the number of unsure children dropped to one, Oliwia, who said she was "in the middle" and she "liked the activities, nothing much to dislike". English is a second language (ESL) for Oliwia and she arrived late into the program owing to a holiday in her home country. However, her sister Nadine, in the same circumstance, was more positive, enjoying science, and loving the experiments. One child, Merryn, said he did not like it now, as it was too hard. Interestingly his brother Tristan had a much more positive outlook, saying he liked it in both

interviews, and looked ahead to the value of learning now about atoms for his future studies at high school. In the post-interview, Tristan expressed how much he enjoyed using chemicals and building molecules.

More differences were seen in the reasons why the children liked science. In the pre-interview, the main reason given was “fun”, whereas in the post-interview the main reason given was the enjoyment of learning about atoms and molecules. Still a quarter of the class mentioned fun, and a quarter of the class now expressed a strong love for science, that it was their favourite subject, indicating their feelings had intensified since the pre-interview. Enjoying the experiments, activities, and models featured strongly in their responses, as did enjoying the challenge of learning about new things they did not know about before. Loughlin, the child with ASD, saw science as a means of making the world a better place, and Andrew, who also liked science, had been prompted to think deeply about the conflict between religion and the Big Bang because of the lessons.

Differences occurred in what the children thought science was, as seen in Table 1. Numbers refer to how many children mentioned each idea, but as children frequently mentioned several ideas, the numbers do not total to the number of children in the class.

*Table 1: Ideas generated by children in response to the question: What do you think science is?*

What do you think science is?	Number of children mentioning each idea	
	Pre	Post
experiments/data	7	7
chemical/mixing/explosions	7	1
the earth/volcanoes/rocks	5	0
discovering/finding or learning about new things or how things or the world works/inventing	4	10
space/sun/galaxies	3	2
gravity/push/pulls/friction	3	0
Periodic table/elements	2	7
engineering/technology	2	1
atoms/molecules/electrons/protons	2	15
cure diseases/cancer/germs/medicine	2	3
animals/nature/plants	2	1
dinosaurs/extinct animals	2	1

Several trends are evident in Table 1. Before the pre-interview, the children had recently studied earth sciences, particularly volcanoes, accounting for the relative popularity of this answer, but it is apparent that not all children were constrained by this recent experience in their suggestions of what science is. Four children were already familiar with the Periodic Table, elements or atoms and atomic structure. Following the intervention, there was a large increase in the belief that science is about atoms and molecules, with more than half the class expressing this view, some of whom and others also mentioned the Periodic Table of elements. Again, children simply referring to what they had recently done could apparently explain this result. However, the numbers mentioning biological and space sciences changed only marginally, so recent experience does not entirely explain the new popularity of atoms and molecules. Experiments were still popular, but the ‘flashy’ idea that science is about chemicals and explosions gave way to more thoughtful interpretations of science, despite the program having included exploding a hydrogen-filled balloon. In particular, there was a large increase in the numbers of children believing that science is about discovering and learning about new things and how the world works.

At the end of the pre-interview we also asked the children where they had learned the science ideas they had spoken of during the interview. In descending order, their responses were school (11), parents (9), mass media – TV and movies (8), older sibling/cousin studying science (7), books (4), Periodic Table/element board (3), science show/museum (3), iPad game (1), and YouTube video (1).

Again, many of the children cited more than one source of their information so the numbers do not match the number of participants.

### The cognitive domain

Notwithstanding the importance of the affective domain, our main interest nevertheless was in seeing what children had learned from participating in the program. Considering only the questions repeated in pre and post-interviews, referring to specific knowledge about atoms, molecules, elements, and sub-atomic particles, scores were assigned to the answers as indicated in the copy supplied in the appendix. Figure 1 shows the change in these scores (out of 50) between the pre and post-interviews.

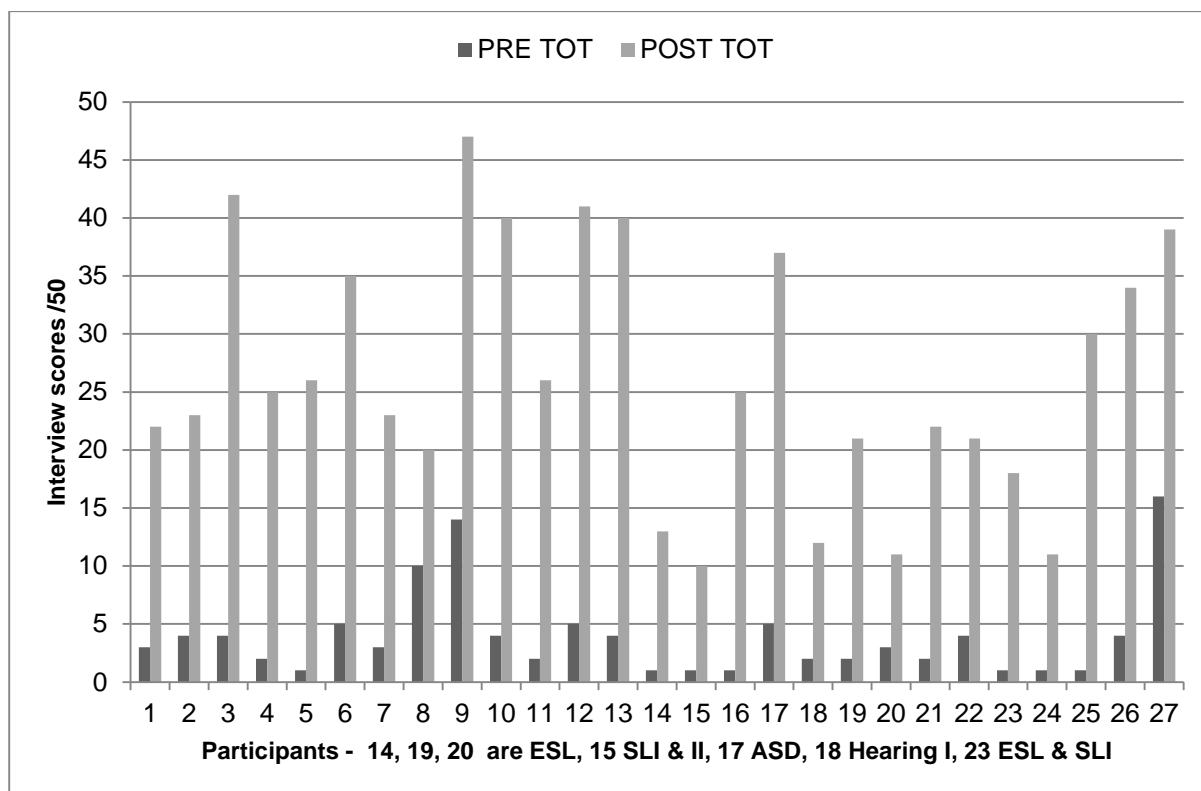


Figure 1: Individual participants' knowledge scores (out of 50) in pre and post-interviews

Firstly, considering the pre-interview scores in Figure 1, it is clear that, while most children had minimal specific knowledge of atoms and molecules before the program, two children (numbers 9 and 27) had substantially more knowledge. These two children (Christian in Year 4 and Marcia in Year 1) are the children of the parent who had pressed for the program to be taken up by the school, which probably explains their pre-knowledge.

Secondly, considering the difference between the pre and post-interview scores, it is clear that every child in the class gained knowledge. In high school, a pass would be awarded to 14 year olds scoring 25 or better on a test incorporating such questions; on that criterion, 14 of these children passed. However, high school tests are often multiple-choice questions, an easier option than being asked face to face for an answer as these children were. Also, considering these children are only 9 years of age, an argument could be made that a score of 20/50 would indicate sound learning. On that criterion, 21 children passed. Given the diversity in this class, this is an outstanding result.

An alternative way of viewing their progress is shown in Figure 2, which maps the percentage increase in the knowledge of participants.

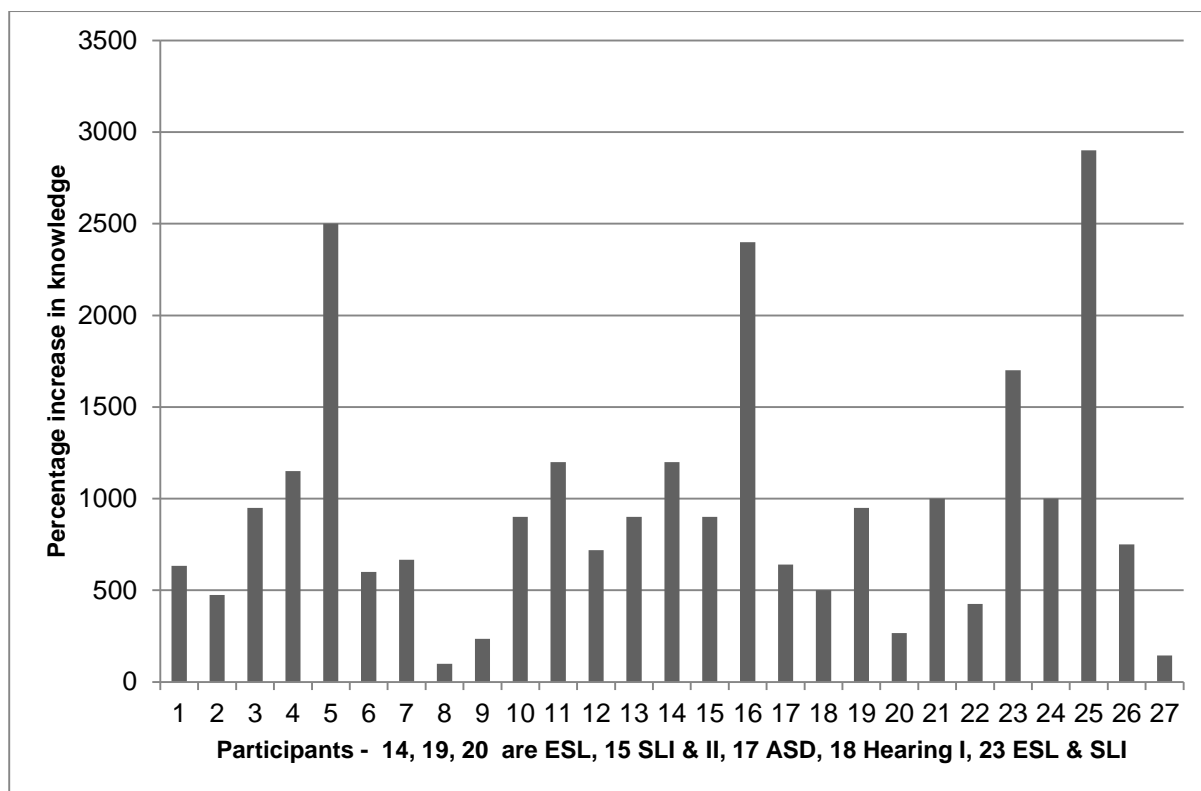


Figure 2: The percentage increase in knowledge of individual participants as a result of the program

Figure 2 indicates that all participants experienced substantial increases in their knowledge. Children with the lowest percentage increases (children numbered 8, 9, and 27) were those with the highest starting knowledge. What is particularly telling is the gain made by children with special needs, as indicated in Figure 2. The intellectually impaired child, Edward (number 15), showed a 900% increase in knowledge. He was personally cognizant of this right from the start. One of the researchers, having completed the pre-interviews, sat in on the first lesson to observe. At the end of the lesson, Edward ran up to her and said, “I didn’t know your questions the other day but now I know what an atom is!” His excitement was palpable. An ESL child, Kensei (number 14), showed a 1200% increase in knowledge as a result of the program, and Joel (ESL and SLI, number 23) showed a 1700% increase.

Further findings will be presented from analysis at a whole group level ( $n=27$ ), for each subsection of knowledge examined: atoms, molecules, elements, and sub-atomic particles.

### Atoms

At the pre-interview, only three children had heard of atoms, but they knew very little else, other than two children knowing that atoms are very small. Not surprisingly, at the post-interview, all children had heard of atoms, all but one knew they are very small and most children offered several additional pieces of information about atoms. In all, 18 children knew that atoms make up everything, 11 could explain exactly how small atoms are, including five remembering a specific analogy used by the specialist teacher, five children launched into descriptions of the sub-atomic particles, and two thought to mention that elements have unique atoms. Only Matthew was unable to expand much on his claim of knowing the word.

When asked to draw an atom, 24 children made no attempt during the pre-interview, one drew a circle with flagella and dots in the middle, one drew a single circle, and one drew concentric circles. In the post-interview, only two children could not attempt a drawing, with one of these drawing the symbol for the element carbon. Ten children drew small dots, solid circles, single circles or circles side by side, two drew circles with connectors like the models, and one attempted to draw the fuzzy ball

model of an atom, explaining that's what it was. The remaining 12 children came closer to drawing the internal structure of atoms, as one drew concentric circles with a nucleus, and six advanced on that by adding particles in the centre and on the rings. Five children drew atoms as concentric circles with positive protons in the nucleus and negative electrons on the rings, and could generally name the specific elements whose atoms they had drawn, as shown in Figure 3.

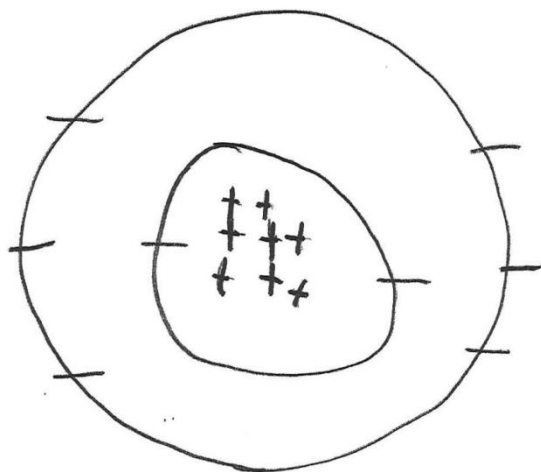


Figure 3: Seb's drawing of an oxygen atom

### Molecules

At the pre-interview, 14 children claimed to have heard of molecules, but that was all most had done, and they could not substantiate this with any other appropriate information. One child suggested it was something in a chemical, two thought it had something to do with liquids, one may have been thinking of models by suggesting it had to do with circles and toothpicks, one suggested germs, another suggested a machine and one said molecules help people survive. Only two children thought that molecules were bigger than atoms, none could name any molecules, and only two children attempted drawings. One drew linked circles and explained these were germs, whereas the other drew an oblong (the molecule) with smaller, filled in particles representing atoms inside.

At the post-interview, all except Edward, the intellectually impaired child, and Danisha, the hearing impaired child, now knew the word 'molecules'. The relatively larger size of molecules compared with atoms was known by 16 children, the others having forgotten or thought they were the same size. When asked for more information, seven children explained molecules were atoms joined together, while another eight children provided this information via a molecular or structural formula. Eleven children named appropriate molecules when asked, and these included water, carbon dioxide, hydrogen gas, methane, ethane, and acids. Seventeen children attempted a drawing, though one drew only a dot and one simply wrote  $H_2O$ . Loughlin (with ASD) drew the electron configurations of oxygen and hydrogen showing the sharing of electrons to make water, as seen in Figure 4.

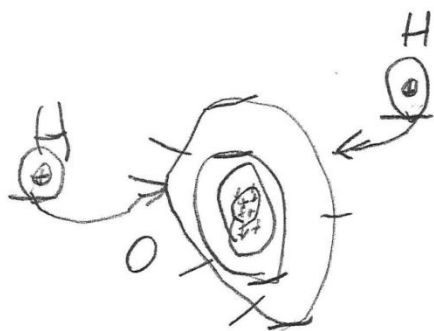


Figure 4: Loughlin's drawing of H and O forming water

The remaining molecules drawn ranged from simple ball-and-stick representations of water, CO<sub>2</sub>, H<sub>2</sub> and O<sub>2</sub>, to complex molecules such as CH<sub>3</sub>CH<sub>2</sub>OH, CH<sub>6</sub>ON<sub>2</sub>, C<sub>2</sub>H<sub>3</sub>ON, and CH<sub>3</sub>CH(OH)CH(OH)NH<sub>2</sub> all drawn correctly as far as bonding and valency were concerned. The children who drew the last three molecules proudly declared they were "their own made-up molecules" and Victoria, who drew C<sub>2</sub>H<sub>3</sub>ON, needed to use the models to make it first before correctly drawing it. Of particular interest was Marcia who is in Year 1 (6 years old). She correctly drew CO<sub>2</sub> and explained the double bonds attaching each oxygen atom to the carbon. Some of the children's drawings were too pale to reproduce well, but Figures 5 and 6 show two of the more complex molecules drawn.

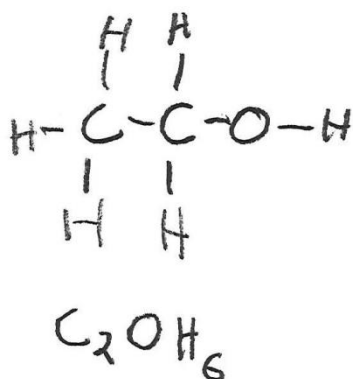


Figure 5: Andrew's structural and molecular formula for ethanol

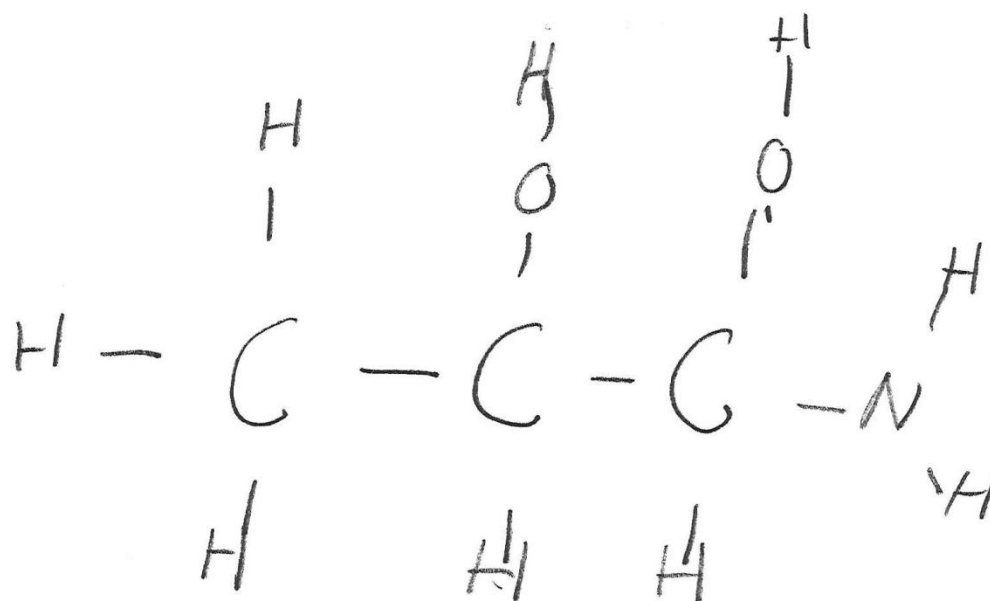


Figure 6: Oliwia (ESL) drew a complex made-up molecule correctly

#### Elements

In the pre-interviews, only four children said they had not heard the word ‘element’, but, when they were asked for more information, it became apparent that only three interpreted the word in its chemical sense. Marcia (the 6 year old) knew it was something with one type of atom, Olinda knew that two letters meant iron, and Christian mentioned that the element gold had gold atoms. Nine children spoke of earth, air, fire and water or variations on this, with two specifically mentioning they had seen this on TV. Tristan also referenced TV and referred to elemental powers, and Loughlin referenced the word ‘element’ as something you are good at, as in, ‘You’re in your element’. Others were unclear in their responses or said they had only heard the word and did not know more about it. Marcia was the only child who could name four elements, and she and her older sibling Christian were the only two who knew any letters representing elements (H, O, Fe, Ca, and Cu).

In post-interviews, only Oliwia claimed not to know the word ‘element’ because she was away at the time, although her sister Nadine had also been away on holiday but recognised the word. Oliwia and two others could offer no further information about elements, Edward and Kensei were unclear, and three children persisted with earth, air, fire, and water variations. Fifteen children specifically said that elements were made of one type of atom, eight mentioned the Periodic Table, examples were given, and three children knew there were 118 in all and that scientists had made some of these, whereas one child mentioned there were 92 natural ones. Other information supplied were that the elements were arranged from lightest to heaviest, and that the atomic number tells us what type it is, and Nathan volunteered that the left hand side of the Periodic Table were metals with loose electrons whereas the right hand side were non-metals with tight electrons. When asked to name elements, eight children could not do so correctly, whereas others began reciting the elements in order from hydrogen and helium, and others named anything from 3-15 different elements. Mark, who had answered the earlier question about what an element is with earth, air, fire and water, answered the question to name some elements with a long list, including titanium, vanadium, chromium, zinc, gold, silver, sulfur, silicon, iron, iridium, mercury, lawrencium, hafnium, samarium, and phosphorus. An equally long list of gold, argon, silver, tin, hydrogen, helium, beryllium, lithium, neon, carbon, oxygen, fluorine, sodium, plutonium, and silicon was given by 6-year-old Marcia, and Hanadi gave the second longest list: copper, iron, hydrogen, helium, lithium, beryllium, boron, carbon, fluorine, oxygen, neon, gold, silver

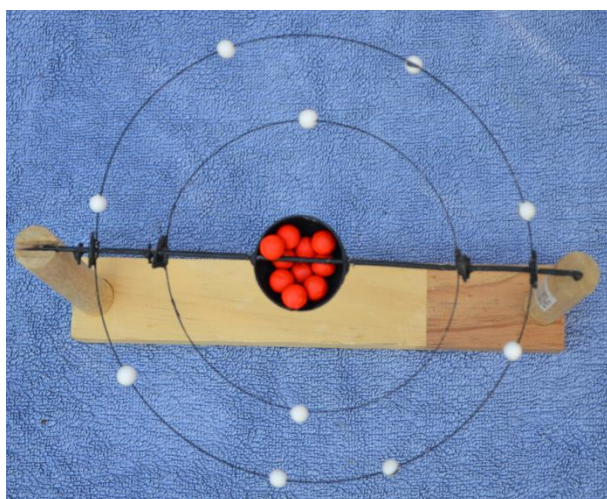
and nitrogen. When asked to supply letter names for elements, only two children (Benedict and Evelyn) could not. Edward knew H is hydrogen, O is oxygen, and C is carbon despite his intellectual impairment and speech and language difficulties. Most children correctly gave the letters for several elements, often from the first 10 in the Periodic Table, with 13 children also knowing Au is gold, and Nathan even knew einsteinium is Es. There were very few errors.

### *Sub-atomic particles*

In the pre-interview, only four children had heard of protons, whereas eight had heard of electrons. However, their further answers indicated that they were conflating electrons with electricity and electronics, rather than referring directly to the sub-atomic particles themselves. The few suggestions regarding the size of protons and electrons were incorrect.

In the post-interview, all children had now heard of both protons and electrons, and all but three (Edward, Danisha, and Merryn, the child who said science was too hard) were now clearly referring to the sub-atomic particles. Six children clearly knew the correct charges and locations of both protons and electrons; and six had the right idea but confused the words 'protons' and 'electrons' either in location or in charge, indicating they had not consolidated the terminology. A further 10 children got either the location or the charge of protons and electrons correct but did not comment on the other criterion. Only two children (Oliwia and Benedict) made it clear that protons and electrons are parts of atoms but could not state the location in the atom of these particles or their charge. Seventeen children knew that both protons and electrons are smaller than atoms, and 17 children explicitly explained the octet rule (the first shell having two electrons and the second shell having eight).

The only 'extra' question asked in the post-interview commented upon here is the requirement to use the atom nucleus-shell model to make neon, as this informs our knowledge of their understandings of sub-atomic particles. The children were asked to find neon in the Periodic Table and then make it, so they had to work out that it was element 10 and what that meant in terms of the locations of protons and electrons. The model is shown correctly completed in Figure 3. Neutrons were not emphasised in the intervention and not included in the model.



*Figure 7: Atomic nucleus-shell model correctly depicting neon (designed and made by I. Stuart)*

The children put the correct heavier red balls (protons) in the central cup representing the nucleus, and located the lighter white balls (electrons) on the wire shells surrounding the nucleus, two on the inner shell, and eight on the outer shell. Every child except Edward was able to use the model to make neon correctly. This indicates that, although some children could not explicitly explain the octet rule, they knew the principle. This understanding was further demonstrated when responding to the question about neon's bonding capability. Most children knew it would not easily bond with other elements because the shells are full/there's no more room/its electrons are tight. Only five children thought it might be able to bond with other elements but could give no convincing reasons why. Interestingly,



once they began using the model, only two children now confused the words ‘protons’ and ‘electrons’, so four children had self-corrected.

## Discussion

We recognise this is a small-scale pilot study with just one class of children. Nonetheless, we find the results startling, especially when considering there were some factors operating against the successful implementation of the program in this context. Firstly, the specialist science teacher had no pre-existing collegial relationship with the classroom teacher, so he felt very much the visitor in her classroom. It also became apparent that she has a very different pedagogy, in that she rarely, if ever, addresses the whole class for instructional purposes. Instead, she moves and instructs each group in turn. As a former high school teacher, the specialist science teacher is used to being able to gain the attention of the whole class for instructional periods of at least ten minutes at a time, and it took him a while to realise this strategy was not successful in this group. He also felt constrained in terms of fully utilising the parents and aides and in using classroom tests to ascertain the individual unaided knowledge of each individual child. This was also a more diverse class in terms of children with special needs than would be typical of a high school science class; so again the specialist science teacher had to make some adaptations ‘on the fly’. For every child to have gained as much knowledge as indicated in Figures 1 and 2 is truly remarkable in any circumstances, doubly so in this case.

The findings will be discussed in terms of the four research questions.

1. What do children aged 9 years believe science is, and what is their attitude towards science?

In the affective domain, children who already liked science generally liked it more, developed more sophisticated understandings of what science is, and appreciated the challenge of learning about atoms and molecules. Only one child thought it was too difficult. The positive response of children with special needs to the program is particularly gratifying.

2. What prior knowledge about atoms, molecules, elements, and sub-atomic particles do children aged 9 years possess?

The results from the pre-interviews indicate that most of these 9-year-olds had relatively little prior knowledge of atoms and molecules, indicating this would be an opportune time to begin instruction, before misconceptions are acquired. Some had encountered the words ‘atoms’, ‘molecules’, and ‘elements’, showing these words are not beyond their sphere of reference, again indicative of this being an opportune age for exposure to this ‘Big Idea’ of science.

It is clear that children are exposed to some ideas about atoms and molecules from various sources, including the mass media. It is of concern that children referenced misconceptions about elements (earth, air, fire, and water) to television. This confirms the potential benefit of teachers deliberately drawing out the conceptions of children in their classrooms with consideration of knowledge they may have acquired from the mass media in order to expose children to the scientific use of these terms. The findings of this small-scale study also support the findings of Jakab (2013), in that more children claimed to have heard of molecules than had heard of atoms.

3. What knowledge about atoms, molecules, elements, and sub-atomic particles can children aged 9 years gain through an intervention designed by a specialist high school science teacher?

Children were able to acquire a great deal of detailed and specific knowledge about all aspects of chemistry to which they were exposed. Children were now more aware that atoms are the building blocks of matter that make up everything, and had gained various degrees of understanding of atomic-molecular structure. Their understanding of molecules was wide-ranging, with fewer than expected being able to express confidently that molecules are atoms joined together, yet some were able to draw complex organic molecules. Confusions regarding the nature of elements were remedied in all but three children, with four other children lacking specific knowledge of what elements are.

However, some children could recite long lists of elements, including some less common ones such as lawrencium, hafnium, and einsteinium. Most were accurate in their knowledge of the symbols used to represent elements, including some of those that are less obvious by not being the capital letter of the element's name, such as gold (Au), silver (Ag), and iron (Fe).

Children now had degrees of knowledge about sub-atomic particles, protons and electrons, although this terminology was not consolidated in all. Nonetheless, when children manipulated the model to make neon, only two children continued to confuse protons and electrons, indicating the importance of hands-on models to help children establish their understandings. That every child other than Edward (who is intellectually impaired) was able to manipulate the model to make neon with correct proton and electron arrangements is outstanding. As former high school teachers, we note that these concepts are often presented without hands-on models to high school students, in deference to their posited capacity to understand abstract concepts, and yet this approach is often unsuccessful in establishing sound understandings. We would suggest that such models would be beneficial whenever children first encounter these concepts, without regard to the Piagetian stage they are thought to be in. However, given the apparent capacity of 9 year-olds to comprehend these concepts with these models, we would suggest that starting at this age would be optimal, providing many opportunities to revisit these concepts over the following years.

The findings clearly indicate that, with appropriate instruction, children of this age are capable of dealing with the microscopic nature of atoms and sub-atomic particles. Such an understanding makes the macroscopic properties of matter, such as the shiny nature of metals, conductivity, and changes of state with temperature, eminently more explainable and comprehensible. We contend that teaching macroscopic and microscopic in tandem is likely to yield better results than the current approach of dealing only with macroscopic properties in primary school, delaying microscopic understandings to high school.

#### 4. How can data obtained in this study inform the future development of the intervention?

Ten hours at one hour a week is not a lot of time to introduce such a wealth of information, nor does it provide ideal opportunities to consolidate this knowledge. The classroom teacher did do some consolidation activities, such as showing some of the specialist teacher's short explanatory videos, in between science classes. However, if tackled over a longer period of time, with more opportunity for diagnostic assessment of progress and consolidation of ideas, it would seem reasonable to suppose that even more dramatic gains in learning could be achieved. This study informs the future development of the intervention in that these data suggest:

- That Year 4, or possibly even Year 3 (before they become confused by what they see on TV or hear from other sources) are opportune times to introduce children to the concept of atoms,
- That taking the program more slowly, which probably means covering less information at this year level and leaving some to subsequent years, would be beneficial,
- The need to be more careful to consolidate the nature of molecules as compared with atoms, and
- The need to be more careful to consolidate the terminology of protons and electrons.

In addition, the specialist science teacher suggests that his introduction of magnets may have confused children's understanding of positive and negative charge and recommends omitting this in future.

A concern raised by the classroom teacher was whether the mathematics knowledge and capability of the children would hamper their understandings of how elements are constructed. However, that so many children grasped the octet rule indicates that at this level this is not an issue. With other classes, the specialist science teacher has introduced all the prefixes for smaller and smaller sizes, and has found children rather enjoy terms such as 'pico-', 'nano-', and 'yocto-', but the classroom teacher vetoed this approach with this class. In general, these concerns remind us that the mathematics capabilities of the children do need to be considered in consultation with the classroom teacher when implementing some aspects of this program.

## CURRENT CHALLENGES FACING THIS RESEARCH

The main challenge will be extending the research to a greater number of diverse schools in the first instance, consolidating our contention that children of this age can successfully learn atomic-molecular theory, and further refining the program. Following this, we would aim to develop a learning progression to introduce these concepts in a spiral curriculum over a number of years, and test the efficacy of this with a longitudinal study. The final research thrust would be to develop a professional development program that is effective in up-skilling existing primary teachers and a program for pre-service primary teachers so that they are confident in their ability to teach atomic-molecular theory.

## SOLUTIONS AND RECOMMENDATIONS

It is hoped that publication of even these preliminary findings will excite interest in this work. Further publications, particularly once the extra interview questions are fully analysed and the retention interviews have been conducted and analysed, will hopefully further engender interest that may translate to collaborations with schools nationally and perhaps internationally. Whilst being suitably cautious and cognisant of the small scale of this research, we conclude that the findings indicate that children have greater capability of understanding the microscopic aspects of atomic-molecular theory than was generally recognised previously. In this, these findings support those of other pioneering researchers mentioned in this chapter, such as Jakab, Liu and Lesniak, Nussbaum, Halpine, and Wiser and Smith.

We contend that appropriate instruction, including the thoughtful use of excellent hands-on models, is critical to children gaining understanding of this 'Big Idea' of science. It is clear that the models were particularly helpful to children in this study, and that they enjoyed using them. Furthermore, the children themselves judged the program appropriate for them; with only one believing it was too hard. They relished the opportunity to challenge their thinking and this furthered their interest in, and enjoyment of, science.

We argue that the Piagetian constructs for curriculum development should be discontinued. We suggest that primary curricula should include the 'Big Ideas' such as atomic-molecular theory at the time when children are encountering these concepts in the mass media, are cognitively ready and show interest in these ideas. Research indicates that if children were exposed to atomic-molecular theory in Years 3 and 4 they would be well primed to capitalise on their interest in genes and DNA in Years 5 and 6. Such would be the advantages of a spiral curriculum in which the macroscopic and microscopic properties of matter are taught concurrently rather than sequentially.

At the very least, science curricula should be sufficiently flexible for teachers to be able to take advantage of opportunities that present themselves. When children ask about atoms and elements, or genes and DNA, teachers should be able to take the time to capture and use this interest to establish science concepts, without stressing about how much set content there is to cover in the mandated curriculum.

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