Conceptual Change in Secondary Chemistry:
The Role of Multiple Analogical Models of Atoms and Molecules

Allan Gordon Harrison

This thesis is submitted as part of the requirements for the award of the degree of Doctor of Philosophy of the Curtin University of Technology

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ABSTRACT

Chemistry textbooks and teachers frequently use a variety of metaphors, analogies and models to describe atomic and molecular structures and processes. While it is widely believed that multiple analogical models encourage students to construct appropriate mental models of chemical phenomena, uncritical use of multiple analogical models may actually be responsible for a number of alternative conceptions in chemistry. Students hear and read about electron clouds and shells, atoms that are like miniature solar systems and balls, and molecules that are simultaneously represented by ball-and-sticks, joined spheres, electron-dot and structural diagrams. A strong case has been made that students try to integrate these diverse analogical models resulting in the generation of unscientific synthetic models. Conceptual change research programs also propose that carefully designed teaching and learning activities can stimulate students to exchange their intuitive and synthetic conceptions for more scientific conceptions.

This thesis investigates the occurrence of students' intuitive and synthetic mental models of atoms and molecules at both a general and specific level. The investigations consisted in the first phase of semi-structured interviews with 48 Year 8-10 science students. While the data were predominantly qualitative the interviews also generated simple quantitative data. The second phase was wholly qualitative and involved the 'researcher as teacher' in the Year 11 class. Portfolios were compiled for each student in the class and six portfolios were interpreted to produce a set of case studies describing the students' learning about atoms, molecules and bonds. These data were derived from transcripts of class discussions and individual interviews; pre-tests, formative tests and post-tests; student essays and worksheets and analogical teaching events. The data were interpreted from a constructivist viewpoint with attention given to credibility, viability and transferability, and dependability. The desire to collect every piece of useful data was constrained by the ethical need to minimise the disruptive effect of the research on the students' normal learning.

The first or general phase of this study investigated the question: With what models of atoms and molecules are lower secondary science students familiar? The interviews about atomic and molecular conceptions held by the Year 8-10 students found, for example, that some students confused atoms with cells because both have a nucleus, while others believed that electron shells enclose and protect the atom. All but two students visualised atoms with large nuclei and close static electrons. A majority of this student sample were confused by ball-and-stick molecular models and had a strong preference for space-filling molecular models because they were more 'real'.
The second or specific phase of this study consisted of an in-depth study of the development of mental models of atoms, molecules and bonds by six Year 11 chemistry students over 40 weeks of instruction. This study investigated the question: Do systematically presented multiple analogical models help students change their conceptions of atoms, molecules and bonds in favour of the scientific view? The students' prior mental models of an atom were dominated by a solar system model with the electrons in simple shells. A variety of metaphors, analogical models and explanations emphasising the diffuse spaciousness of atoms helped three students restructure their conceptions in favour of the scientific concept. Students also were encouraged to identify the shared and unshared attributes of familiar molecular models and, in time, three students became competent multiple modellers. It is claimed that these three students changed their conceptions of atoms and molecules in the sense that they realised that models are thinking and communicative tools, not reality itself. The significant change in these students' thinking was their recognition that atomic and molecular analogical models are context-dependent.

The phase two study's pre-occupation with conceptual change or knowledge restructuring raised an important methodological question: Is a multi-dimensional approach a better way to interpret conceptual change learning? or, are the various theoretical perspectives on conceptual change complementary? The study's theoretical framework found that conceptual change learning can be interpreted from epistemological, ontological, motivational, holistic explanatory and developmental perspectives. The collection and analysis of the data showed that student modelling ability and Perry's model of intellectual development were powerful interpretive tools when data needed to be examined from multiple perspectives. The six case studies support the assertion that multi-dimensional interpretive frameworks have superior credibility and viability compared to uni-dimensional studies.

Finally, the research raised several questions requiring further investigation. No direct support was found for the claim that dissatisfaction is central to conceptual change. This issue needs much more study due to the popularity of discrepant event teaching. While a multi-dimensional conceptual change model has been synthesised, this model needs further refinement as does the issue of how to monitor the status of students' conceptions. A most promising line of pedagogical research is the value of teaching scientific modelling through the use of multiple systematic analogical models.
ACKNOWLEDGMENTS

I would like to express my sincere thanks and appreciation to all my family, friends and colleagues who have helped in one way or another in bringing this thesis to fruition. This thesis brings together almost four year's work and during that time, many people have contributed to its success.

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My wife Beth, and my children, Danielle, Nathanael and Fiona have unstintingly supported my work despite the time and material cost to them. Without their support, I could never have completed this work. I hope I can repay their sacrifice.

The overall study of conceptual change learning was a team effort and I want to thank Grady Venville and Louise Tyson for their ongoing intellectual support and ideas. I would also like to thank the "residents" of Room 217. The friendship, humour and tolerance of Cath Milne, Joan Gribble, Wendy Speering and David Geelan helped keep us all sane. The staff at SMEC also offered many papers and helpful suggestions from time-to-time. I wish to particularly thank Associate Professors Leonie Rennie, Darrell Fisher, John Malone and Dr John Wallace for their encouragement and help.

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PREFACE

Probably the most enduring feature of human history is mankind's continuing quest for knowledge and understanding. This relentless urge to know, to know about the past, the present and the future seems to be the determining feature of the human spirit. Almost 3000 years ago Solomon, who made learning a virtue, wrote that

By wisdom a house is built, and through understanding it is established;
Through knowledge its rooms are filled with rare and beautiful treasures.

(Proverbs 24:2, 1978)

These ideas portray the practical and the aesthetic dimensions of human thought, dimensions that persist on one hand as science, mathematics and technology, and on the other as art, literature and the humanities. The right to learn practical skills and develop aesthetic values is described in Article 26 of the Universal Declaration of Human Rights and states that "Everyone has the right to an education ... Education shall be directed to the full development of the human personality and to the strengthening of respect for human rights and fundamental freedoms" (Shamaapande, 1995, p. 305). Knowledge and understanding is therefore a two-edged sword because it provides the keys to self-realisation and acts as a safeguard against exploitation. This is the reason why meaningful education is an inalienable right for every person irrespective of age, race or gender.
CHAPTER 1
STUDENTS' UNDERSTANDING OF ATOMS, MOLECULES
AND CHEMICAL BONDS

Introduction

Once upon a time, it was enough to teach children the facts and processes of "the 3Rs", but the knowledge explosion of the 20th Century, coupled with the information revolution of the past decade, means that schools can no longer teach all the facts and processes that young people could expect to use in their future lives and employment (Hurd, 1994). Indeed, it has become difficult to even know what jobs will be available in 10 years time. If attention is turned to science, yet another problem emerges: Most of the negotiated body of knowledge called Science was accumulated over the last 300 years through a process of accretion, argumentation and revolution (Kuhn, 1970; Laudan, 1984). Three centuries of scientific knowledge has produced such an enormous body of knowledge that it requires hundreds of sub-disciplines to maintain order in this knowledge. It is quite unreasonable to expect, or attempt, to teach even the fundamentals of science during the five years of secondary science education. But school science teachers are faced with a bigger problem than just teaching the facts and processes of science; they also have to unteach the intuitive conceptions that students have developed outside the classroom. Research has shown that there are major conceptual differences between intuitive science and scientists' science (Driver, Squires, Rushworth & Wood-Robinson, 1994; Pfundt & Duit, 1994) and the intuitive conceptions that are inconsistent with scientist's science now are called alternative conceptions. School science education therefore inherits two warrants: to extend students' science knowledge bases and to be aware of students' alternative conceptions.

The Study's Context

The major study reported in this thesis is just one part of a much larger study which was conducted by the author in his Chemistry and Physics classes at a new independent school in Perth, Western Australia, during 1994. Limitations on the thesis length precluded reporting the combined physics and chemistry learning of the students involved. Chapter 5 therefore is limited to reporting and discussing six students' learning about atoms, molecules and chemical bonds. The remainder of the research is being progressively reported in journal and conference papers and to date, 15 conference and journal papers have been written. These papers are described in Appendix 1.
General Aim of the Study

The particulate nature of matter is fundamental to chemistry and has a significant impact on knowledge in physics, biology and earth science. The specific interests of this study are students' understandings of atoms, molecules and chemical bonds. The superordinate aim of this research is to rigorously investigate conceptual change learning relating to student understanding of the abstract chemical concepts of atoms, molecules and chemical bonds. Learning about atoms and molecules involves two knowledge changes: the addition of new information to each student's knowledge base and the replacement of inadequate models (like the solar system atom) with more scientific models (like electron clouds). Because atoms and molecules are unobservable, teachers and textbooks employ a series of analogical models to describe atomic and molecular attributes and this justifies the subordinate aim of this study, namely, to investigate the role of metaphors, analogies and models in conceptual change learning.

At the outset, it is important to add a scientific qualification to this study. Chemical purists may complain that some of the proposed changes to students' conceptions mentioned in the previous paragraph (electron clouds) are scientifically incomplete. This is accepted. But one of the study's boundaries was the Western Australian Syllabus document for Year 11 Chemistry (Secondary Education Authority, 1994). Consequently, the conceptual content of this study was limited to the cognitive objectives stated in that syllabus statement.

Background to the Study

Teaching with Analogies

The Teachers' Use of Analogies project (Treagust, 1989) highlighted the unpredictable and ambiguous role that analogies play in learning science; Glynn (1989) calls instructional analogies "two-edged swords" because of their ability to simultaneously inform and mislead different students. In 1993, the author evaluated a model for enhancing teacher presentation of instructional analogies and showed that when analogies were presented in a systematic manner, the resultant student conceptions of refraction of light were compatible with scientists' science. These results were published by Harrison and Treagust (1993) and applied to a range of science analogies (Harrison, 1994; Harrison & Treagust, 1994a, 1994b). Although this research showed that student conceptions became more scientific when analogies were presented in a systematic manner, the conceptual change mechanism was unclear. Was the enhanced student understanding simply better recall or better understanding? Treagust, Harrison, Venville and Dagher (1996) then used a problem-solving protocol to reinterview the students interviewed by Harrison (1993). When the status
conditions of the Conceptual Change Model (Hewson and Thorley, 1989; Posner, Strike, Hewson & Gertzog, 1982) were used to interpret each student's responses, it became evident that the systematic analogy produced conceptual changes in a significant number of the students.

Scientific Modelling

But are these results transferable to other abstract and conceptually difficult science concepts? Would the experience of systematically teaching refraction of light using a concrete model (Harrison, 1993) work with chemistry's models of atoms, molecules and bonds? A review of the chemistry education literature identified a set of alternative conceptions relating to atoms, molecules and bonds and showed that these alternative conceptions were widespread amongst secondary science students (Andersson, 1990; de Vos, 1990; Fensham & Kass, 1988; Lee, Eichinger, Anderson, Berkheimer & Blakeslee, 1993; Ingham, 1991; Novick & Nussbaum, 1981; Nussbaum & Novick, 1982; Renstrom, Andersson & Marton, 1990; Sandomir, Stahl & Verdi, 1993; Scott, 1992; Stavy, 1990). Recent modelling research (e.g., Gilbert, 1993; Grosslight, Unger, Jay & Smith, 1991; Vosniadou, 1994) supports the notion that the unsystematic use of models can maintain or even generate alternative conceptions. Likewise, concepts that rely on multiple models often confuse students (Carr, 1984; Garnett & Treagust, 1993a, 1993b) and misapplied models can disrupt student understanding (Bent, 1984). It was therefore hypothesised that systematic instruction in the use of atomic and molecular models could enhance student understanding of atoms and molecules by changing student conceptions in favour of the scientific view.

Mental Models

Even though the term "mental models" is widely used in the science education literature, the way mental models are used in this study needs to be clarified. Vosniadou (1994) explained that mental models "refer to a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning" (p. 48). Throughout her paper, Vosniadou called her interpretations of students' conceptions of the Earth, force and heat, mental models. Norman (1983) however, pointed out that mental models are intrinsic descriptions of objects and ideas that are unique to the knower and arise and evolve "through interaction with a target system" (p. 7). Mental models need not be technically accurate, but they must be functional. Norman went on to warn that "people may state (and actually believe) that they believe one thing but act in quite a different manner" (p. 11) and for this reason it should be remembered that all data and interpretations pertaining to student mental models are just that, interpretations. Several contributors in Gentner and Stevens (1983) used the construct "mental model" to describe student understanding and this
term was also used throughout by Vosniadou (1994). In this thesis, the term 'mental model' is used to describe the researcher's interpretations of an individual student's conceptions of atoms, molecules and bonds.

Models

Models are also subject to semantic variation. Models can refer to objects like scale models or toys; methods for representing ideas and relationships like symbols, equations and graphs; or ways for doing things like the Conceptual Change Model described in Chapter 2. By way of clarification, a typology of models is provided in Chapter 3. Mental model is a quite different construct and will be used exclusively in the way described in the previous paragraph.

Epistemological and Ontological Presuppositions

In social settings, the philosophical and methodological presuppositions held by the various participants influence meaning at every level (Cohen & Manion, 1980; Guba & Lincoln, 1989; Patton, 1990) and this study is no exception. Two philosophical issues that play an important role in this study are epistemology and ontology. The meanings ascribed to these terms are somewhat fluid, therefore their use in this thesis will be explained. While it is difficult to assign exact meanings to these terms, the study is not hindered provided that the reader understands how the author has used these terms in the conduct, analysis and reporting of the events described in this thesis.

Epistemology is taken to mean knowledge and its justification, that is, how and what the individual thinks about what he or she knows. In regard to the teacher/researcher and students involved in this study, epistemology means what each knows, how well it is known or believed, and how the knowledge is used. The case studies in this thesis are particularly interested in describing each student's mental models in terms of their intelligibility, plausibility and fruitfulness. Also, Norman's (1983) reservations about the accessibility of students' mental models applies to student epistemologies. However, the constructivist stance taken in this research allows that each interpretation of a student's understanding is just that, the researcher's interpretation.

Ontology can be differentiated from epistemology even though it contributes to a person's epistemology. In this study, ontology is taken to mean how the teacher/researcher and the students viewed reality. Do material and social realities enjoy an independent existence or are they human constructions depending for their viability on human thought? In this study, ontology is intrinsically linked to student interpretations of scientific models because discernible changes in the way students viewed analogical models were taken to be viable indicators of conceptual change. Whenever a model was seen less as an object-reality and more as a process or thinking tool, this was interpreted as ontological change.
These comments relating to the role of epistemology and ontology in conceptual change interpretations harmonise with the multi-dimensional interpretive framework developed by Treagust (1996) and Tyson, Venville, Harrison and Treagust (in press).

**Conceptual Change Learning**

A study of the conceptual change literature showed that there was insufficient consensus amongst the various schools of thought on conceptual change (or knowledge restructuring) to produce an agreed model of how conceptual change occurs. Various authors described conceptual change in terms of epistemology (Hewson, 1981, 1982; Hewson & Hewson, 1992; Posner et al., 1982; Strike & Posner, 1992), ontology (Chi, Slotta & de Leeuw, 1994; Vosniadou, 1994), motivation (Pintrich, Marx & Boyle, 1993), holistic explanatory coherence (Thagard, 1992a), evolutionary accretion (Duschl & Gitomer, 1991; Villani, 1992) and development (Carey, 1985). The immediate challenge therefore, was to develop a comprehensive and coherent description of conceptual change. It seemed reasonable that an understanding of how students restructure their knowledge of atoms, molecules and bonding could emerge from a study that combined conceptual change learning strategies with the systematic use of metaphors, analogies and models.

**Study Rationale**

**Analogies and Models in Chemistry**

The foregoing comments justify investigating secondary science students' knowledge of, and learning about atoms, molecules and bonds for three reasons. First, the role and suitability of the metaphors, analogies and models used in chemistry classes are unclear. The literature shows that many students believe that matter is continuous, that microscopic atomic properties reflect macroscopic properties like colour and phase, and that atoms are insubstantial. Apart from Sandomir et al. (1993), there appears to be an absence of information on how students react to models that depict atoms as ball-like or as miniature solar systems; electrons as shells and clouds; or molecules as ball- and-stick, space-filling or electron-dot models. In view of this gap in the literature, it seemed unwise to commence a teaching/research project without knowing more about students' prior conceptions of atoms in general and electrons in particular. Therefore, the study reported in Chapter 4 (Harrison & Treagust, in press) probed student conceptions of atoms and molecules to provide a base-line for the subsequent year-long study in Year 11 Chemistry that comprises Chapter 5.

**Modelling and the Learning of Science**

The second reason for studying Year 11 chemistry students' conceptions of atoms, molecules and bonds was a desire to learn more about how secondary students use
scientific models. Gilbert (1993) points out that "models play a crucial role in the practice of science" (p. 5) and that "models are one of the main products of science" (p. 9). Therefore, to think scientifically requires modelling skills. How does this notion sit alongside the frequently stated goal of curriculum designers that science courses aim to make students 'think like scientists' and that students should do science in a way that imitates the 'scientific method'? Hurd (1994) and Duschl and Gitomer (1991) challenge the 'student as scientist' analogy and Grosslight et al. (1991) cast doubt on the ability of students to adequately model scientific phenomena. There is, therefore, a significant gap between the ideal science classroom and actuality.

The detailed review of the analogies and modelling literature in Chapter 3 takes up this issue and explores systematic ways for improving student modelling of scientific phenomena. There is also an important role for analogies in conceptual change theories (Chi et al., 1994; Posner et al., 1982; Vosniadou, 1994) because metaphors and analogical models can act as either a resource for conceptual change or a cause of alternative conceptions (see Chapter 2). Perry's (1970) model of intellectual and ethical development also is useful because it predicts that student understanding of scientific phenomena may be enhanced by the concurrent use of multiple models. Multiple modelling and critical reflection on the analogical models used to represent atoms, molecules and bonds therefore was integrated into the Year 11 chemistry program to examine this prediction.

A Multi-dimensional Framework for Interpreting Conceptual Change

The third justification for this study consisted of a desire to develop a multi-dimensional framework for analysing conceptual change learning. Treagust (1996) proposed that conceptual changes need to be diagnosed from at least three perspectives, that is, epistemological, ontological and motivational perspectives. Harrison and Treagust (1996) went further and added holistic explanatory coherence, evolutionary accretion and developmental perspectives to this list. For a multi-dimensional interpretive framework to be credible, therefore, it must be shown to provide a superior explanation of conceptual change learning to any perspective on its own. This issue alone provides a sound reason for doing this study.

Research Questions

The issues discussed in the Study Rationale spawned the set of questions that comprise the Research Problem and these specific questions are subsumed within three broad Research Questions. The Study Rationale records the historical order of the author's research over the past four years and the Research Questions reflect the order of these issues in this thesis. Research Question 3 which deals with the nature of conceptual change is substantially answered in Chapter 5; however, this necessitated
the theoretical discussion of conceptual change learning in Chapter 2. This is the reason for discussing Research Question 3 before the other Research Questions.

Research Question 1

With which models of atoms and molecules are Western Australian pre-Year 11 chemistry students familiar; and what is the relative status of these models for these students?

This question contains a number of subsidiary items: What does an atom look like? Do pre-Year 11 students use single or multiple models to describe atoms? From the student's viewpoint, are these models real or representative? What conceptions do pre-Year 11 students have of electrons, electron shells and electron clouds? Is an atom compact or spacious? Do the properties of atoms and molecules resemble the material properties of the parent substance? What idiosyncratic views do pre-Year 11 students have of atoms and molecules?

Research Question 2

Do systematically presented metaphors and analogical models, and multiple models, contribute to conceptual change in learning about atoms, molecules and chemical bonds?

This question also divides into a number of parts: Is the learning of a new metaphor or analogical model conceptual change? When students revise or exchange their metaphors and analogical models, is this conceptual change learning? Is the toleration/employment of multiple models conceptual change? Should changes to a student's modelling ability be classified as conceptual change learning?

Research Question 3

Do the various theoretical perspectives on conceptual change learning complement each other?

The components of this research question include: Is conceptual change learning always a rational-cognitive process? Is conceptual change learning global or local? Is conceptual change learning revolutionary or evolutionary? Are conceptual status changes valid indicators of conceptual change learning? What role does dissatisfaction play in classroom conceptual change learning? Are other learning measures like modelling ability and intellectual development indicators of conceptual change? Is a multi-dimensional approach a better way to interpret conceptual change learning?

The calibre of the answers to these questions depends on two things: the quality and appropriateness of the data collected and the power and sophistication of the interpretive framework. It is essential that the study possess a valid and reliable
theoretical framework for the data's collection and analysis. The methodological issues that affect data collection and analysis will be discussed in the next section.

**Theoretical Framework**

*Qualitative Research*

When embarking upon educational research, several methodological orientations are possible. Is the study to be quantitative, qualitative, or a mix of each? While the past decade has witnessed a reduction in the how much, how often, quantitative approach in favour of the qualitative, naturalistic typology, each method has its strengths and weaknesses. The challenge then, is to select the methodology that will provide the best information, and possibly, some answers to the research questions.

Commenting upon the quantitative/qualitative dichotomy, Patton (1990) points out that it is not "necessary to be a qualitative methods purist. Qualitative data can be collected and used in conjunction with quantitative data" (p. 60). The real point is that study sophistication stems from matching the research methods to the research questions and the contextual frame of reference. Patton proposes that "multiple methods and a variety of data types can contribute to methodological rigor" (p. 61) and he calls a purposeful mixing of methods, "a paradigm of choices." The mix of methods also should be calculated to impart flexibility to the research process. However, researchers do need to be careful not to confuse and misapply the products of quantitative and qualitative research. Quantitative data lends itself to generalisation; but because qualitative conclusions are "ultimately context bound, based on personal knowledge, and repeatedly, independently constituted when the reader of the research interacts with the author's text" (Cizek, 1995, p. 27), generalisation is precluded. Provided these limitations are observed, mixing methods is acceptable.

In this interpretive study, qualitative data predominates. Some quantitative data were collected in the base-line study of Year 8-10 students' conceptions of atoms and molecules (Chapter 4) but the data relating to the role of metaphors and analogical models in conceptual change learning were wholly qualitative (Chapter 5).

*Constructivism and Qualitative Research*

Erickson (1986, p. 119) describes qualitative research as "ethnographic, qualitative, participant observational, case study, symbolic interactionist, phenomenological, constructivist or interpretive." Merriam (1988) employs a similar list of terms when arguing in favour of case studies and she points out that case study discussions "are embedded in the growing body of literature on qualitative research and naturalistic inquiry." Guba and Lincoln (1981) preferred the term 'naturalistic' to describe qualitative research and later (Guba & Lincoln, 1989) subsumed this into the
constructivist paradigm. To summarise, naturalistic research, qualitative research and interpretive research are equivalent names for the same type of investigation (Spector & Glass, 1991).

"Interpretive participant observational research" (Erickson, 1986, p. 119-120) has its origins in anthropology and is that form of research that is particularly interested in asking the question "What is happening here?" (p. 121). Merriam's version (1988, p. 16) states that "in a qualitative research [project] the paramount objective is to understand the meaning of an experience." Consequently, interpretive research should be as non-interventionist as possible, it is an approach in which the observer enters into the subject's activities, observes, and interprets the data from a human perspective. This investigation of the role of metaphors, analogies and models in conceptual change learning falls short of being a truly non-interventionist study. Nevertheless, it remains an interpretive study because the interpretations are focussed on the questions, "what is happening here?" and, "what do these student comments and actions mean from a human perspective?" The teacher/researcher's intervention was limited to supplying the students with extra analogical models, showing the students how to systematically consider both the shared and the unshared attributes of each analogical model and to encouraging the students to critically evaluate their conceptions. The study qualifies as non-interventionist in the sense that the study was not a scientific experiment involving control or treatment groups.

The qualitative research paradigm is essentially a social constructivist method because the emphasis is upon the meaning of words and actions as they apply to the actors themselves (Erickson, 1986; Gallagher, 1991). Even though the unit of analysis in this study was the individual student, a significant proportion of the data was generated within social contexts. A spoken statement's meaning is judged by the hearer, it is the hearer's intrinsic understanding of the statement that is true for them, in that social context, at that time. Thus, Guba and Lincoln (1989) define truth as

> the best informed (amount and quality of information) and most sophisticated (power with which the information is understood and used) construction on which there is consensus

(although there may be several constructions extant that simultaneously meet that criterion) (p. 84).

This definition is useful because it recognises that different people, hearing the same statement at the same time, will construct different understandings from the same data.

The intrinsic beliefs and attitudes of individuals and groups cannot be easily determined by superficial or quantitative research. Erickson's (1986) reference to Malinowski's ethnographic research records that "he was able to identify aspects of the [subject's] world view that they themselves were unable to articulate" (p. 123). The
tool that exposed these innermost personal feelings was a sensitive interview technique. Positivists in Malinowski's day criticised such investigations calling them unscientific because they denied a rigid cause-and-effect relationship between the environment and human behaviour. Social behaviour was seen to be the effect of external factors controlling a person's behaviour in much the same way as Newton's laws determine the behaviour of moving particles. The constructivist epistemology highlights the weakness of that criticism by showing that human beings are not mechanistic in the way they perceive reality. Individuals construct understanding by generating their own best fit of new information into their current world view.

The Study of Conceptual Change Should be Qualitative

Conceptual change learning involves identifying changes to conceptual frameworks which, by virtue of their nature, can only be detected by qualitative probes. Conceptions or mental models consist of interconnections between schema (Rumelhart & Norman, 1981) which the knower usually manifests in problem-solving, written or verbal descriptions about the conception or through concept maps, pictures and diagrams. Details of conceptual status are best adduced from comments that the student makes about relevant conceptions: "evidence that comes directly from the student, evidence that is in the form of a comment on the status of the conception" (Hewson & Thorley, 1989, p. 546). It is worth noting that all of the conceptual change studies reviewed in Chapter 2 depended on qualitative data.

A similar qualitative case can be made for studies of students' metaphors and analogical models. Because metaphors and analogical models draw upon familiar commonplace objects and events, in a study like this, the only meaning of significance is the meaning that is constructed in the student's mind. The status of conceptions involving metaphors and analogical models is a function of how the student interprets the metaphor or analogical model. Determining what the student thinks involves finding out as much as the student can tell or demonstrate about his/her conception. This is even more important when dealing with multiple models because the relative status of the different models is also important.

But many people have difficulty enunciating their understanding and students' non-articulated explanations have implications for this study. In a class of students drawn from diverse socio-economic environments, no meaning can be taken for granted because meaning is socially determined (Solomon 1987) and semantic differences abound (Sutton, 1992). Therefore, for teaching as well as for research reasons, it is important that the teacher/researcher pays careful attention to each student's understanding of the metaphors and analogical models that are used throughout this study. Conceptual understanding of metaphors and analogical models is a function of
the student's analogical mapping and transfer. The only interpretations that should be made and accepted then, are those that are supported by repeated, detailed descriptions of the student's conception.

**Why Use a Case Study Approach?**

The study of conceptual change reported in this thesis was, from the outset, conceived as a set of longitudinal case studies (Merriam, 1988). Case studies are rigorous comprehensive stories that describe contemporary events involving many variables that have strict boundaries. Far from being loose and speculative, these case studies are soundly based in constructivist theory and are built out of written and spoken statements, personal actions and social interactions (e.g., Hennessey, 1993). The final product, the case study story, is an intensive, holistic analysis of an individual or group situation and contains detailed descriptions of phenomena, ideas and changes.

As happens in all naturalistic investigations, case studies are constrained by independent and dependent boundaries. In this study, the phenomenon (conceptual change learning), the subject (chemistry), and the topic (atoms and molecules) constituted independent boundaries because the researcher chose to investigate these areas. However, the Year 11 class, the students in the class and the syllabus, were dependent boundaries because once the decision was made to study conceptual change in chemistry, the researcher was limited by available classes in the school where he worked as a teacher. Even the researcher himself constituted a dependent boundary because he was limited by his knowledge, skills, philosophical commitments, interests, aims and aspirations.

But why do case studies? The quality of an investigation's outcome is usually positively correlated with the quality of its design; and design is normally influenced by the problem's shape, the questions it raises and the desired end-product. Studying conceptual change learning is a diffuse problem because the questions it raises are often unforseen, and even though end-product theories are emerging, there is a decided lack of consensus as to how knowledge is restructured (Merriam, 1988; Patton, 1990). Consequently, conceptual change research involves delving into students' mental models by listening to what they say, reading what they write and watching what they do (Osborne & Freyberg, 1985; White & Gunstone, 1992). But Norman (1983) insists that mental models are incomplete, unstable, without firm boundaries and constantly evolving, and that what people say they think is often only part of the story. Therefore, any investigation of conceptual change needs to be long-term and needs to collect as much information as possible from as many sources as possible. Merriam (1988, pp. 6-21) argues that qualitative case studies are the best way to deal with items like the problem's changing shape, the questions it raises along
the way, and the desired end-product because case studies are particularistic, descriptive, heuristic and inductive. She provides brief definitions for each of these characteristics:

*Particularistic* means that case studies focus on a particular situation, event, program, or phenomenon.

*Descriptive* means that the end product of a case study is a rich, "thick" description of the phenomenon under study.

*Heuristic* means that the case studies illuminate the reader's understanding of the phenomenon under study.

*Inductive* means that, for the most part, case studies rely on inductive reasoning. (Merriam, 1988, pp. 11-13)

Each of these four characteristics satisfies one of the needs of this study. First, the particular phenomena involved in this study are students' conceptions of atoms, molecules and bonds and the events comprising conceptual change learning. Second, this thesis is a descriptive study because its aim is to provide a long-term detailed description of conceptual change learning in Year 11 chemistry. Third, this study is heuristic because its aim is to elucidate conceptual change learning involving analogical models of atoms, molecules and bonds; and finally, the study is inductive because the interpretations involve inductive reasoning. Furthermore, expanding the investigation's time-span to make it as comprehensive as possible justifies the choice of longitudinal case studies for this research.

There are two phases to this study. As stated earlier, Chapter 4 describes a survey-interview study of 48 Year 8-10 students; the aim of this study was to document typical pre-Year 11 students' preconceptions of atoms and molecules. Chapter 5 contains six longitudinal case studies, each of which is a year-long story recounting and interpreting changes to one student's conceptions of atoms, molecules and bonds. Each story uses a number of perspectives to focus on ways in which each student's conceptions of particulate phenomena changed and also tries to identify links between conceptual changes and changes in student's understanding of the analogical models used to depict atoms, molecules and bonds. The specific methodologies for the studies reported in Chapters 4 and 5 are contained in those chapters. It is, however, useful to discuss some general aspects of the methodology in this chapter.

*Student Portfolios*

A chronological portfolio was compiled for each of the ten students in the Year 11 class. Eight portfolios were analysed and interpreted and written up as longitudinal case studies but only six are discussed in Chapter 4. The six case studies were purposefully chosen (Patton, 1990) because they provided a representative cross-section of the students in the class and also they contained good examples of
conceptual change learning (or the lack of it). The case studies that were left out were either repetitive (the same findings were reported for other students) or were from low achieving students whose data were too limited or ambiguous to support meaningful interpretations. The data from two students were not analysed because they were incomplete.

Portfolios were chosen because they have been increasingly recognised as powerful tools for describing student conceptual development (Duschl & Gitomer, 1991; Gitomer & Duschl, 1995). Each portfolio, where possible, contained all of a student's written work pertaining to atoms, molecules and bonds. Four other sources of data about student conceptions of atoms, molecules and bonds were pretests, lesson transcripts, student comments and teacher/student discussions, and a formal interview. Because of their qualitative nature, each piece of information in the portfolio needed to be interpreted to generate analysable data. The first level of interpretation mostly consisted of collecting, sorting and arranging in chronological order the students' work, test answers, lesson transcripts, comments, pretests, essays and transcribed interviews. The interpretation of each portfolio was then written up as a case study.

In each case study the data were analysed in terms of status of conceptions (Hewson & Thorley, 1989), ontological changes (Chi et al., 1994), explanatory coherence (Thagard, 1992), modelling ability (Grosslight et al., 1991), motivation and social affect (Pintrich et al., 1993), and intellectual development (Perry, 1970).

Both phases of the study involved multiple readings of the data. The Chapter 4 data required three readings to extract the ten reported features of atoms and molecules, but the Chapter 5 data involved re-reading the data from each of the perspectives described at the end of the previous paragraph. In both cases, the nub of the question, as Erickson puts it, was "what is happening here, specifically? What do these happenings mean to the people engaged in them?" (p. 124). This type of reflective question helped define what was needed to be known about the role of analogical models in learning about atoms, molecules and bonds. This questioning style guided the exploration of each student's understanding of the various analogical models that were used in the classroom and it also helped the researcher make some sense of how the various analogical models affected each student's conceptions.

On the matter of validity and reliability, because this study was naturalistic rather than controlled, each interview (Chapter 4) and each class event (Chapter 5) was multivariate. In order to generate reader confidence in the conclusions, wherever possible an audit trail has been provided: "Just as an auditor authenticates the accounts of a business, independent judges can authenticate the findings of a study by following the trail of the researcher" (Guba & Lincoln, 1981). It is hoped that the reader will be able to follow the events, data generation and reasoning, and so concur with the
findings. Or, if issue is to be taken with the study's outcomes, at least the critic will understand how the reported assertions were derived. More is said about these issues in the next section.

Research Rigour in this Study

Rigour is just as important in research conducted from a constructivist disposition as it is in studies of a positivist nature. Although constructivism accepts that it is the individual who constructs meaning from discourses or events, it nevertheless holds that the meaning must be compatible with the words and the actions as they were heard and observed. Where positivism concerns itself with validity, reliability and objectivity, the constructivist paradigm replaces these issues with credibility, dependability and confirmability, respectively (Guba & Lincoln, 1989). Parallel with Guba and Lincoln, Patton (1990) also describes validity in constructivist terms like plausibility, authenticity and viability.

In the following paragraphs, the traditional notions of validity, reliability and objectivity are contrasted with their more recent interpretive counterparts. The purpose of this discussion is to indicate to the reader that these issues of rigour have been kept in mind throughout this study and that many of the actions taken were implemented to make this study believable and to confer viability to the interpretations found in Chapters 4 and 5.

Triangulation

Qualitative studies in particular have their credibility enhanced by the use of multiple measures. The 'triangulation' metaphor is drawn from navigation in which the certainty of an object's position is increased by stating its location relative to two or more points. Patton (1990, p. 464), describes four forms of triangulation.

Methods triangulation involves different techniques for data collection such as quantitative and qualitative methods. In Chapter 4, the 48 Year 8-10 students were surveyed, interviewed and asked to draw diagrams; the Chapter 5 data consisted of student written work, lesson and discussion of transcripts, and a summative interview.

Triangulation of sources within a particular method in classrooms contrasts, for example, observation vs interview; public vs private opinions; consistency of statements over time; different status (e.g., teacher vs student). The compilation of a portfolio of all pretests, tests and examinations, free-form essay, diagrams and an interview resembles sources triangulation in the sense that the student, the teacher and an independent interviewer contributed materials to the portfolio.
Analyst triangulation employs multiple observers and/or interpreters. One example is the advocacy/adversary model in which the data are interpreted from opposing viewpoints. This method, however, was not suitable for this study.

Theory triangulation examines the study’s different foundation principles of action and interpretation. The use of a multi-dimensional interpretive framework comprising epistemological, ontological, motivational, holistic explanatory coherence, evolutionary accretive, and developmental perspectives makes theory triangulation especially important in this study. The way in which the multiple perspectives were applied is discussed in Chapter 5.

It is usually assumed that looking at the same phenomenon from differing perspectives increases the certainty of the interpretations. However, Mathison (1988) shows that this is not always the case, since differing perspectives may simply highlight the differences, not the similarities. For example, people who are instantly recognised when their face is visible, may be unfamiliar when only their back is seen. Mathison continues,

In practice, triangulation as a strategy provides a rich and complex picture of some social phenomenon being studied, but rarely does it provide a clear path to a singular view of what is the case. I suggest that triangulation as a strategy provides evidence for the researcher to make sense of some social phenomenon, but that the triangulation strategy does not, in and of itself, do this. (p. 15).

Mathison then pointed out that data from two or more angles can be convergent, inconsistent or contradictory. While there are major differences in each of these types of data, they may well be explicable within the study’s context. In fact, examining the indeterminate and the divergent data may ultimately enhance the interpretations. This was the situation in Dan’s case study because frequent discrepant items in his case contradicted the conceptual progress he was apparently making.

Credibility as Validity

Validity is concerned with the issue of whether we are measuring what we say we are measuring. Conventionally, validity comes in two forms - internal validity and external validity. These conventional validities are artefacts of positivism. "Internal validity is defined ... within the positivist paradigm as the extent to which variations in an outcome or dependent variable can be attributed to controlled variation in an independent variable" (Guba & Lincoln, 1989, p. 234). This position assumes that each and every situation can be stripped of all its variables but one, and that the variable can be experimentally manipulated to definitively demonstrate its contribution to change. Simply put, this is the determination of internal cause and effect.
Guba and Lincoln observe that "external validity can be defined positivistically as the approximate validity with which we infer that the presumed causal relationship can be generalised to and across alternate measures of the cause and effect, and across different types of persons, settings and times" (1989, p. 234). This means that internally valid findings can be validly extended to future circumstances. There is, though, no expectation that these longitudinal case studies will lead to generalisations because the unit of analysis is the individual and the study allowed as many variables as emerged during the study’s progress.

Patton (1990) addresses the above issues in much the same way as Guba and Lincoln (1989). Patton recommends both openness and integrity in the conduct of the fieldwork and in the reporting of the results.

The discipline and rigor of qualitative analysis depends upon presenting solid descriptive data, which is often called 'thick description' (Geertz, 1973; Denzin, 1989), in such a way that others reading the results can understand and draw their own interpretations. (Patton, 1990, p. 375).

Merriam (1988) speaks in a similar vein when she advises leaving "an audit trail" (p. 172) for readers to follow. In Patton's words, validity is replaced by "plausibility", "authenticity", "credibility" and "viability" (pp. 461-469). He asserts, that

The ultimate test of the credibility of an evaluation report is the response of information users and readers to that report. This is a test of face validity. On the face of it, is the report believable? Are the data reasonable? Do the results connect to how people understand the world? (p. 469).

Guba and Lincoln arrived at a similar conclusion when they enunciated six steps for their criterion of "credibility" (1989, p. 237). The six steps consist of prolonged engagement, persistent observation, peer debriefing (searching for alternative meanings), negative case analysis (analogous to statistical significance), progressive subjectivity (reflection upon developing constructions), and member checks in which the stakeholders (subjects) react to the findings. All of these activities combine to enhance credibility. A reading of the six case studies (Chapter 5) shows that steps 1-5 are each discernible in this study. The decision to exclude member checks was made on ethical grounds because it was felt that further demands on the students' learning time was unacceptable.

*Dependability as Reliability*

Reliability is usually defined as a measure of repeatability or consistency: Would the same outcomes result if this experiment was replicated with the same or similar subjects in the same or in a similar context? From a constructivist stance, reliability in interpretive research is replaced by the notion of dependability (Guba & Lincoln,
1989). "Dependability ... is concerned with the stability of data over time" (p. 242). From the traditional viewpoint, alterations in methodology and hypotheses expose studies to the charge of being unreliable. But in studies that are characterised as interpretive, methodological changes and shifts in constructions are expected and will occur as such studies become increasingly sophisticated. "Far from being threats to dependability, such changes and shifts are hallmarks of a maturing - and successful - inquiry" (p. 242). Because conceptual change learning changes conceptions, it would be impossible to repeat this study with the same students. It would be just as impossible to find another class of students with the same characteristics as these six to repeat the study. Besides, the case studies do not claim to be generalisable, all that Chapters 4 and 5 claim is that this is what happened with these students in their particular context at that time.

Having replaced traditional validity with credibility, Guba and Lincoln (1989) assert that "dependability parallels conventional ... reliability" (p. 242). Speaking in constructivist terms, they point out that "shifts in hypotheses, constructs and the like are thought to expose studies to unreliability. But methodological changes and shifts in constructions are expected products of an emergent design dedicated to increasingly sophisticated constructions" (p. 242). Their advice to challenges of unreliability is to make the process trackable by leaving an audit trail. Throughout this study there has been an overt desire to make the process and the interpretations trackable while trying to avoid over-reporting.

**Confirmability as Objectivity**

Guba and Lincoln describe this criterion as the "positivist demand for neutrality and requires a demonstration that a given inquiry is free from bias, values and/or prejudice" (1989, p. 235). This is a clinical pre-occupation, where it is assumed that all variables, bar one, have been controlled and that the outcomes reflect the effect(s) of the experiment alone. The results are not a function of the intrinsic, human qualities of the investigator and/or the subject (or anyone else, for that matter). Constraints of this kind cannot be applied to ethnographic research because the focus is people and people vary in all kinds of ways. It is neither possible nor is it ethical to try to control people's behaviour or values.

The constructivist epistemology therefore replaces objectivity with confirmability (Guba & Lincoln, 1989).

Unlike the conventional paradigm, which roots its assurances of objectivity in method - that is, follow the process correctly and you will have findings that are divorced from the values, motives and biases, or political persuasions of the inquirer - the constructivist paradigm's assurances of integrity of the findings are rooted in the data themselves. (p. 243).
Rather than eliminate personal preferences, bias and affective values, this thesis is interested in the effect of these aspects of students' conceptual ecologies (Posner et al., 1982) on their conceptual learning. These are the sorts of factors that are important (Pintrich et al., 1993) in ethnography and social environments.

**Validity, Reliability and Objectivity in this Case Study**

The foundation assumptions of validity, reliability and objectivity are grounded in positivism. Guba and Lincoln (1989) argue that "traditional criteria are unworkable for constructivist, responsive approaches on axiomatic grounds" (pp. 235-6). They hold that

- internal validity, which is nothing more than an assessment of the degree of isomorphism between a study's findings and the real world, cannot have meaning as a criterion in a paradigm that rejects a realist ontology. If realities are instead assumed to exist only in mentally constructed form, what sense could it make to look for isomorphisms? (p. 235)

In this sense, conventional validities and reliabilities are inappropriate for this study. The three research questions have been framed to minimise the researcher's assumptions about any student's epistemology, ontology, social motivational disposition, developmental or intellectual position. The point is that these are the issues that the study wants to probe and they are interacting to greater or lesser degrees at all times such that no factor can be isolated to determine its specific effect. The interpretations will only be able to describe the personal and contextual factors, the learning interactions, the changes that occurred, and to describe their apparent effects. Out of this, an interactive or multi-dimensional model of conceptual change may emerge in some situations.

A critic could charge that such a study is undisciplined, unpredictable and indeterminate. But qualitative case study research and conceptual change interpretive frameworks do employ grounded theories. The grounded theories constrain this study because the theories impose boundaries on the teaching and learning environment, on the type of data that is collected and on the way the data are interpreted and reported. It is in these situations that the constructivist notions of rigour are most applicable.

However, any assertion about how conceptual change occurs in any situation and with any individual must be seen for what it is, a mental construct. In this study, these mental constructs are a synthesis involving the teacher/researcher and the student. It would be a pretence to claim that such an outcome was devoid of personal values, biases and idiosyncrasies. Nevertheless, Guba and Lincoln (1989) emphasise the need for the assertions in interpretive research to be consistent with the context from which they are derived. They state that, "like objectivity, confirmability is concerned with assuring that data, interpretations, and outcomes of inquiries are rooted in
contexts and persons apart from the evaluation and are not simply figments of the evaluator's imagination" (p. 243).

For this reason, the data reported in this thesis are thick descriptions. The evidence for conceptual change in respect to atoms, molecules and bonds rests in the records of what was said and done, and what that means to the reader.

While it was impractical to comment upon credibility, dependability and confirmability in relation to every action taken during the study, the presence or absence of these qualities should become evident during the descriptions given in Chapters 4 and 5. It suffices to say that as many constructivist rigour criteria as were applicable at any time, were considered and applied to the work in the classroom and to the data collection, generation and interpretation. With regard to triangulation, data were collected from as many vantage points as possible, bearing in mind the study's constraints. The story recounted in Chapters 4 and 5 endeavours to satisfy all these issues of rigour.

It would not be honest to claim that these theoretical underpinnings were always foremost in my mind. Amidst the rush, pressures, conflicts and distractions of the normal classroom, there were times when specific ideals were forgotten or time ran out. My only claim is to have endeavoured to have tried to make the most of each opportunity and to faithfully record each event. After all, the interpretations are no more than my personal construction of what I saw and heard. With these shortcomings in mind, it is important to discuss the larger issue of researcher ethics and bias.

**Ethics and Bias**

*Qualitative Research Increases Ethical Risks*

The increasing popularity of qualitative research has made many researchers rethink the ethics of intruding on student learning. Quantitative research was generally accepted as part of the educational setting because the majority of its methods resembled or used normal educational testing instruments like the tests and observations that schools use to evaluate curricula, materials, teaching methods and student achievement (Howe & Dougherty, 1993). The benefits of these quantitative evaluations usually outweighed their disruptive effects. Likewise, the use by teachers of 'action-research' methods to improve their teaching was sanctioned as being of ultimate value to the students. Therefore, the ethics of quantitative and action research usually consisted of gaining the principal's consent and informing the students and their parents. Informed consent in quantitative research was straightforward because each instrument's administration was easy to quantify and the questions were both fixed and socially acceptable. Consequently, most cases of this type of educational research have been exempted from detailed ethical review.
Qualitative research, however, should not be regarded as quite so benign. "Qualitative research has two features - intimacy and open-endedness - that both significantly muddy the ethical waters and exclude much of it from the scope of special exemptions [applicable to] educational research" (Howe & Dougherty, 1993, p. 18). The problem with qualitative research is its open-endedness as this makes its direction, depth and duration unpredictable. Furthermore, lengthy discussions and interviews with students imposes on their learning time. While it can be argued that discussing understanding is tutoring that can remediate alternative conceptions, students may not believe that they can freely choose to participate (or not) because the researcher is their teacher and he/she controls their marks and grades. This situation existed in this study. Howe and Dougherty argue that 'informed consent' in much qualitative research can be neutralised by the open-endedness factor. Also, the intimacy (closeness, e.g., one-to-one interactions) of repeated discussions or interviews can alter the dynamics of the teacher/student relationship. While it can again be argued that this may positively motivate one student, it must be allowed that it can negatively motivate another.

These issues are compounded by the transformation of students from 'subjects' (quantitative research) to 'participants' (qualitative research) with whom meaning has to be negotiated. Teacher/researchers also should be aware of the power imbalance in any interactions with students. Qualitative research of this kind has a subtle but significant weakness. The weakness is a student's desire to please his/her teacher, a kind of Hawthorne effect. It is much easier for quantitative researchers to disguise their aims and hide their agenda but it is inevitable that students will, to varying degrees, perceive what their qualitative teacher/researcher is looking for and provide that response. The incentive to please the teacher may be subliminal or overt, but it must be considered. A safety-valve of sorts in longitudinal studies is methods, sources and theory triangulation (Patton, 1990). All the same, teacher/researchers should be as alert to signs of participant bias as they are to their own biases and presuppositions.

Another ethical issue consists of separating the roles of teacher and researcher. An experienced teacher/researcher (Wong, 1995) recounted a classroom incident in which the needs of the class conflicted with his research.

I began to feel uneasy about continuing my line of questions with Toni. The rest of the class was clearly losing interest and I was running the risk of losing the focus of the lesson. However, this opportunity to understand Toni's explanation of this phenomenon might never present itself again. We had just scratched the surface and we were making interesting progress (Wong, 1995, p. 23)
But as Wong tried to probe and improve Toni's understanding of the phenomenon by asking her more questions, Toni became frustrated because she could not provide what her teacher wanted, others in the class became restless, 'switched off' or complained that their answers were being ignored. Finally, these circumstances resulted in the teacher losing his focus on the lesson and his research. This dilemma was anticipated in this study and similar situations to that described by Wong arose on several occasions.

The ethical constraints experienced in the Year 11 chemistry class consisted of three forms. First, there were situations where, during discussions, a student's incomplete explanation hinted at the presence of an alternative conception. The presence and nature of alternative conceptions are of central importance to the researcher in a conceptual change study. But a teacher may be reluctant to deal with alternative conceptions at their point of exposure because the continuity of the lesson may have higher status. The teacher also might feel that if the alternative conception was not held by any of the students, then raising the issue at that time may introduce the alternative conception to one or more students who may then adopt it. This risk was absent from the Year 8-10 interview study because the interviews were one-on-one. Individual students did not hear each other's alternative conceptions (unless they were related afterwards) and there was an in-built bonus for the student: the interviewer was able, on several occasions, to tutor and correct the student's alternative conception.

A second ethical issue is instructional time. The inclusion of activities in the teaching program should be based on educational merit alone; however, a teacher/researcher is tempted to include activities that predominantly serve his/her research. While the present research was subsumed within the Year 11 chemistry program, the use of pretests was an overt intrusion and some of the discussions (at least their length) may have been covert intrusions. It is essential that the teacher ensure that intrusions of this nature, at the least, are of conceptual benefit to the students. Time was not an issue in the Year 8-10 study because the interviews were conducted in the last week of Semester 2 following the conclusion of all instruction and testing.

A third issue is the allocation of attention to students. Students have different personalities. Is it ethical to try to modify students' personal behaviours in the interests of data collection? Pressuring a student to be involved can be justified as 'extending their degree of interaction', but such a research bias could embarrass the student if he/she is incapable of increased involvement. This actually occurred in the Year 11 class: Gina resisted attempts to involve her yet still scored the highest mark in the class. It seemed that pressuring her would have compromised her progress. Also, suppressing active students can be demotivating if they begin to think that the teacher no longer values their contribution. Suppressing active students is also detrimental to
the class because active students often provide the drive that keeps a lesson going; therefore, changing the dynamics to suit research needs may prejudice the entire class. The individual nature of the Year 8-10 interviews probably had the reverse effect. Some of the Year 8-10 students probably had not previously had so much 'teacher' attention.

Other Ethical Considerations

Throughout this study, issues of confidentiality in data collection and fairness in reporting were given high priority. Confidentiality requires student anonymity and this was done by using pseudonyms in all written papers and in this thesis. The data are privileged information and are only available to the researcher because of each student's cooperation. Confidentiality also means that the teacher/researcher should deal sensitively with each student's comments in the data and that conceptually deprecating remarks are unacceptable in-class and in written reports. It is given that all reports should be as fair and true as possible.

Consent for this study was obtained from the principal of the school in which the teacher/researcher taught. Parents were provided with a description of the study (Appendix 2) and invited to contact the principal or the teacher/researcher if they had any questions or reservations. No parent responded and the nil response was treated as tacit approval. Increased university requirements for seeking informed consent since the inception of this study indicate that this procedure was inadequate. Due to the small number of students in the Year 11 chemistry class, it would have been possible to negotiate a more responsible form of consent with all but one student's parents who lived overseas. The fact that none of the parents queried the research may indicate that the research was responsibly executed; however, future investigations should address informed consent more fully and include a clause providing for a student's withdrawal from the study at any time.

Significance and Concluding Remarks

The study that unfolds in the following chapters is important because it attempts to do four things. First, it reviews and critiques the current literature on conceptual change learning. The review and critique is then used to synthesise a multiple perspectives model of conceptual change which wherever possible considers six issues consisting of epistemology, ontology, motivation, holistic explanatory coherence, evolutionary accretion and age-dependent development (Chapter 2). Second, the study investigates the role of metaphors, analogies and models in science learning. When this study was conceived, students' scientific modelling ability was considered to be a minor issue; however, as the research developed, it became evident that improvements in students' scientific modelling abilities were important indicators of strong conceptual change.
Chapter 3 therefore reviews the literature on representational thought. Third, the study aims to expand the science education knowledge base with respect to secondary science students' conceptions of atoms and molecules (Chapter 4). Finally, wherever possible, the six perspectives on conceptual change learning are used to interpret Year 11 chemistry students' learning of atoms, molecules and chemical bonds when multiple metaphors, analogies and models are used in a systematic way (Chapter 5). Taken together, Chapters 2-5 present a unified picture of conceptual change theory, the role of analogies and models in scientific thought, a comprehensive description of Year 8-11 students' mental models of atoms and molecules, and meaningful learning as conceptual change.

The study's methodology is qualitative supplemented by some quantitative data in Chapter 4. The majority of the data were organised to produce 'thick descriptions' which were interpreted from a naturalistic viewpoint. The Year 8-10 data were interpreted to yield patterns and conceptual themes that are reported in diagrams, tables and summaries. In contrast, the inductive interpretation of the Year 11 data generated longitudinal case studies describing each student's conceptual experiences. The study also draws on the constructivist notions of credibility, confirmability and viability to establish its rigour and, because of the long-term nature of the Year 11 study, takes into account ethical considerations, practical and theoretical limitations, and is aware of the potential for researcher bias in the findings. First of all then, the reader is invited to share the author's analysis and critique of the various theories of conceptual change learning.
CHAPTER 2
REVIEW OF THE RELATED LITERATURE ON CONCEPTUAL CHANGE

Introduction
Modern science education research has amply demonstrated that typical schools are less than effective in overcoming students' intuitive conceptions about science (Yager, 1991). Too often, teachers think that students will think like scientists if they are taught the scientific method and are shown a few classic experiments. Klapper (1995) argues that science and its methods are nowhere near as logical and linear as represented by teachers and textbooks and earlier Nussbaum and Novick (1982) pointed out that changing students' conceptions is more complex than previously assumed.

In practice, too many textbook writers and teachers assume that when basic science conceptions are to be introduced, the job is done by simply demonstrating a few "classical" experiments in a simplified form. It seems as if they believe that the very observation or performance of such experiments are sufficient for the learner (apparently by "logical necessity") to internalise the new scientific conception. They treat these classical experiments as if their structure serves a critical role in initiating conceptual change, independently of the readiness of the learner. (p. 186)

The function of this chapter is to review and critique the current conceptual change theories and attempts to construct a multiple perspectives framework for interpreting conceptual change learning. Specifically, this chapter sets out to provide background for answering the research questions, particularly Research Question 3 which asked: Do the various theoretical perspectives on conceptual change learning complement each other? The review first examines rational-cognitive models that describe conceptual change as epistemological and ontological processes. This discussion then becomes a consideration of motivational factors and asks whether conceptual change is revolutionary or evolutionary. Finally, the chapter considers whether holistic explanatory coherence and developmental models also influence conceptual change learning. Interest in these six perspectives of conceptual change required the inclusion of Perry's theory of intellectual and ethical development, Bachelard's epistemological profiles and Grosslight et al.'s modelling levels in the discussion.

Learning as Conceptual Change
Learning often is characterised as a process of conceptual change (Hewson & Hewson, 1992). Conceptual change means that there is a change in the way learners conceptualise their world, and even though learners often change their minds about all sorts of things, adoption of the consensus position of expert understanding in the various knowledge disciplines is limited. This pessimistic view is tempered by
advances in constructivist conceptual change learning theories which may well enhance classroom teaching and learning (Strike & Posner, 1992).

Conceptual change in science has been described as changes to students' epistemologies and metaphysical commitments (Posner et al., 1982); ontological changes in the way students believe science describes their world (Chi, et al., 1994); changed mental models of natural phenomena (Vosniadou, 1994); developmental conceptual change (Carey, 1985); changes due to motivational, social and self-interest factors (Pintrich et al., 1993) and changes due to the superior holistic explanatory power of one theory over another (Thagard, 1992). Substantial bodies of research over the past 15 years have attempted to unravel the complexities of conceptual change learning because an understanding of this process offers the best possibility for reforming learning at all ages (Driver, Asoko, Leach, Mortimer & Scott, 1994; Duschl & Gitomer, 1991; Hewson & Hewson, 1992; Posner et al., 1982; Strike & Posner, 1985, 1992).

That there are all sorts of changes to people's conceptions is not seriously disputed, but how it occurs, is. The more rational-cognitive explanations for conceptual change (knowledge restructuring) emerged from an assumption that conceptual change during schooling is partly analogous to the conceptual revolutions of mainstream science (Hewson, 1981; Posner et al., 1982; Thagard, 1992a). In this analogy, strong conceptual change is often called accommodation (Posner et al., 1982). The accommodation metaphor can describe the ability of the eye's lens to change its power to focus on near or far objects; or it could be the giving of a home to a wanderer. Either way, accommodation resembles learning because in learning, one's focus on and view of a natural phenomenon changes. Whichever way one interprets the accommodation metaphor, natural phenomena, human ideas, and the world they describe, change.

Personal Construction of Knowledge

Constructivism currently provides the best explanation for how people learn by proposing that knowledge is constructed in the mind of the knower by the knower (Tobin, 1993). People experience the world round about them through their senses and these sensations are interpreted to produce the images or perceptions of reality that we call knowledge. While some experiences can be new, almost every sensory input replicates previous experience in some way or other. It is rare for an individual to construct knowledge in isolation because almost all knowledge is socially constructed and negotiated (Solomon, 1987). In fact, many ideas are not experienced first-hand at all, and the majority of classroom learning, including discovery learning, occurs within a social context. Indeed, much learning is discourse-based; like stories,
explanations, discussions and Socratic exchanges (Vosniadou & Brewer, 1987). Even science itself is dependent upon human thought because "[s]cience does not exist as a body of knowledge, separate from knowers. On the contrary, science is viewed as a set of socially constructed understandings of events and phenomena" (Tobin & Tippins, 1993, p. 4).

All the same, constructivism does not deny the existence of reality as did the sceptics of old. Even radical constructivists like von Glasersfeld do not deny an 'absolute reality'; but assert that "we can define the meaning of 'to exist' only within our experiential world and not ontologically" (von Glasersfeld, 1992a). In this sense, the purpose of modern constructivism is to explain how knowledge is acquired and interpreted by the individual. The implications of constructivism to both individual knowing and to science will be revisited in later sections of this chapter when conceptual change learning is addressed in greater detail. Contributions from the literature will show that all learning is somehow influenced by what the learner already knows and by his/her epistemological commitments. Driver expresses it thus:

Central to this perspective is the historically important view that learning comes about through the learner's active involvement in knowledge construction. Within this broadly 'constructivist' perspective learners are thought of as building mental representations of the world around them that are used to interpret new situations and to guide action in them. These mental representations or conceptual schemes in turn are revised in light of their fit with experience. (1989, p. 481-2)

Put another way, people construct their current conception of a phenomenon as an interaction product between their experiences (past and recent) with the phenomenon and their past conceptions of the phenomenon. Thus, we interpret our world, and what we know at any instant in time is no more than our interpretation of that world. It also may be conjectured that we never see any phenomenon or idea the same way twice because knowledge, like experience, is in a constant state of flux. It also is probably true that each person sees each event, hears each idea, and reads each account in a slightly different way each time those experiences are revisited. In fact any claim to be able to describe the world exactly as it is, is challenged by von Glasersfeld:

From my point of view, anyone who claims to have knowledge that represents the world objectively, that is, as it might be prior to our experiencing it can justify his claim only on the basis of mystical revelation. (1992a, p. 31)

The knowledge that identifies and informs our culture is itself a human construction. Knowledge does not exist of itself, knowledge is born, it lives and is transformed in minds because knowledge is the purposeful product of human intellectual activity. This assertion is as equally applicable to science as it is to the arts. We probably have less difficulty in the case of the arts in admitting that knowledge is a human invention. Nevertheless, history shows that even apparently physically grounded disciplines like science and mathematics have been powerfully influenced by human thought.
throughout the ages. How else could inappropriate theories like the flat earth, the geocentric universe and the spontaneous generation of life have survived for so long if it were not because of powerful social, political and religious influences? As Bronowski argues in the *Ascent of man* (1973), these ideas and others, succumbed to better human ideas, to better theories, not better experiments. Driver et al. (1994) argue that Galileo's "notion of acceleration did not emerge in a non problematic way from observations but was imposed upon them" (p. 6, italics added). Galileo did not have the material means to sufficiently quantify motion to justify his assertions, yet he saw beyond his observations and invented a theory that explained what he saw. Kuhn (1970) asks,

> Why did that shift of vision occur? Through Galileo's individual genius, of course. But note that genius does not manifest itself in more accurate or objective observation of the swinging body. ... When Galileo reported that the pendulum's period was independent of amplitudes as great as 90°, his view of the pendulum led him to see far more regularity than we can now discover there. (p. 119)

Einstein's theories of relativity appear in the same light - the theory preceded the substantiating observations. Scientific knowledge is a human construction and understanding the processes that breathe life into scientific theories should be part of science teaching and learning.

That constructivist principles are central to teaching and learning should be clear for the following reasons:

1. With regard to instruction, the notion of teaching must be separated from training - Training aims and focuses on the trainee's performance, i.e., observable actions. In contrast, teaching aims at and focuses on the student's understanding, i.e., conceptual operations.

2. With regard to language, it has to be kept in mind that knowledge is a network of conceptual structures and, as such, cannot simply be transferred by the use of words because it must be constructed by each individual knower.

3. Then there is the fact that teaching is a social activity, it involves others whom the teacher intends to influence. Learning however, is a private activity, in the sense that it has to take place in the student's own mind. To guide learning therefore, the teacher will have to have some notion of the concepts the students already have and how they relate them. (von Glasersfeld, 1992a, p. 33)

von Glasersfeld's role for social influences in learning is interesting. Solomon (1987), Pintrich et al. (1993) and many teachers, believe that social interactions strongly influence individual constructions of knowledge. Furthermore, Pintrich et al. and Thagard (1993) argue that "hot irrational" methods of knowledge construction are just as important as the traditional "cold rational" cognitive pathways (expanded later in this chapter).

Hewson and Hewson (1988) also support the proposition that student conceptions are generated through constructivist pathways:

> The wide range of student [conceptions] ... is readily interpreted from a constructivist perspective. This assumes that humans are knowing, active, purposive, adaptive, self-aware
beings whose knowledge and purposes have consequences for their actions. They construct their own knowledge, using their existing knowledge in order to do so. In the process of construction, they develop relatively stable patterns of belief. They construct knowledge in ways which are to them coherent, and useful. These ways are, however, influenced by communication with other human beings so that the knowledge constructed by each individual need not be completely personal and idiosyncratic. (p. 604)

If knowledge is constructed by the learner, what can teachers do to prevent or remediate alternative conceptions? A common misreading of constructivism suggests that each and every personally constructed idea is equally viable. This position ignores the fact that every society possesses sets of consensus understandings or bodies of knowledge that are vigorously negotiated and defended. Scientists' science is just one of society's sets of agreed theories and processes, and this science has been negotiated by the community over time. This does not mean, however, that science is static. In fact, science is dynamic and evolves because, as new observations are made, models and theories are modified and, if we accept Kuhn's (1970) thesis, at times of conceptual crisis scientific revolutions take place. But where does education fit into a constructivist theory of knowing? As Tobin and Tippins state; "[T]he teacher, representing society, has an obligation to educate students (i.e., to have students construct knowledge they do not seem to have, because we think it would be good and useful for them to have it [von Glasersfeld, 1992b, p. 2]) [in order] to assist them in learning what is regarded by society as viable knowledge" (1993, p. 5). Thus, the teacher's role is to structure the learning environment in whatever way is necessary to stimulate the student to reconstruct his/her knowledge so that the student's understandings become acceptable to the social milieu. In this light, conceptual change teaching and learning is clearly grounded in constructivist epistemology.

This brief description of knowledge construction should discourage the idea that students' conceptions are inconsequential. Students' conceptions may be quite different to scientists' conceptions but this does not mean that they are non-functional. In fact students' alternative conceptions are tenaciously held and are highly resistant to change because the student finds them useful (Driver, 1989, Hashweh, 1986). These characteristics of student alternative conceptions explain why science educators have invested considerable efforts in an attempt to understand conceptual change learning. It is both premature and superficial to believe that students will readily relinquish their personal and communal knowledge. Students must be given very good reasons to do so; and even then, it will be the student who makes the decision to reconstruct his/her conceptions, not the teacher.

*Student Misconceptions are Viable Alternative Conceptions*

Science educators recognise that students do not enter instruction with blank minds (a tabula rasa); from the earliest age children accumulate sensory-motor information about
their surroundings which they interpret to generate their understanding of their world (Bliss & Ogborn, 1994; Carey, 1985). As the infant becomes a young child, the child's intuitive science is often described as 'children's science' (Gilbert, Osborne & Fensham, 1982). The cognitive structures within which children's conceptions are embedded are termed 'alternative frameworks' (Driver and Easley, 1978) for, although these conceptions differ markedly from science concepts, children's intuitive conceptions are relevant and workable for them. Alternative conceptions however, are often embryonic or novice theories; that is, they are roughly crafted explanations for the limited set of experiences so far encountered by children (Hewson & Hewson, 1988; Shapiro, 1988). This is not to say that adults do not possess similarly intuitive theories; it is saying that the alternative conceptions found in the classroom are mainly the child's making with some input from adults.

Research to date has identified a broad spectrum of alternative student conceptions which contain sets of common alternative conceptions that appear to be mostly independent of context (Driver, Squires, Rushworth & Wood-Robinson, 1994, Pfundt & Duit, 1994). For example, eight sets of common alternative conceptions are:

(i) the particulate nature of matter - students believe that matter is continuous (e.g., Andersson, 1990; Nussbaum & Novick, 1982; Renstrom et al., 1990; Scott, 1992);

(ii) heat energy - heat and temperature are undifferentiated and resemble the caloric theory of 18th and 19th centuries (e.g., Erickson, 1985; Linn & Songer, 1991; Wiser & Carey, 1983);

(iii) mass, volume and density - these concepts are indistinctly differentiated and used indiscriminately (e.g., M. G. Hewson, 1986);

(iv) electricity - students believe that current is consumed or they use clashing current theories (e.g., Dupin & Johsua, 1989; McDermott, 1993; Cosgrove & Osborne, 1985; Shipstone, 1985);

(v) mechanics - an object at constant velocity possesses a force which keeps it moving, position indicates speed, plus a variety of confusions in dynamics (e.g., Champagne, Gunstone & Klopfer, 1985; Minstrell, 1982; McDermott, 1993; Trowbridge & McDermott, 1980; Viennot, 1979);

(vi) astronomy - the world is a round flat cake and other intuitive astronomical alternatives (e.g., Nussbaum & Novak, 1976; Vosniadou & Brewer, 1987);

(vii) biology - living, dead and non living alternative conceptions (e.g., Carey, 1985);

(viii) light - ideas like light travels further during the day than at night, or rays emanate from the eye to seen objects (e.g., Shapiro, 1988; Stead & Osborne, 1980).
Whilst this list is incomplete, it demonstrates that the literature contains resources that inform teachers and researchers who want to change students' alternative science conceptions (for more detailed coverage see Driver et al., 1995).

Children's science theories are "generally less coherent, less precise, and less extensive than accepted scientific theories [but] they have some interesting commonalities" (Hewson & Hewson, 1984, p. 3). Commonalities exist because children's theories are generated outside of formal instruction, differ markedly from accepted scientific theories, are consistent across groups, and are amazingly durable in the face of instruction. The term 'alternative conceptions' is preferable to 'misconceptions' because most alternative conceptions have been generated and applied in real-life situations. Furthermore, 'misconception' has a positivist ring; and if it is acknowledged that students do construct their own knowledge as an interaction product between prior conceptions and present instruction and/or experience, it seems unreasonable to make a value judgment (mis-conception) when the weakness may reside in the curriculum, not the student.

The challenge accepted by schooling is to transform children's inappropriate conceptions into scientifically acceptable understandings enabling each young person to become an informed productive citizen in a sophisticated and technological world. Changing children's science into scientists' science, however, involves much more than just adding propositions or exchanging items of material knowledge; conceptual change challenges the learner to make epistemological and ontological adjustments to his/her thinking. Epistemological change involves changes to how the learner views knowledge and knowledge justification (von Glasersfeld, 1991a). Ontological change involves reinterpreting certain scientific phenomena so that they are understood, for example, as processes instead of material entities (Chi et al., 1994).

*Conceptual Change as a Superordinate Description of Learning*

In 1982, Posner et al. published the influential paper in which they described learning as a rational process of conceptual change. The Conceptual Change Model (hereafter called the CCM) simultaneously arose from, and supported, research into students' alternative conceptions; and this theory provided a paradigmatic foundation for many subsequent studies of knowledge restructuring. Prior research was firmly based in cognitive psychology and had described the nature and substance of children's alternative conceptions. However, Posner et al. largely derived the CCM from the then current philosophy of science in an attempt to account for the robustness of alternative conceptions and to synthesise a leaning model that would explain conceptual change. Contributors from the philosophy of science who helped shape
Posner et al.'s theory were Thomas Kuhn (1970), Imre Lakatos (1970) and Stephen Toulmin (1972).

A four stage model: dissatisfaction, intelligibility, plausibility and fruitfulness In its simplest form, Posner et al. described the CCM as a process incorporating four stages or issues. First, it was proposed that a learner must experience some degree of dissatisfaction with his/her central or organising concept(s).

Central concepts rarely directly entail anything about experience. Rather they suggest strategies and procedures whereby phenomena may be assimilated. Central concepts are thus not judged in terms of their immediate capacity to generate correct predictions. They are judged in terms of their resources for solving current problems. ... Central concepts are likely to be rejected when they have generated a class of problems which they appear to lack the capacity to solve. (Posner et al., 1982, p. 213)

When central conceptions degenerate as a resource for solving problems, and anomalies abound, and a replacement central conception is available, the learner may undergo conceptual change if the replacement concept satisfies the conditions of the CCM. That is, if the learner is dissatisfied with his/her current conceptions and if the proffered conception is intelligible, plausible and fruitful, then conceptual change may take place. The three conditions that succeed dissatisfaction are:

(i) the new conception must be intelligible, i.e., it must be minimally understood by the learner for it to be considered as a replacement for the dysfunctional central concept(s).

(ii) If the new central concept is suitably intelligible, then it also may possess an adequate degree of plausibility or be sufficiently believable for the learner to apply the new conception to previously solved problems and to the anomalies that the previous conception could not resolve. To achieve plausibility, the new conception also needs to be consistent with the learner's current epistemological commitments and metaphysical beliefs as well as being consistent with other knowledge, theories and past experiences.

(iii) Finally, if the new central organising conception achieves intelligibility and plausibility for the learner, can it "suggest the possibility of a fruitful research program" (p. 214), i.e., does it open for the learner new avenues of inquiry and extend the horizons of his/her understanding?

It must be emphasised that, for there to be a change in the learner's central conceptions, it is the learner who must become sufficiently dissatisfied with his/her current conception to even consider the new conception. If the new conception becomes intelligible, plausible and fruitful, the new conception may displace the old one. Because this form of conceptual change affects central organising conceptions, it is called accommodation.
**Conceptual ecology** The preceding section discussed the cognitive role of prior conceptions on future learning. Posner et al. (1982) addressed this aspect of the learning equation by discussing the importance of the learner's current knowledge, epistemology and ontological beliefs, collectively describing these items as the learner's "conceptual ecology" (p. 214) This is Toulmin's (1972) term and it is used by Posner et al. to describe the set of concepts that govern conceptual change in an individual. In a footnote, they state

> We understand this view in direct opposition to traditional empiricism. Empiricism's central commitment, that there is nothing in the mind not first in the senses, requires people to be able to learn something in the total absence of prior concepts. We believe this to be impossible. A mind which began as a blank tablet would remain so, for it would lack the means to investigate experience. (1982, p. 213)

A person's conceptual ecology includes anomalies generated by the prior conception; analogies and metaphors that suggest and promote new intelligible ideas; epistemological commitments which include personal explanatory ideals and general views about the nature of knowledge; metaphysical beliefs about science and science concepts; and knowledge in other fields as well as competing conceptions which promote or inhibit the acceptability of the new central conception.

**Conceptual change as a rational process** The description of learning as a four stage process represents conceptual change as a logical and rational enterprise: "Our central commitment in this study is that learning is a rational activity" (Posner et al., p. 212). While their focus was upon conceptual change as the accommodation of new central conceptions into the learner's conceptual ecology, assimilation of new information was nevertheless recognised as a viable, though less radical, form of conceptual change. Lest the description of the accommodation model of conceptual change seem easy and straight-forward, the authors noted that this was not the case. Sufficient dissatisfaction with one conception concomitant with an acceptable level of intelligibility, plausibility and fruitfulness for a replacement conception is infrequently achieved. To start with, students have an array of strategies for neutralising discrepant evidence intended to engender dissatisfaction. Students may simply reject the observational theory that produced the conceptual conflict; they may display a lack of concern for experimental findings believing that these findings were irrelevant to their current conception; they may compartmentalise their knowledge to prevent the new information from conflicting with their existing beliefs (e.g., "Science doesn't have anything to do with the 'real' world"); or they may attempt to assimilate the new information into existing conceptions (e.g., 'Newtonising' relativistic phenomena) (adapted from Posner et al., 1982, p. 221) (see also Gunstone, 1990).

The realization that accommodation was a radical change did not of necessity mean that conceptual change would be rapid and abrupt: "Indeed, there are good reasons to
suppose that for students accommodation will be a gradual and piecemeal affair" (p. 223). The image of accommodation as a four step process was qualified by noting that initially, many students will recognise neither the detail nor the implications of the competing theory.

For them, accommodation may be a process of taking an initial step towards a new conception by accepting some of its claims and then gradually modifying other ideas, as they realise the meaning and implication of these new commitments. ... each new adjustment [lays] the groundwork for further adjustments ... where the end result is a substantial reorganisation or change in one's central commitments. ... it involves much fumbling about, many false starts and frequent reversals of direction (all from p. 223).

Similarly, the assertion that conceptual change was a rational process did not seem to preclude affective influences; however, this paper clearly depicted accommodation of a new central conception as a rational and intelligible activity.

*Strike and Posner (1985)* The conceptual change theory was further expounded in a second paper. Additional items, expansions of previous ideas and qualifications were added. The 1982 work which implied a nexus between conceptual change in scientific communities and classroom learners (after Kuhn's scientific revolutions) was suitably qualified.

We are not claiming that learning theory is isomorphic with the philosophy of science. For example, an understanding of how communities of scientists select or reject new conceptions is an important part of understanding conceptual change in scientific communities, but has little to do with individual learning. We are claiming, however, that questions having to do with individual learning have certain generic structural features, whether they concern a scientist struggling with a new idea on the forefront of knowledge or with a child trying to understand elementary concepts about motion. (Strike & Posner, 1985, p. 213)

*The role of empiricism* A significant expansion concerned prior knowledge versus empiricism. Strike and Posner (1985) reinforced their 1982 foundation principle that learning is all about expanding, modifying, or making major changes to previous knowledge. They explicitly state that knowledge does not simply arise from experience. Rather, it arises from the interaction occurring during problem solving between our experience and current conceptions. (p. 214)

... empiricism gives us no reason why we should consider current conceptions as relevant to learning. Empiricism implies that conceptions are taken directly from experience and that current conceptions are unnecessary to learning. Views which emphasise conceptual change, however, assume that students' ability to learn and what students learn depend on the conceptions they can bring to the experience. Empiricists are inclined to see learning as additive. Learning is a matter of accumulating experiences ... Conceptual change views, however, are likely to emphasise the transformation of conceptions in the process of learning. (p. 215)

Recognising that students possess intuitive conceptions of their life-world (in varying degrees of completeness and sophistication) justified the view of learning as accommodation of new concepts or conceptual change. The model's four conditions for an accommodation were restated as

1. There must be a dissatisfaction with existing conceptions.
2. A new conception must be minimally understood.
4. A new conception should suggest the possibility of a fruitful research program.
   (Strike & Posner, 1985, p. 216)

Added to the factors comprising a student's conceptual ecology were exemplars and images, i.e., mental images and prototypical examples, and a role for past experiences that may serve to influence what the learner believes to be reasonable and acceptable about the new conception (compared to the old).

**Conceptual status** Conceptual change came to be characterised as a competition between two conceptions. This revision incorporated Hewson's (1981, 1982) idea of conceptual status. Dissatisfaction with the old conception, accompanied by a consideration of the relative strengths (and weaknesses) of the new conception's intelligibility, plausibility and fruitfulness, determined which conception achieved the higher status. If the prior conception had higher status, accommodation would not proceed, however, if the replacement conception achieved higher status, accommodation could progress for the time being. Accommodation, however, involves both understanding and acceptance. While accommodation could proceed, support for a new conception may decline whenever the student's understanding was insecure or where the student's conceptual ecology prevented the student from becoming committed to the new central conception because of its implications. The student may actually change conceptions, but later return to the initial conception, or any accommodation that occurred may have been too tenuous to be detected.

**The 1992 "Revisionist Theory"** Even more recently, Strike and Posner refined their thinking on conceptual change for both "empirical and theoretical reasons" and revisited the theory to answer "several lines of criticism" (Strike & Posner, 1992). The substance of the revision was twofold. First, conceptual ecology's role was expanded and reargued to account for the genesis, prevalence and resilience of student alternative conceptions. Strike and Posner (1992) declare that "a developmental view of conceptual ecology is required" and "an interactionist view of conceptual ecologies is required" (both p. 148 and 163). This revision altered the thrust of their theory; nevertheless, their commitment to learning as a rational-cognitive activity remained paramount. Second, they indicated that affective influences such as motivation, goals, values and attitudes and the institutional and social sources of components of the learner's conceptual ecology need to be considered.

Two smaller changes were evident, first, a stated link to the ideas of Piaget and second, a limitation on the types of changes that count as conceptual change. In 1982, conceptual change was characterised as the accommodation of a new central concept within the learner's conceptual ecology. Posner et al. distanced themselves from
Piagetian accommodation and assimilation as illustrated by this footnote: "These are Piaget's words, but in using them we do not intend any commitment to his theories" (1982, p. 212). In 1992 however, they state "we are interested in a phenomenon that is analogous to ... Piaget's notion of an accommodation." To use a turn of phrase, this concession accommodated the conceptual change theory (with its origins in history and philosophy of science) with cognitive psychology.

Second, Strike and Posner (1992) stated that

a learner who is able to replace a Newtonian or an Aristotelian view of motion with Einstein's has undergone the type of conceptual change with which we were concerned. Someone who learns that it is raining outside or who learns that hot air rises, has not. The distinction holds even if the latter cases of learning involve the replacement of one belief or concept with another. Our theory of conceptual change concerns the alteration of conceptions that are in some way central and organising in thought and learning. Most cases of altered belief do not count." (p. 148)

If this type of accommodation is so rare, what is the utility of CCMs in informing the teaching and learning of science? Few normal science classrooms address in-depth concepts of the type posited above, and classes rarely have the time to fully achieve this type of conceptual change. The exclusiveness of this type of conceptual change appears to be self-limiting and to reduce its worth as a pedagogical enterprise. Strike and Posner (1992) answered criticisms like this by emphasising "that we have always regarded attempts to turn our four components of conceptual change into four steps of instruction as misinterpretation of our intent" (p. 172). Nevertheless, they explicitly state on the same page that they believe that their exposition of learning as conceptual change has implications for teaching strategies and resources and go on to enumerate potential benefits.

Misconceptions and contextual factors One of the reasons for the 1992 "revision" was to answer criticisms stemming from too brief a discussion of misconceptions in 1982 (Strike and Posner used 'misconception'). Strike and Posner discussed the major contribution that the alternative conceptions literature had made to understanding and reforming science learning. They proposed, however, that describing alternative conceptions was too simplistic because the literature often assumed that student preconceptions were well formulated, representational and iconic theories. Instead, they asserted that many people "may not have beliefs about how something works so much as they have images of how it works or 'body language' about how it works. These representations may function as a source of initial and incorrect intuitions" (p. 156) about the concept being taught. This hypothesis is supported by Treagust et al. (1996) where it was found that although students had experienced bending of light as it passed from light to water and vice versa, students possessed no personal or learned theory of refraction. Further, Strike and Posner (1992) proposed that particular
alternative conceptions may not pre-exist, but "may be generated on the spot as a consequence of instruction" (p. 158).

Our initial formulation of a theory of conceptual change emphasised the importance of creating dissatisfaction with current conceptions. This emphasis may seem appropriate if one assumes misconceptions are like paradigms, in that they exist in highly articulated form and are supported by much current evidence and a history of successful use ...

However, if a misconception is weakly conceptualised and tends to be preferred by the learner because of something in the student's conceptual ecology, such as a misleading metaphor or way of talking, strategies that focus on rooting out these pieces of a conceptual ecology that generate the misconception and replacing them with more felicitous concepts may be appropriate. (pp. 158-159)

Support for this hypothesis also can be found in Vosniadou (1994) who described students' foundation ideas as ontological and epistemological presuppositions (like Posner et al.'s central organising concepts). Vosniadou studied children's conceptions of the shape of the earth in four cultures and found that children's theoretical frameworks were grounded in a naive physics; of which, one central presuppositions was the child's personal definition of 'up' and 'down' and the presupposition that unsupported objects fall in that 'down'ward direction. 'Down' was static for the child because he/she believed in a flat earth. When these children were introduced to the notion of a round earth, a significant number constructed a synthetic model of the earth in which people lived on a flat surface inside a spherical earth or they lived on the flat surface of a flattened sphere. Vosniadou suggested that these alternative conceptions arose because "students add the scientific information to their existing conceptual structures without changing their underlying beliefs and presuppositions" (1994, p. 55). Thus, the alternative conceptions were generated during formal instruction.

This hypothesis was the essence of Strike and Posner's (1992) 'revisionist theory' because the focus of remediation was moved firmly from the alternative conception itself to the faulty conceptual ecology that spawned it. Nevertheless, the four stage CCM retained its central position in describing the conditions for conceptual changes. Strike and Posner argued that teachers should pay attention to a student's conceptual ecology, identify the trouble spot, and introduce into the student's experience suitable alternative metaphors, analogies and scientific terms. Grayson's (1994) notion of 'concept substitution' resembles this approach. These approaches are quite different to drowning the student's alternative conception in a "sea of anomalies" (Kuhn, 1970). Thus, whenever the student's conceptual ecology contains a misleading metaphor or analogy, replacement with a tested metaphor or analogy (presented in a systematic manner) should facilitate conceptual change.

Each learner's conceptual ecology therefore comprises a substantial part of the context within which learning and concept formation takes place and is a significant contributor to the nature and status of a student's conception. In one of their
examples, Strike and Posner (1992) showed how it was altogether logical for a student to conceive that a thrown or batted ball will carry with it a force that degrades during flight. The students' experience with throwing, watching and catching balls both generated and maintained the alternative conceptions. This meant that the students' conceptual ecology also must be central to determining the means of remediation. Beliefs about reality, past images and experiences interact with interesting contexts to generate conceptions that are at odds with science but which harmonise with the student's ontology and epistemology.

*Conceptual ecology factors interact with one another* The 1982 paper showed how conceptual ecology influenced the learner's conceptions but did not admit that learner's conceptions influence conceptual ecology. The 1992 paper accepted that this view may mask influences that current conceptions have on the student's future perceptions and ideas. Strike and Posner (1992) hold "that scientific conceptions and misconceptions are also part of the conceptual ecology and that all the parts of a conceptual ecology must be seen as dynamic and in constant interaction and development." (p. 160) This re-evaluation stems in part from criticisms by Perkins and Simmons (1988) who asked "why do students often cling stubbornly to naive concepts even when they have been shown demonstrations and given arguments that reveal profound difficulties in those naive concepts?" (p. 309). Counter examples may fail to overcome alternative conceptions because the conceptions within the learner's conceptual ecology are so garbled that they mask the counter examples or lead to misinterpretation of the counter examples.

*Interaction between cognitive and affective factors* "A third difficulty with our initial formulation of the theory [was] our tendency to see it as overly rational" (Strike & Posner, 1992, p.161). Within classrooms, much more can be happening than just the rational assessments of scientific theories. The principal concern of some students could be achievement of a good grade, for others it could be maintenance of self-esteem in the face of learning difficulties and for others, academic rationalism may dominate. Students who find a topic's conceptual challenges insurmountable may even retreat into a position where they believe every view, including their own, is tenable. This last situation makes reform of alternative conceptions even more difficult. The central issue in these dispositions are students' motives and goals and the sources, both institutional and social, from which attitudes and emotions arise. Strike and Posner (1992) support this argument with empirical evidence stating that "our work suggests an interaction between success in learning physics and coming to see the world as a rational place" (p. 174).

The interactionist view of conceptual change emerged from empirical work that considered both cognitive and affective factors
For instructional purposes, the crucial line of inquiry is to describe the conceptual ecologies that interact with instruction, to understand how they interact, and to devise instructional strategies that interact in productive ways with the students' current concepts. (Strike & Posner, 1992, p. 173) (italics added)

To reinforce their commitment to social factors in learning, the authors stated that "our view is not neutral about the social character of knowledge. While scientific concepts may be human constructions, they are predominantly social constructions into which the young are initiated" (p. 170). Strike and Posner proposed that coming to know scientific concepts included a great deal of talk including arguing, explaining, use of metaphors and discussion of counter examples. Furthermore, they recommended that teachers of subjects like physics should work with students' conceptual ecologies by fostering conceptual change interactions which emphasised qualitative explanations over numerical solutions to problems.

**In conclusion** Strike and Posner (1992) proposed that

What in our judgment seems principally required by our theory is for teachers to teach science as though the world were a rational and intelligible place. Perhaps it would be better to say that they should teach science so that students can see that it is a rational and intelligible place. (p. 171)

This attempt to expound the theory of conceptual change from the viewpoint of the theory's originators is only part of the story to date. It is hoped that this exposition faithfully represents the views of Strike, Posner and their colleagues. The discussion must now, of necessity, address the significant but differing tack taken by Peter Hewson and his associates. Before departing, however, it is important to summarise the argument so far.

Conceptual change describes learning during which the learner accommodates a new concept into his/her conceptual ecology at the expense of some prior conception. This change is by definition, a change in the learner's central organising conception(s). Learners normally use central conception(s) in a phenomenological way: making sense of everyday occurrences, predicting, explaining and theorising about natural phenomena. As a matter of course, every change to the central conception(s) occurs rationally because of perceived dissatisfaction with old conceptions set against the perceived intelligibility, plausibility and fruifulness of new conceptions. The outcome of this competition decides the course of conceptual change; accommodation may only occur when the status of the new conception exceeds the status of the old. The learner's conceptual ecology provides the context within which conceptions are transformed when a range of rational, social and motivational factors are brought into play.
**Conceptual Capture and Conceptual Exchange (Hewson & Hewson)**

*Conceptual change*  Subsequent to the formulation of the CCM (Posner et al., 1982), Hewson (1981, 1982) expanded and qualified his commitment to the CCM. The central issue of the original conceptual change theory, that all learning involves some degree of interaction between new experience and pre-existent conceptions, was entirely preserved. On the other hand, Piaget's assimilation and accommodation (terms that have caused some confusion) were replaced with conceptual capture and conceptual exchange respectively. Hewson proposed that when a person holding a specific conception (called C) is introduced to a new conception (C'), four fates are possible for C'. First, C' may be rejected; second, it may be rote memorised; third, C' may replace C by conceptual exchange; or fourth, C' may be reconciled with C by conceptual capture. Conceptual capture correlates with assimilation and conceptual exchange with accommodation. Hewson continues with an example:

> The belief that there are no elephants in the city zoo would be changed without any fuss upon the arrival of two elephants from elsewhere. On the other hand, the change from a belief in a geocentric to a heliocentric solar system, whilst still being an example of conceptual change, would have an effect far wider than that caused by the arrival of two elephants if, for the person concerned, it held a position as central, as important as it did for Copernicus and Galileo. (1981, p. 386)

While Hewson (1981, 1985; Hewson & Thorley, 1989) recognised both instances as conceptual change, later writings show that Strike and Posner did not (1992). Two quotations illustrate this difference: "processes of conceptual capture and conceptual exchange are both examples of *conceptual change* (Hewson & Thorley, 1989, p. 543); conversely, "our theory of conceptual change concerns the alteration of conceptions that are in some way central and organising in thought and learning. Most cases of altered belief do not count." (Strike & Posner, 1992, p. 148)

The elephant belief change is conceptual capture and is both straightforward and places relatively few demands upon the learner because the new information can be reconciled within the existing conceptual framework. The solar system change is conceptual exchange and will place greater intellectual demands on the learner because the learner could not find both conceptions simultaneously intelligible and plausible. It would be expected, as is the case, that conceptual capture is a more common event than conceptual exchange. In conceptual exchange, the learner's difficulty resides in the need to decide between unrelated and/or conflicting conceptions. This is where the higher order operations of plausibility and fruitfulness become operational and create conceptual conflict in the learner's mind (Hewson & Hewson, 1984). A learner will be reluctant to believe and trust a conception that challenges his/her central commitments, irrespective of whether these commitments were derived from evidence,
logic or metaphysics. Furthermore, no conception can become fruitful unless it is first intelligible and plausible.

Conceptual conflict Conceptual conflict, however, needs to be differentiated from discrepant event teaching strategies and cognitive conflict situations. Discrepant event teaching involves placing before the student a situation that cannot be answered by the student's alternative conception but which can be explained by the scientific concept (Dykstra, 1992). Cognitive conflict occurs when the student recognises the incapacity of his/her conception while acknowledging the intelligibility of the scientific concept. Conceptual conflict, though, is an even higher order process because it more adequately "considers learning from an epistemological point of view than does 'cognitive conflict'" (Hewson & Hewson, 1984, p. 1). Conceptual conflict arises within the learner's conceptual framework when the learner believes that the competing conceptions are irreconcilable. This means that, for the learner, the new conception has become at least plausible, for unless the two conceptions are believable, they cannot conflict conceptually, nor can dissatisfaction arise. Dissatisfaction or disequilibrium (sometimes extreme disequilibrium, Gorsky & Finegold, 1995) is essential for conceptual exchange to occur. Despite the use of different terms, Gorsky and Finegold used "cognitive conflict" in the same way as Hewson and Hewson employed "conceptual conflict."

Early efforts to change student thinking emphasised identifying students' alternative conceptions followed by a focus stage in which students experienced a situation where the students' conception conflicted with the scientific concept. The students were then challenged by "a critical test of the various views; and they [were] confronted with the test evidence" (Cosgrove & Osborne, 1985, p. 114). Learning episodes of this type concluded with an application phase designed to consolidate the scientific concept. This approach was a distinct improvement on simply telling or showing students that they were wrong. The CCM, however, accounted for much more because it explained why a student felt that a new conception was worth considering (i.e., it is intelligible and plausible) and explained how the exchange occurred (because the student was dissatisfied with the old conception). Lest this sound too easy, many conceptual conflicts fail because students instead become dissatisfied with the new conception resulting in the old conception being retained. Whether CCM learning results in success or failure, it is the elements of the learner's conceptual ecology that determine the fate of any new conception. Conceptual ecology determines the degree of intelligibility, plausibility, fruitfulness and dissatisfaction that can arise.

Conceptual conflict can only be resolved by the learner, and resolution hinges on the comparable statuses of the competing conceptions. Hewson (1981) argued that in
addition to considering the four conditions of the CCM, in any conflict between C and C' there was also a need to consider the reconcilability of C and C' with each other. Whenever C and C' can be reconciled and both are at least plausible, conceptual capture may result in C and C' coexisting within the learner's conceptual framework. Conversely, if C and C' are irreconcilable, and if C' attains fruitfulness, dissatisfaction with C may be sufficiently strong for C' to replace C by conceptual exchange. Hewson and Hewson (1992) proposed that the possibility of conceptual extinction for C is untenable because it is improbable that a learner would totally forget past conceptual experiences. Hewson and Thorley (1989) put it like this "it is, however, unlikely that a conception will become unintelligible, i.e., once we know what an idea is, even if we no longer believe it, we are likely to remember it" (p. 542).

Hewson's 1982 paper expanded and reinforced his 1981 argument in a case study of learning special relativity theory. The conditions of the CCM helped the subject (SL, a physics tutor) confront his metaphysical commitments that caused him to inappropriately integrate special relativity into a Newtonian framework. Hewson states "that when [SL] was made aware of these influences, he exchanged his commitments for those underlying the theory [of relativity]" (1982, p. 63). Conceptual exchange occurred because the status of SL's initial conception fell while the scientific conception's status rose.

How then does the status of a conception change?

Status does not change spontaneously - it is only lowered if there is cause for dissatisfaction, and it only rises if sources of dissatisfaction are removed and some advantage gained. Dissatisfaction with an existing conception C can occur

(a) if an analysis of experience shows that C is no longer necessary;

(b) if C is seen to be irreconcilable with new knowledge C' which cannot be ignored,

(c) if C is seen to violate some epistemological standard, such as appearing inelegant, clumsy, unduly complicated, or ad hoc.

Alternatively, dissatisfaction with a new conception C' can occur

(i) if C' is seen to be irreconcilable with firmly held existing conceptions C ...

(ii) if the implications of C' are seen to be unacceptable;

(iii) if the experimental or logical basis for C' appears to be doubtful. (Hewson, 1982, p. 65)

Affective influences The case study of SL's conceptual change raised the issue of motivation. Evidence, logic and changes to metaphysical beliefs may need to be bolstered by other good reasons for 'changing your mind', and in this case, scientific community values played a role in mediating SL's conceptual capture.

If SL wants to make his way in physics, he has to come to terms with relativity. As a graduate student he has to learn it, as a tutor he has to teach it to his students. (1982, p. 70)
There would also be the external motivation arising from the necessity to find relativity plausible in order to feel part of the physics community. (1982, p. 72)

[it] seems to be that SL wants to reduce the dissonance caused as a result of the change [to his metaphysical beliefs]. (1982, p.73)

External motivation can open the way for advancing the status of a conception from plausible to fruitful and it can help the learner realise that it is worth making the effort to resolve conceptual conflicts. Self-interest is a significant but variable factor in a whole host of conceptual change scenarios; Pintrich et al. (1993) addressed this factor in detail (discussed later in this chapter).

From the instructional perspective, Hewson described a relatively linear teaching intervention for achieving conceptual exchange with SL. This entailed identifying and revealing to SL the position that he had adopted and contrasting SL's conception with Einstein's. Thus, the advantages of relativity were highlighted, discussed and clarified. Inevitably, it was the learner, SL, who had to become dissatisfied with his prior conception; it was SL alone who made the decision to change his mind (subjectively maybe). In summary, conceptual capture can only become conceptual exchange provided

(i) the learner's initial conception loses status;

(ii) at the same time any reconciliation between the initial conception and the scientific conception also loses status;

(iii) the status of the scientific conception rises;

(iv) dissatisfaction with the initial conception rises as a result of these status changes.

Alternative conceptions do interfere with instruction and an almost complete catalogue of common alternative conceptions is now available (Driver et al., 1995; Pfundt & Duit, 1994). However, teaching practices appear to have lagged well behind the findings of alternative conceptions and conceptual change research. The CCM suggests that first, student alternative conceptions and metaphysical commitments should be diagnosed; second, that course materials be taught with the students' current conceptions in mind; and third, that alternative conceptions be specifically addressed.

Hewson and Hewson (1983) support Posner et al. (1982) by emphasising the centrality of students' prior knowledge in learning. The Hewsons showed that when knowledge of students' alternative conceptions influence instructional design and implementation, conceptual changes may occur. New information is often inserted into pre-existing conceptual frameworks; but if the pre-existent frameworks are predominantly non-scientific, conceptual capture can place scientific concepts alongside alternative conceptions. The result can be limited or faulty explanations,
"synthetic models" (Vosniadou, 1994), neutralisation or rejection of the desired conception.

Once students' prior conceptions have been adequately diagnosed, instructional strategies can be employed that differentiate student views into their constituent parts, parts of which can be shown to be intelligible and fruitful while others are not. Conceptual differentiation resembles Ausubel's progressive differentiation (Novak, 1984). Once the deficient conceptions have been identified, the teacher and the student can work towards conceptual exchange. Experiences, problems and explanations capable of concomitantly lowering the status of the the alternative conception while raising the status of the desired conception should be applied in a way that generates learner dissatisfaction with the deficient conception. This is the essence of Grayson's (1996) concept substitution. Conceptual exchange is often best achieved by showing that the new conception has superior explanatory and predictive power to the prior conception (Thagard, 1993). Conceptual bridging "in which important abstract concepts can be linked with meaningful common experiences" (Hewson & Hewson, 1983, p. 733) helps make the new conception more plausible and fruitful. This is the approach advocated by Posner et al. (1982) where they identified analogies and metaphors within the learner's conceptual ecology as a productive route for changing prior conceptions. Bridging analogies (Brown & Clement, 1989) have also been used successfully to produce conceptual exchange in students' understanding of abstract phenomena. When successful, the progression from intelligibility through plausibility into fruitfulness concomitantly increases dissatisfaction with the old conception and leads to reconciliatory integration of scientific concepts into a learner's conceptual framework at the expense of non scientific conceptions. Whenever this process succeeds, conceptual exchange occurs.

The conceptual ecology metaphor The analogy between scientists' and students' learning played a significant role in formulating the original CCM (Posner et al., 1982). The "analogy is [actually] drawn between the conditions under which conceptions change rather than between the conceptions themselves" (Hewson & Hewson, 1984, p. 4). The conditions include the four stages of the CCM plus the learners' conceptual ecology. The 'conceptual frameworks' and 'conceptual ecology' metaphors are Toulmin's (1972) and the conceptual ecology metaphor invokes a range of interesting cross-domain mappings such as

(i) the variety of species in an ecosystem represents the variety of ideas and concepts that could be expected in a cognitive domain;

(ii) as the survival of species is subject to natural selection, ideas and concepts too, must be suitably fit to survive;
(iii) just as the natural environment contains differing niches, e.g., producer, consumer, decomposer, etc., the intellectual environment has similar niches such as "cultural beliefs, language, accepted theories as well as facts and events" (Hewson & Hewson, 1984, p. 5);

(iv) as ecosystems are vibrant, dynamic places in which an equilibrium is maintained, the intellectual environment responds homeostatically to, and accommodates disequilibriums (Ginsburg & Opper, 1969); and

(v) as organisms need to adapt to survive, there needs to be "an intellectual adaptation to the ecological niche of the scientific knowledge and endeavours of the times" (Hewson & Hewson, 1984, p. 6).

As with all analogies, the conceptual ecology metaphor ultimately breaks down. Succession within an ecosystem leads to the local disappearance and sometimes, general extinction of one or more species. Hewson and Hewson (1992) reject this possibility in favour of the increase-decrease in conceptual status. The metaphor accommodates this notion because just as populations wax and wane, the status of competing conceptions "increase or decrease ... [in] learning without difficulty ... when present views can be reconciled with what they learn" (Hewson & Hewson, 1992, p. 61). This aspect of the metaphor was not openly addressed by Hewson and Hewson (1984, 1992); nevertheless, it can be teased out of their writings. It is well established that metaphoric and analogical mappings should include both the shared and the unshared attributes to avoid inappropriate conclusions (Glynn, 1991; Harrison & Treagust, 1993; Zook, 1991).

Dissatisfaction Reference has already been made to the necessity of satisfying all the conditions of the CCM for conceptual exchange to occur. It is worth reiterating that the apparent difference between Posner et al.'s (1982) model and Hewson and Hewson's descriptions is the role of dissatisfaction. Posner et al. described dissatisfaction as if it were the activating event for any conceptual change. Hewson and Hewson, however, described dissatisfaction as arising out of the interplay between the relative statuses of the old and new conceptions. This seems a more plausible and fruitful modus operandi when the considerable differences that exist within students' epistemologies are considered. Different students will probably experience differing degrees of dissatisfaction at different points as they strive to achieve conceptual equilibrium.

Hewson and Hewson conclude their discussion of conceptual ecology by observing that

It is important to note how essential the epistemological commitments of the student are to conceptual conflict. Without an epistemological commitment to internal consistency, the conflict will not be recognised. Without a epistemological commitment to generalizability,
the conflict will not lead to the rejection of the alternative conception. The contents of a student's conceptual ecology are critical determinants of any conceptual change which he or she undergoes. (1984, p.6)

While commitment to internal consistency is not essential for the new conception to be deemed intelligible (Hewson, 1981), it is necessary for the conception to be considered plausible (Hewson & Hewson, 1984). Commitment to internal consistency also is an essential prerequisite for recognising the incommensurability of clashing conceptions. Generalizability seems to belong more to the issues of plausibility and fruitfulness because a conception that is intelligible and plausible can be reconciled and captured but only fruitful new conceptions can generate sufficient dissatisfaction to displace the prior alternative conception (conceptual exchange) (Hewson, 1981). Indeed, it would be unintelligible, implausible and unfruitful for a learner to exchange his/her prior conception for the new conception without there being very good reasons to do so, namely, dissatisfaction with the old; and this dissatisfaction depends entirely on there being sufficient conceptual conflict within the learner's conceptual ecology to make this happen.

The Need to Make Conceptual Status Explicit

Employment of conceptual change teaching within the constructivist learning paradigm has much to recommend it as a way to reform students' alternative conceptions. Hewson's (1985) proposal that the "implications of the conceptual change model for addressing alternative conceptions are straightforward" (p. 685) consisted of a test diagnosing the student's alternative conception, remediation lowering the status of the alternative conception, and remediation raising the status of the scientific conception. The reported cases targeted the alternative conception that same position means same velocity. Diagnosis and both stages of remediation were performed using a microcomputer program. The results indicated that lowering the status of the 'position means velocity' conception made possible an increase in the status of the constant separation while moving means constant velocity concept. It is probable that learning situations exist where the lowering of the alternative conception's status and the raising of the scientific conception's status occur side-by-side. The increasing plausibility and fruitfulness of an appropriate replacement conception may well lower the prior conception's status.

Refinement of this process is evident in Hewson and Thorley's (1989) discussion of the CCM and the possible student outcomes when conceptual change teaching is attempted.

During conceptual change a learner either implicitly or explicitly is involved in seeing whether the conditions outlined [CCM] are being met. The conditions are therefore very important for teachers who want to influence the course of conceptual change in their students. They need to be able to monitor the status of their students' conceptions, because it
is the case that students are probably unaware of the status change they are undergoing, particularly in these terms. (p. 543)

Teachers are encouraged to explicate for their students the changes in status occurring during instruction because students need to know how and where their conceptions are changing for these changes to be consolidated. A perusal of the science education literature revealed a large number of studies purporting to be conceptual change teaching studies; however, Hewson and Hewson (1992, p. 59) state that

Hewson and Thorley (1989) reviewed the ways in which the CCM has been used in the literature and found that the prediction of status change has been widely assumed to be the case in different instructional approaches, but has not been checked. Indeed, many studies in which conceptual change was claimed were evaluated with regard to changes in student conceptions and it was found that in very few cases were the conjectured changes in status demonstrated. Further, the literature contains a variety of criticisms that the CCM is itself incomplete or limited. More will be said about this later. Suffice to say that Hewson and Thorley (1989) recognised this criticism and agreed that more substantial means were needed to monitor and validate claims of changes to students' conceptions. They therefore posed the question: "What evidence do people give of the status their conceptions have for them?" (p. 545).

For instance, there are semantic problems with the meaning of the actual words used by students. For instance the word "force" is ambiguous as it could be used in an colloquial, impetus or Newtonian sense. The intelligibility of students' statements about conceptions is fairly easy to determine (i.e., are the statements internally consistent), but what of plausibility or fruitfulness? To determine the plausibility and the fruitfulness of conceptions used by students, it is important to identify the ways in which the conception is used (clues to whether it is believed) and manipulated in context with other conceptions to which it is connected (i.e., is it used to solve problems and to generate new ideas and connections). If all the student does is talk about the conception's content, then deciding its status can be problematic; "what is needed is evidence of a different kind, evidence that comes directly from the student, evidence that is in the form of a comment on the status of the conception" (p. 546).

This is where detailed transcripts of student discourses are valuable. Not only is the science content of the discourse available, but so too are the student's comments about how he/she feels about the conception. How the student chooses to use the conception in concert with other conceptions and situations reveals whether the student feels that for him/her, the conception is true or extendable (plausible and fruitful). Arguments, questions and 'what if' situations can be good indicators of conceptual conflict as one conception vies with another for support and viability. Evidence of this last kind - dissatisfactions - is probably the most compelling in assessing status changes.
Similarly, evidence of an epistemological kind is compelling because whenever the student's conceptual ecology is engaged and metaphysical commitments, exemplars, analogies and metaphors, and previous experiences are resourced, belief (or lack of it) and usefulness of the conception often become explicit. While the variety of comments conveying belief (or lack of it) are boundless, they are often unmistakable when they do emerge. The same can probably be said of evidence of fruitfulness. In the absence of the use of technical language by students, e.g., actually saying that conceptions are intelligible, plausible and fruitful, the teacher or researcher has to interpret the student's dialogue. In this enterprise, quality evidence is essential.

In concluding their discussion of what counts as evidence, Hewson and Thorley (1989) conclude that:

What is revealing about the list [of conceptual descriptors] is that these are not phrases that state, develop or explain the content of the conception itself. They are statements about the conception. They include opinions, attitudes, feelings, etc. (p. 549)

It is important to note that evidence of status cannot be derived, in principle, from details of the content of the conception itself. It can only come from comments about the conception: dissatisfaction, intelligibility, plausibility and fruitfulness all refer to the learner's viewpoint. Such evidence is therefore in the metacognitive realm. For example, 'discrepant event' demonstrations or anomalies are often utilised in conceptual change teaching. The use of such strategies is necessary for creating dissatisfaction with non-scientific conceptions, but it is not sufficient. It is also crucial to know how such events and anomalies are experienced by the learner. (p. 550)

Students Talking About Their Conceptual Status

Assessing changes in status in the above way is quite difficult and most teachers have neither the time nor the skills to diagnose the status of their students' conceptions. Thus, Hennessey (Hennessey, 1993, Hewson & Hennessey, 1992) taught her students the language of the CCM and by consensus, established the students' meanings of these terms. The students used the CCM's terms -intelligible, plausible and fruitful - during science lessons and in interviews about science concepts, enabling Hennessey to identify instances of conceptual capture and conceptual exchange learning. Familiarity with the terms of the CCM was first established with reference to familiar concepts and only then applied to discussions about a new concept.

Hennessey (1993) qualified the study stating that "the research being conducted was not distinct from practice" (p. 4) because the elementary students were taught science by her for the full six years of their K-6 schooling. The in-class comments and the interview responses to questions about forces acting on a book sitting on a table provided convincing evidence of conceptual exchange. However, the results must be tempered by also considering the affective influences that may have been operating in each class setting. As Pintrich et al. (1993) point out, social influences (in this case a desire to please the teacher) may have made as great a contribution to conceptual
change as the rational elements of the teaching. This does not, however, devalue the findings, it just reinforces the need to view conceptual change learning as an interaction product of cognitive and motivational forces.

Summary

Hewson and Hewson (1992) maintain that the two principal factors that determine the progress of conceptual change learning are the conditions that influence conceptual status and the individual’s conceptual ecology. By conditions, they meant the three epistemological factors discussed in Posner et al. (1982).

1. Is the conception intelligible to the learner? That is, does the learner know what it means?

2. Is the conception plausible to the learner? That is, if a conception is intelligible to the learner, does s/he also believe that it is true?

3. Is the conception fruitful for the learner? That is, if a conception is intelligible to a learner, does it achieve something of value for him/her? (Hewson & Hewson, 1992, p. 60)

The crucial issue is that it is the learner alone who decides whether or not these conditions have been met by a competing conception. And against what criteria is the new conception evaluated? It is within and against the pre-existent features of the learner's conceptual ecology that this evaluation occurs. If the new conception achieves a higher status at each of the above three stages, then dissatisfaction may be strong enough to engender conceptual exchange.

If the new conception conflicts with an existing conception, i.e., one that already has high status for the learner, it cannot be accepted until the status of the existing conception is lowered. This only happens, according to the CCM, if the learner holding the conception has reason to be dissatisfied with it. The learner's conceptual ecology plays a critical role in determining the status of a conception because, amongst other things, it provides the criteria in terms of whether he or she decides whether a given condition is (or isn't) met. (Hewson & Hewson, 1992, pp. 60-61)

This cognitive-rational description of learning does not stand alone in the science education and cognitive psychology literature. Varying degrees of criticism have been levelled at the standard CCM of Posner et al., Strike and Posner, and the Hewsons. A number of competing descriptions of knowledge restructuring have been advanced that emphasise ontological, holistic, developmental/incremental and social/motivational perspectives of learning. Some of these alternative perspectives will now be discussed.

Further Perspectives on Knowledge Restructuring

Over the past ten years, a number of influential papers have appeared that have characterised conceptual change as either weak or strong (radical) restructuring of conceptual frameworks (Carey, 1985; Chi et al., 1994; Thagard, 1989, 1991, 1992a; Vosniadou & Brewer, 1987; Vosniadou, 1994; 1986). An important difference
between these descriptions of conceptual change and Strike, Posner and the Hewsons' approach was the lack of a systematic model for describing knowledge restructuring from the perspective of the learner's conceptual ecology. This is not saying that the student's epistemological commitments and prior knowledge were ignored, it simply says that conceptual change was described from a number of different perspectives. Each of these discussions contributes to our understanding of how individual thinking changes with development and experience.

Just as Posner et al. (1982) used Piaget's assimilation and accommodation to introduce their theory articulating the substantial features of the process by which a person relinquishes one set of central organising concepts in favour of another incompatible set, Vosniadou and Brewer (1987) employed a similar starting point. As well as acknowledging Piaget, Vosniadou and Brewer drew on Rumelhart and Norman's (1981) schema theory to identify three ways in which existing schemata can be modified: first, accretion by which new information is gradually added to existing schemata; second, tuning in which interpretive categories evolve; and third, restructuring whereby more substantial changes to knowledge lead to the generation of new mental structures. Vosniadou and Brewer were most concerned with this third change, restructuring.

By definition restructuring means that there was a pre-existent structure which is changed or reconstructed. Students' pre-instructional schemata can be enriched by the addition of new pieces of information and new concepts without the overall pattern of the schema unchanging. This is a weak restructuring and usually "involves the creation of new high-order relations between the existing concepts" (Vosniadou & Brewer, 1987, p. 62). For instance, a student who thinks that the earth is a one-sided, flat, round, disc who comes to accept that there are people on both sides of the earth by visualising the earth as a two-sided, flat round disc (like a layer-cake) has undergone weak restructuring. The student's conception of a flat earth with the Sun encircling the earth has not changed; just another side has been added to explain the fact that it is always light somewhere for someone. Weak restructuring can be compared to assimilation and conceptual capture.

On the other hand, schemata can be so radically reorganised by deletion and addition of key concepts that conceptual change occurred because the initial conception was eclipsed by the new conception. An example of radical restructuring would be the replacement of the stationary flat earth with a spherical earth revolving around the Sun. Strong restructuring is like accommodation or conceptual exchange.

Vosniadou and Brewer understood weak and radical restructuring in a manner similar to Carey (1985) and agreed with Carey that particular restructurings of knowledge
were domain-specific and not categorical, cross-domain intellectual developments like Piaget's stage developments. Carey, Vosniadou and Brewer identified similarities between weak-radical restructuring and the novice-expert dichotomy. Experts surpass novices in many more ways than just knowing more; experts organise their knowledge in more abstract relational ways and employ problem solving techniques that are much more logical and systematic. Carey, Vosniadou and Brewer both called their simpler change weak restructuring, but for the more dramatic conceptual change, Vosniadou and Brewer called it radical while Carey termed it strong restructuring. Apart from the words used, radical and strong restructuring are identical for most intents and purposes. An example of strong conceptual change was the change from the "'no motion without a force' to 'no acceleration without a force'" (Carey, 1986, p. 1126).

Whilst in their paper, Vosniadou and Brewer (1987) felt confident about describing the observable features of student conceptual restructuring, they admit that "it is not clear, however, what role prior knowledge plays in radical restructuring" (p. 56). Further, while they posit that there appear to be important differences between the mechanisms driving weak and radical restructuring, they felt unable to provide a cogent explanation and believed that much more work needed to be done. Carey spoke similarly: "I will not attempt to provide criteria for telling whether a particular case of restructuring involves [strong restructuring]" (1986, p. 1127). Later, Carey stated her belief that there was no cogent representational or mechanism-of-change explanation for conceptual change and that this was a problem that would only be solved by a cooperative effort between cognitive scientists and science educators (p. 1129). It is curious that none of these authors discussed the substantial work of Posner et al. (1982) nor Hewson (1981, 1982), even though the CCM was disseminated prior to Carey's, Vosniadou's and Brewer's work. This is particularly perplexing in view of the work done by Posner et al. in arguing the importance of the learner's conceptual ecology (accentuating the role of prior knowledge) in the functioning of the CCM (itself a theoretical mechanism-of-change explanation).

Nevertheless, Vosniadou and Brewer do generate fruitful avenues for future research, claiming that this research should be aimed at

(a) what changes occur with development, (b) whether these changes can be described in terms of weak and/or radical restructurings of prior knowledge, and (c) what mechanisms can account for the observed changes. It is only then that theory based instructional research will be possible. (Vosniadou & Brewer, 1987, pp. 56-7)

With respect to pedagogical techniques capable of enhancing knowledge restructuring, they further state that:

In our view there are two candidate mechanisms for the kind of radical restructuring that may occur in children's acquisition of domains such as astronomy. These two mechanisms are (a) Socratic dialogues; and (b) analogies, metaphors and physical models.
We believe that the recognition of anomalies can serve an important function in initiating schema restructuring, but is not by itself the optimal way for the child to acquire new knowledge. (p. 61).

As commented earlier, the beginnings of "theory-based instructional research" is evident in the work completed on conceptual ecologies and the CCM. Vosniadou and Brewer's work does, however, support the research of Posner et al. and Hewson by showing that there are two types of knowledge restructuring: on one hand assimilation, conceptual capture or weak restructuring, and on the other, accommodation, conceptual exchange or radical restructuring.

Interactionist Models

Vosniadou (1994) proposes that infants commence their cognitive lives with innate predispositions that are both generalised and dynamic and that for young children, "concepts are embedded in larger theoretical structures from the start" (p. 46). The recent literature appears to contain two options for explaining knowledge acquisition in very young children: first, an empiricist view that all knowledge is generated directly out of experience, and second, a constructivist pathway in which all new knowledge is generated from the interaction of new experience with past conceptions. Vosniadou's thesis clearly favours the interactionist model (compare Strike and Posner, 1992) and unless one allows an infinite regress of learned conceptions, one must agree to the existence of some pre-formed conceptual entities into which the infant's first experiences fit. This appears to be her approach but she does not admit to innate "frameworks" as strong as those proposed by nativists like Chomsky.

Vosniadou's basic premise is that learners possess framework theories which contain ontological and epistemological suppositions (commitments?) and various specific theories. Each learner's knowledge is grounded in framework theories within which the specific theories interact with each other in a coherent way. It thus follows that conceptual changes to the framework theory are the most fundamental that can take place during learning and that changes to the framework theory must have implications for all the specific theories embedded therein. Conceptual changes to specific theories should be easier to accomplish, be less dramatic and have fewer consequences than changes to the learner's framework theory. Changes to either the framework theories or specific theories in the framework are called revisions and may involve changes to beliefs, ontologies or epistemologies. Changes may also occur within the relational features of a theory. The simplest type of conceptual change then, would be enrichment (addition of information) to conceptual structures. Enrichment appears to be analogous to Vosniadou and Brewer's 1987 notion of weak restructuring and revisions to framework theories appear to match radical restructuring; but the status of
revision to specific theories is unclear both in relation to Vosniadou and Brewer's 1987 model or to the standard CCM.

A Role for Mental Models

A significant addition to the debate was the role proposed for mental models. According to Norman (1983), mental models are intrinsic descriptions of objects and ideas that are unique to the knower and arise and evolve "through interaction with a target system" (p. 7). Mental models need not be accurate, but they must be functional. Norman cautioned that "people may state (and actually believe) that they believe one thing but act in quite a different manner" (p.11); and for this reason it should be remembered that all data and interpretations derived from interviews and learning discussions are no more than the investigators' interpretations (Duit & Treagust, 1995). Several contributors in Mental Models (Gentner & Stevens, 1983) used the construct "mental model" (p. 48) to describe student understandings and this term was used extensively by Vosniadou (1994) to describe her's and her colleagues' interpretations of children's conceptions. There is therefore, a real need to distinguish between mental models within the subject (which are never really accessible) and the reported mental models that are but representations of a subject's knowledge (Norman, 1983).

Vosniadou (1994) states "that the mental models individuals generate or retrieve during cognitive functioning are the points at which new information is incorporated into the knowledge base" (p. 48). The mental models employed by a learner are descriptors or indicators of their ontological and epistemological framework presuppositions and these mental models act as conduits to and from the underlying framework theory. The premise is that information gained about students' mental models elucidates some of the features of the underlying framework theory. Indeed, the mental models can themselves be alternative conceptions (e.g., people living inside a hollow earth or people living on top of a flat disc or on both sides of a flattened sphere, p. 53). Alternative conceptions could be generated as the student integrated (conceptually captured) scientific terms and concepts into incompatible ontologies, epistemologies and framework theories. Of greater concern was the fact that the alternative conceptions often arose as a consequence of instruction and this observation was consistent across the four cultures studied by Vosniadou and her colleagues. This finding concurs with Strike and Posner's (1992, p. 158) theory that certain alternative conceptions are generated during instruction.

An additional observation was that the students' preferred mental model exerted a powerful influence on subsequent data acquisition. Information that was incompatible to the current mental model was either not integrated by the child or had to be modified
in a way that made it compatible with the model. Thus, the child's current mental model constrained subsequent knowledge acquisition. That is, the inappropriate model acted as a barrier to conceptual change towards scientific concepts.

**Children's Changing Conceptions of the Earth**

Vosniadou's description of conceptual change used a methodology similar to that of Carey (1985). Vosniadou tracked the changes in children's conceptualisations of the Earth that emerged as they proceeded through elementary schooling. (Research into young children's conceptions of the earth was reported by Nussbaum and Novak (1976) and Nussbaum (1979) but was not referenced by Vosniadou.) Typically, in Grade 1 these children conceived the Earth as a flat disc with people living on only one side. As schooling progressed the children often developed transition views in which their model of the Earth was a synthesis of children's and scientists' ideas and later, they adopted the scientific model of the Earth as a sphere revolving around the Sun with people living all over the Earth's surface. The presuppositions in the children's initial theoretical framework that supported the unscientific models and which also constrained the acquisition of scientific concepts of the Earth, changed as their models matured.

The ontological presuppositions in the young child's framework theory consisted of (a) the Earth was solid and stable, (b) the directional frame was a simple up/down, and (c) gravity was consistently down. According to the child, up/down depended solely on his/her frame of reference and as up/down bears the same relation to the Earth's surface all over the Earth, the Earth must be flat. And since these ontologies governed the child's acceptance of models, the model allowed by the child could only change provided there were prior ontological changes. Epistemological presuppositions were simpler. The young child's knowing about knowing consisted of believing that things were as they seemed to be. Conceptual change required changes to the child's ontology and epistemology with these changes being manifest as changes in the child's preferred model of the Earth. Vosniadou also proposed that

> the process of conceptual change appears to proceed through a gradual revision of the presuppositions and beliefs of the specific and the framework theories (p. 63) [and] ... conceptual change is not conceptualised as a sudden shift from one theory to another, but a continuous process which happens gradually as the different kinds of constraints, and particularly those that belong to the framework theory, are reinterpreted. (p. 66)

It is this description of the effect that ontological and epistemological presuppositions have on knowledge acceptance or rejection, that is most useful in Vosniadou's theory of conceptual change. Her argument appeals as a useful means for interpreting student responses to the variety of models used in science.
A cautionary note should be sounded. Vosniadou and Brewer (1987, p. 61) recommended a Socratic teaching style as a means of introducing anomalies that should stimulate knowledge restructuring. The literature cited earlier in connection with the CCM, persuasively argued that students need better reasons than a plethora of anomalies to cause them to change their conceptual commitments. Vosniadou and Brewer also recommended using analogies, metaphors and models to stimulate conceptual change; however, there is widespread agreement that analogies are conceptually two-edged swords (Duit, 1991a; Glyn, 1989). This thesis will later argue that analogies and models can enhance conceptual change. Nevertheless, major refinements are needed in the use of both anomalies and analogies before they can claim to be significant contributors to conceptual restructuring.

Vosniadou (1994) concentrated on the replacement of unscientific presuppositions by pointing out that "the focus of instruction must be the presuppositions and not the misconceptions" (p. 67). However, she stated that young "students need ... a lesson on gravity and a lesson on how round things can sometimes appear to be flat" (p. 67, italics added) in order to change their unscientific conceptions of the Earth. The consensus of the research discussed so far is that unless students becomes dissatisfied with their preconceptions, adding information will have minimal effect. To be fair, Vosniadou also pointed out that "the presentation of counter intuitive facts ... cannot by definition lead to conceptual change because it does not provide students with all the information they need to have to revise their intuitive theories" (p. 67). All the same, this final recommendation seems to over-emphasise the capacity of added facts and transmission learning to remediate highly robust alternative conceptions.

Hewson and Hewson (1992) amply demonstrated the need in all these cases to carefully probe students' alternative conceptions, identify the epistemological (and ontological) barriers, and focus remediation activities on lowering the status of the unscientific conception while raising the status of the scientific conception. Only when the student becomes dissatisfied with the old conception, and chooses to relinquish the old conception for the new, does radical or strong restructuring eventuate. The factors that generate dissatisfaction can be quite diverse and include cognitive, epistemological, ontological and affective influences. Furthermore, the changes in conceptual status are embedded in and are dependent upon the learner's conceptual ecology (of which presuppositions are a part).

Indeed, it is unfortunate that Vosniadou made no reference to the CCM nor its architects because that work seems to offer explanations for many of the changes she reported and seeks to enhance. Vosniadou has shown that it is important to strengthen the theoretical links between the role of ontology, epistemology and outward changes in children's thinking. The growing understanding of the influence of the knower's
conceptual ecology in forming, maintaining and changing core conceptual commitments (or framework theories) has been well formulated and documented in the CCM.

*Conceptual Change in Childhood: A Developmental Perspective*

Carey's (1986) approach accessed the history and philosophy of science (Kuhn, Toulmin and Feyerabend), cognitive science and science education research, and her theoretical base recognised the existence in children of "alternative conceptual frameworks" (p. 1129). Carey's *strong* form of restructuring involved changing children's alternative conceptual frameworks into scientific frameworks, for instance, the change from an impetus conception of motion to the Newtonian conception discussed earlier. *Weak* restructuring involved adding extra information and/or establishing new relations between pre-existent conceptions so that old problems were solved in different ways and, overall, more problems could be solved. *Weak* restructuring of conceptual frameworks was akin to becoming more expert without necessarily changing one's foundation ontology or epistemology.

*Conceptual change in young children* In her monograph, Carey (1985) detailed the changes that occurred during children's intellectual development between ages 4 and 10. Carey's study identified the knowledge items that changed during this period and she described in detail the changes to children's conceptions of "living thing, animal, person, plant, the concept of a particular species, ... and concepts of various body parts and bodily processes" (p. 181). For example,

> five year-olds think that category membership is determined by appearance and behaviour; 9-year-olds think it is determined by deeper biological considerations. I have argued that these results too can be understood in terms of changes in children's conceptualisation of bodily processes. (p. 184)

Carey asserts that the principal difference between young children and 10-year-olds and adults is how they reason from the known to the unknown. Young children employ a model of inductive projection (derived from information processing learning models) by which they attribute properties of familiar animals to unfamiliar examples. By contrast, 10-year-olds "reason from category membership and knowledge of biological function, producing patterns of attribution that vary from property to property" (p. 185). A second difference was that 4-year-olds only projected living properties to new animals if these properties had been first learned on people. Projection did not occur if the new property was learned on a non-human animal; 10-year-olds, however, had escaped this constraint. A third difference was that with 6-year-olds, success in the attribution of new properties depended on the similarity of the source and recipient, whereas adults attribute information between objects based on superordinate categories that include both objects.
Changes in the conceptualisation of physical phenomena by children in the same age range (4-12 years) were also described by Carey (1991). The second set of case studies (succeeding the biological case studies discussed above) concentrated on material/nonmaterial issues with a particular emphasis on the concepts of weight and density. She argued against the "conjecture that commonsense physical concepts develop only through enrichment" by asserting that the biological and physical science case studies show that "some of the child's concepts are incommensurable with the adults" (p. 269). She went on to say that "the central phenomenon that suggests developmental cases of incommensurability is the same as the one that suggests historical examples as well" (p. 269). The historical parallels lie in the 17th century idea that heat and temperature were one, a concept called degree of heat (Wiser & Carey, 1983) and Aristotle's idea of speed (incorporating average and instantaneous velocity, Kuhn, 1977).

Until Black differentiated heat and temperature, progress in understanding thermal interactions was limited in much the same way that chemistry was stymied by the phlogiston theory. Carey's point is that children cannot progress to an adult or scientific conception of matter until they differentiate extensive concepts like weight from intensive concepts like density. Differentiations like this involve much more than enrichment, they involve conceptual restructuring or conceptual change. Carey provided extensive data which indicated that children do change their conceptions of matter and that this change is of the strong type, that is, it affects their central organising conceptions. In her conclusion, Carey declared that

> Concepts change in the course of knowledge acquisition. The changes that occur can be placed on a continuum of types - from enrichment of concepts that maintain their core to evolution of one set of concepts into another that is incommensurable with the original. (p. 288)

It would appear that Carey used incommensurability in the same way as Hewson and Hewson (1984, p. 6). Carey's position is that incommensurability is strongly linked to language differences or to differences in mental imagery (compare with Vosniadou's mental models). Children and adults, laymen and scientists often appear to communicate when in fact they are not actually sharing meaning. Again, when they apparently communicate, their messages are often garbled because their common words do not have shared meanings.

In order to resolve incommensurability, Carey posits that three types of conceptual change are possible:

1. Differentiation, as in Galileo's drawing the distinction between average velocity and instantaneous velocity (see Kuhn, 1977).

2. Coalescences, as when Galileo saw that Aristotle's distinction between natural and violent motion was a distinction without a difference and collapsed the two into a single notion.
3. Simple properties being reanalysed as relations, as when Newton reanalysed the concept weight as a relation between the earth and the object whose weight is in question. (p. 262)

Differentiation, as Carey used it in her studies, resembles Ausubel's progressive differentiation; certainly both processes serve the same end by separating incompatible concepts. Likewise, coalescences may resemble Ausubel's reconciliative integration. Differentiations were clearly the leading processes in Carey's analysis of children's developmental conceptual change in the age range 4-12. The changes that occurred over those years were ontological as well as epistemological as indicated by her closing remarks:

Changes of this sort go beyond mere enrichment. New ontological distinctions come into being (e.g., material/immaterial), and in terms of this distinction, entities previously considered ontologically distinct (e.g., objects and water) are seen to be fundamentally the same. The acquisition of knowledge about objects involves more than changes in beliefs about them. The adult can formulate the belief that "Objects are material"; the infant cannot. (1991, p. 290)

Restructuring and Conceptual Change

Two successive conceptual systems are structurally different in the weaker sense if the later one represents different relations among concepts than the earlier one does, and if patterns of these relations motivate superordinate concepts in the later system that are not represented in the earlier one. ... Two successive conceptual systems are structurally different in the stronger sense if the transition between the two involves conceptual change: the presence versus absence of conceptual change is the essential difference between the two types of restructuring. (Carey, 1985, p. 186)

Notwithstanding the provision of classic examples from physics (Aristotelian vs Galilean motion), Carey does not provide explicit transferable criteria that can be used to differentiate weak restructuring (which is not conceptual change) from strong restructuring (which is conceptual change). The ability to make these judgments in a nonarbitrary way must be a superordinate quality of an acceptable theory of conceptual change. It may be that the emphasis given to inductive projection (and its underlying information processing model) constrained this study and also limited the inclusion of many other factors that are today recognised as being significant in mediating and describing conceptual change.

In the main, Carey's approach (and Vosniadou's is similar) is a description of developmental conceptual change (i.e., age related) but she has little to say about mechanisms that could facilitate conceptual change in the classroom. Nevertheless, it is important to have a panoramic view of the changes that occur during a child's elementary years. Developmental conceptual change (or is it just conceptual growth?) is an example of evolutionary changes to children's conceptual frameworks and seems to sit well alongside the accretion model of conceptual change (Duschl & Gitomer, 1991; Laudan, 1984; Villani, 1992). It is probable that developmental conceptual
change involves conceptual capture but it is an open question whether conceptual exchanges occur during early childhood years.

**Conceptual Change as Ontological Tree Swapping**

While it is evident that learning one scientific concept may be easy, learning another can be quite difficult. Chi et al., (1994) posit that the differences in learning difficulty are related to the degree of categorical, ontological difference between the students' and the scientists' conception. Chi et al. propose that each knowledge item can be assigned to either a Matter (or objects) "tree", a Processes (or events) "tree" or a Mental States "tree" (p. 29). The 'tree' metaphor-model is informative because Chi et al. (and Thagard, 1992) describe each ontological category as spreading out like a phylogenetic tree into subsidiary, hierarchical levels.

Individual ontological attributes determine and are determined by the assignment of phenomena to one or other of the three 'trees.' An ontological attribute "is a property that an entity may potentially possess as a consequence of belonging to that ontological category" (Chi, et al. 1994, p. 29). Item attributes appear in three forms: defining attributes which items must possess, characteristic features that items most frequently have, and ontological attributes which items may exhibit. Chi and her colleagues define "conceptual change ... as learning that changes some existing conception" and emphasise that "the meaning of a concept is determined by the category to which the concept is assigned" (p. 27). This vision of conceptual change is expanded further:

The main concern will focus on the mere existence of major ontological trees, since reassigning a concept from its initial tree onto another tree is the crux of our notion of conceptual change. (p. 29)

In sum, ontological distinction underlies our notion of conceptual change: Conceptual change occurs when a concept has to be re-assigned to an ontologically distinct category (across trees). (p. 31)

From this perspective, it is clear that when a learner reconceptualises a phenomenon so that its ontological attributes move from say, a matter tree to a processes tree, conceptual change has occurred. According to Jung (1994), conceptual change in physics involves a

very important categorical change ... the change from substance to process, discussed under various disguises by so different men as Whitehead, Toulmin, Prigogine and ... Bopp. The mass points of classical mechanics may be looked upon as the final echo of Greek unchanging and indestructible being. The change from substance to process also changed the conception of identity. I need only to mention the Pauli Principle and nonclassical statistics here, in order to make clear that far-reaching conceptual changes are involved. (p. 104)

Jung had already noted that

talks of revolutionary changes in science go far back into the past. In fact, physics itself has always been felt to be the result of a revolution of 'modes of thought', to use Kant's phrasing. (p. 104)
Within tree movements, however, are problematic. If conceptual re-assignment is from one branch to a parallel branch within the same tree, it is unclear whether or not Chi et al. call these instances conceptual change. "The earlier in the trees ... that the learner’s conception branches from the scientists’ conception, the greater the degree of conceptual change in bringing them together" (Chi et al., 1994, p. 31). But can conceptions be sufficiently close within a tree that reconciliation ceases to be conceptual change and becomes no more than growth in expertise (as asserted by Carey)? Obviously, minor branchings like whether a whale is a fish or a mammal are easily reconciled; more fundamental differences like 'no force, no motion' and 'no force, no acceleration' are much more difficult to resolve. Thagard (1992a) recognised this difficulty when he defined nine levels of change, all of which he called conceptual change.

*Constraint-Based Interactions*

Within the Processes tree, Chi et al. distinguish between two major sub-categories, 'Constraint-Based Interactions' and 'Events' by showing that Events have a definable beginning and ending whereas Constraint-Based Interactions do not. An example of an Event was a baseball game and an example of a Constraint-Based Interaction was an electric current. A baseball game has a start, a progression and an end; an electric current simply exists as long as an electric charge moves within an electric field. That an electric current depends upon the existence and correct orientation of Matter entities is evident, yet it is not Matter it is a Process. Current is a Constraint-Based-Interaction dependent upon and constrained by Matter entities.

It is this difference between Matter entities and Constraint-Based Interactions that characterises many alternative science conceptions. Chi et al. point out that many students mistakenly interpret Processes phenomena as Matter phenomena. For instance, the naive impetus theory depicts force as substantial, that moving objects contain a force-substance that is consumed as the object moves. Similarly, electric current is visualised as an object (e.g., the water circuit analogy) and the circulation of the blood is seen as the sum of its material parts (rather than as a pressure-volume process). Consequently, conceptual change has occurred when students replace Matter attributes with Process attributes in their phenomenological explanations (e.g., replacement of the flowing water analogy by the electric field model for an electric current).

*The Incompatibility Hypothesis and Alternative Conceptions*

Chi and her colleagues acknowledged that they had made three assumptions or suppositions: the epistemological assumption that there were three superordinate knowledge categories, Matter, Processes and Mental States; a metaphysical
assumption that many science concepts were Constraint-Based Interactions; and a
psychological assumption that many alternative conceptions existed because students
confused Processes and Matter entities. They conjoined these three perspectives to
frame a theoretical account of why students have difficulty learning certain science concepts.
This difficulty stems from the mismatch or incompatibility between the categorical
representations that the students bring to an instructional context, and the ontological
category to which the science concept truly belongs.

When a student's initial representation of a concept is incompatible with the concept's
veridical ontological status then learning the concept requires conceptual change, meaning
that the concept's categorical membership has to be re-assigned across trees. (p. 34)

This Incompatibility Hypothesis is used to account for the proliferation of alternative
conceptions during instruction. Students often attribute Matter ontological properties
to Processes phenomena like force, electric current and evolution. Conceptual
incompatibility is accentuated by analogies like the circulating water model for electric
current. Because water is matter, student's place electric current in the "liquid" Matter
subcategory and attribute to it properties like "has volume", "occupies space" and
believe that electric current "can be stored in the battery" and "can be used up" (all p.
34). Incompatibility due to the assignment of entities to incorrect 'trees' becomes a
barrier to effective learning and unless conceptual change re-assigns the entities to their
correct 'trees', only limited knowledge growth can occur.

Under the Incompatibility Hypothesis, it is the ontological status of a student's initial
conception of such concepts which renders them difficult to learn, since acquiring the correct
conception requires a shift in ontological status (radical conceptual change). (p. 35)

It is probable that this incompatibility is similar to Hewson and Hewson's (1984)
incommensurability of conceptual frameworks. Incommensurability is so radical a
distinction that it was likened to Kuhn's different paradigms. Chi et al.'s comments
indicate that incompatibility, like incommensurability, is a major barrier to conceptual
change. For the student, nothing short of "tree switching" (Chi et al., 1994) or
conceptual exchange (Hewson, 1981, 1982) can resolve the dilemma. This is why
students often find the challenge too severe, or they may make the transition only to
regress at a later date. Chi et al. reviewed a large body of incompatibility data in the
literature and concluded that naive conceptions tended to be robust (difficult to
overcome), consistent over time and situations, persistent across age and schooling
levels, homogeneous between different students in a group, recapitulations of
historical concepts (like medieval views), and systematic (either coherent or
fragmentary).

Alternative conceptions which were not incompatibile, that is, not characterised by all
or some of the previous six features, could be remediated relatively easily. Chi et al.'s
own data on eighth graders' learning about the circulatory system was of this type.
When students assigned their conception to a branch of the ontological tree to which
the scientific concept belonged, compatibility was likely, and reconciliation towards the scientific concept did not involve a radical conceptual change. This was learning that Posner et al. (1982) called assimilation and which Hewson (1981, 1982) called conceptual capture.

**Summary** Chi et al. characterised conceptual changes as strong or radical restructuring of knowledge when phenomena moved from one ontological 'tree' to another. A weak form of restructuring also was allowed consisting of the accumulation of additional information (or nodes within a person's conceptual framework) and the creation of new connections and relationships. However, Chi et al. did not call even an increase in expertise, weak restructuring. There is, nevertheless, a substantial gap in Chi et al.'s explanation. They fail to commit themselves as to how movements between distant branches within the same tree should be described. Similarly, Mental States are neither described nor discussed yet the authors assert that Mental States is one of the three superordinate categories.

If Mental States is a genuine 'tree', then learning that transfers phenomena from Matter or Processes 'tree' to the Mental States 'tree' must also be conceptual change. This has implications for student use of mental images and analogical models. Grosslight et al. (1991) described changes in students' modelling abilities in terms of changes in students' beliefs about a model's representation and use. For example, Level 1 modellers believe 'it is true' that there is a one-to-one correspondence between the model and reality and Level 3 modellers only see models as thinking tools. The maturation and sophistication of mental images and models may provide sound evidence of conceptual change towards or within the Mental States 'tree' (Perry, 1970; Finster, 1989, 1991). Changes in the way a student deals with multiple models, expansion of a student's repertoire of mental images and models, and qualifying the allowable ways in which models can be used could be confirmatory evidence for Chi et al.'s 'tree' switching or Hewson's conceptual exchange.

**Concepts, Conceptual Change and Epistemic Change**

Thagard (1989, 1991, 1992a) asserts that conceptual change involves much more than mere belief revision (i.e., the simple addition or deletion of beliefs about a concept) because mere belief revision does not "account for why some revisions are harder to make than others, and why some revisions have more global effects" (1991, p. 103). Thagard defines concepts, which are central to his concerns, as mental representations that play significant roles in thinking and knowing. He provides at least ten roles for concepts: categorisation, learning, memory, deductive inference, explanation, problem solving, generalisation, analogical inference, language comprehension, and language production (1991, pp. 104-5). Thagard showed that the first eight roles necessitate the
involvement of conceptual structure in belief revision; he argues that belief revision involves more than the addition or subtraction of propositions, changed belief is a form of knowledge restructuring.

The discussion focussed on one example, the reclassification of a whale from fish to mammal. Generalisation and analogical inference introduced a kind link between whales and mammals resulting in other mammalian features being attributed to the whale in question. This undoubtedly involved conceptual structure and Thagard argued that each of the first eight concept roles were involved to some extent. Part-whole hierarchies along with kind categories "serve to structure most of our conceptual system, providing backbones off of which other conceptual relations can hang" (p. 110). The majority of these concept roles apply in most reconceptualisations, however, they may not be universally applicable as Jung (1994) cautions in observing that the "part-whole-scheme, which served so well during two centuries, does no longer function within the elementary particles" (p. 105) domain. In physics, a new paradigm is being considered. Nevertheless, this trend does not detract from Thagard's historical comments.

Beliefs about kind and whole-part relationships are especially important in conceptual change and "deciding that whales are mammals and not fish is a significant alteration to our kind hierarchy" (Thagard, 1991, p. 113). Concepts are complex structures and while it would be futile to produce criteria that specified where one concept ceased and another started, Thagard does propose a nine stage hierarchy (weakest to strongest) of conceptual changes.

1. Adding a new instance, for example that blob in the distance is a whale.
2. Adding a new weak rule for example that whales can be found in the Arctic Ocean.
3. Adding a new strong rule that plays a frequent role in problem solving and explanation, for example that whales eat sardines.
4. Adding new part-relation, for example that whales have spleens.
5. Adding new kind-relation, for example a dolphin is a kind of whale.
6. Adding a new concept, for example, narwhal.
7. Collapsing part of a kind-hierarchy, abandoning a previous distinction.
8. Reorganising hierarchies by branch jumping that is, shifting a concept from one branch of a hierarchical tree to another.
9. Tree switching, that is changing the organising principle of a hierarchical tree. (Thagard, 1992a, p. 35)

While changes 1-6 speak of additions, they function in the same way by deletion. Thagard posits that change 8, "branch jumping", is common in scientific revolutions and that number 9, tree switching, is the type of change that occurred when Darwin reclassified 'human' as animals and Einstein reinterpreted everyday space and time as
relativity's space-time. Darwin's reclassification of humans as animals could be interpreted as *branch swapping*, but Darwin did more than just recategorise humans, "he changed the meaning of the classification" (Thagard, 1992a, p. 36) by *exchanging* a similarity classification for a historical, descent-based system. This is the strongest type of conceptual change possible, *tree swapping*.

Whether Thagard used tree swapping in the same sense as Chi et al. (1994) is unclear, however, his comments on Chi's research (Thagard, 1992, p. 260), suggests that both use branch swapping in similar ways. Thagard (1991) summarised his thesis:

> I conclude, therefore, that an understanding of conceptual development in science and everyday life is an essential part of epistemology. Merely attending to belief revision will miss crucial aspects of epistemic change. ... [In] scientific revolutions, whole systems of concepts get altered or replaced. ... Hence conceptual change is more than belief revision, and epistemology needs a theory of concepts just as much as does psychology. (p. 118)

*The Theory of Explanatory Coherence*

Elsewhere, Thagard (1989) addressed the question of whether scientific cognition is "cold" (i.e., rational, computational) or 'hot' (motivational, emotionally driven). His thesis is that conceptual change is a rational process explained by his "Theory of Explanatory Coherence." Thagard supports his theory by demonstrating that a suitable computer program can arrive at the same conclusions as the scientists involved in major historical scientific revolutions. The program, ECHO, reproduces (albeit crudely) the connectionist structure of the mind and when ECHO was provided with Lavoisier's oxygen propositions and hypotheses alongside the competing phlogiston propositions and hypotheses, ECHO's repeated iterations concluded that Lavoisier's theory possessed the superior explanatory coherence.

ECHO and the theory of explanatory coherence evaluated three scientific revolutions (Lavoisier, Darwin and Wegener's plate tectonics) and demonstrated that

> These runs shows that the principles of explanatory coherence proposed above have the holistic gestalt properties that seem to be required for understanding the replacement of conceptual schemes. ... ECHO is a model of cold cognition, in that it considers only the relation of competing theories to evidence and to each other, saying nothing about the interests of those who adopt theories (Thagard, 1991, pp. 76-7).

On the motivational front, Thagard acknowledged that self-serving interests are not neutral with respect to belief revision and conceptual change; however, he noted that current understandings of how "motives can bias beliefs" are not well developed.

*Epistemic Change is Superordinate to Conceptual Change*

Epistemic change is Thagard's superordinate heading for both belief revision and conceptual change and the taxonomic nature of epistemic change is illustrated in Figure 1. This dichotomy may be similar to assimilation/ accommodation (Posner et al., 1982), conceptual capture/conceptual exchange (Hewson, 1981, 1982), weak/radical
restructuring (Vosniadou & Brewer, 1987) and weak/strong restructuring (Carey, 1985, 1986). Thagard's purpose in using this dichotomy appeared to be to distinguish epistemological changes which did not involve and affect conceptual structure from those changes which reorganise concepts and/or their hierarchical relations.

Simple conceptual reorganisation that involves mere extension of existing relations differs from the revisionary sort represented by branch jumping, which involves moving concepts around in the hierarchies and rejecting old kind-relations or part-relations as well as adding new ones. Belief revision, concept addition, and simple reorganisation of conceptual hierarchies are common in the development of scientific knowledge, but we shall see that branch jumping and tree switching are much rarer events associated with conceptual revolutions [e.g., Lavoisier's chemical revolution]. (Thagard, 1992a, p. 37)

![Diagram of epistemic change]

**Figure 1: Thagard's taxonomy of kinds of epistemic change.** (1992a, p. 37)

Thagard's conceptual change is thus characterised by major revisions to the knower's conceptual structures involving one or more epistemological additions, deletions,
reorganisations or redefinitions of hierarchies such as branch swapping and tree switching. Development and replacement of one conceptual structure by another occurs neither by rote nor by the learner laboriously retreading the discoverer’s path. Conceptual change instruction involves incorporation of scientific concepts and rules and learning to think with the new system: "The major mechanism by which this strengthening takes place is scientific argument" (1992a, p. 59). According to Thagard, the historical overthrow of the phlogiston theory took several years. In this regard Thagard's thesis conflicts with Kuhn's (1970) premise that scientific revolutions do not complete their course until the major proponents of the prior theory are dead. While this was true for Priestley, says Thagard, many of his followers, principally Kirwan, were converted as a result of their vigorous arguments with Lavoisier and his colleagues and by repeating Lavoisier’s experiments.

Conceptual replacement thus depends upon the superior explanatory coherence of one theory over another. The exercise of discourse, argument and thinking about a competing theory involves a variety of concepts, weak and strong rules and their changing connections within an individual's conceptual structure during the conflict. Experience with competing concepts and their application to problems should identify the more coherent theory from the explanatory perspective. Thagard summarises:

In this way, a theory of explanatory coherence can be the driving force behind theory replacement and major conceptual change. The crucial point is that the new conceptual system does not arise by piecemeal modification of the old one. Rather the new one must be built up largely on its own, and its replacement of the old is the result of a global judgment of explanatory coherence. (Thagard, 1992a, p. 60)

It is indeed useful to explain scientific conceptual revolutions in these terms. But of what use is this mechanism to novices like secondary school and college students? Thagard expresses optimism and some caution:

We can contrast conceptual change in scientists during revolutionary periods in the history of science with conceptual change in children and in students learning science. There are points in common between conceptual change in the history of science and conceptual change in ordinary learners, but there may also be important differences. Ordinary learning is not simple accretion, but it may not be as systematic or as revolutionary as conceptual revolutions in science. (1992a, p. 246)

In an attempt to illuminate the question "Do children undergo the same kinds of conceptual change as scientists" (1992a, p. 251) Thagard reviewed the extensive literature on this subject. He commenced with Carey (1985) and worked through Chi (1988, 1991), Kiel (1989), Vosnai'dou and Brewer (1987, 1990) and diSessa (1988), and concluded that there were two tenable hypotheses. Carey proposed that children are like scientists because they reject animist theories in favour of more scientifically coherent concepts. Chi's contrary view states that children simply acquire biology and physics concepts without comparing scientific ideas with their intuitions, i.e., the old beliefs simply fade away. diSessa's position that children hold phenomenologically
primitive ideas that are unsystematic and incoherent accords with this view. Combining this literature with his ideas led Thagard to conclude that the issue was unresolved.

It seems, however, that children's new theories will much more frequently incorporate or disregard their old ones, rather than supplant or sublate them. A valuable role for teachers can be to ensure that children become aware of how theories that they have or should have outgrown conflict with what they are being taught in school. (1992a, p. 259)

Most usefully, Thagard identifies a set of research questions whose full or part resolution should advance understandings of conceptual change and children's learning of science.

**Summary** It is important to remember that the central plank in Thagard's explanation of radical restructuring is the theory of explanatory coherence. He believes that it is the explanatory breadth or holism of the successful theory that makes it successful. Similarly, holistic changes to an individual's fundamental epistemology are dramatic and revolutionary. With regard to children's learning, he closed with this comment:

From research to date, conceptual development in children appears to be less revolutionary than what occurs in science since it does not involve branch jumping or tree switching. Whether explanatory coherence plays a role in theory development in children is an open question. (1992a, p. 263)

**Complementary Conceptual Change Research**

*The History and Philosophy of Science*

**The challenge** If conceptual change is to be readily identified and systematically described, then much more is called for than ad hoc sets of descriptions of changed understanding. When Dykstra (1992) wrote, "how can we describe conceptual change?" (p. 40), he in effect asked: Are there different categories of conceptual change? What are the conditions that initiate and sustain conceptual change? and, What sorts of evidence indicates that conceptual change has actually occurred? Identification of conceptual change should, therefore, diagnose the degree to which learners have restructured their beliefs about the world and how it works.

Nussbaum's (1989) observation that "the problem of understanding conceptual change among students is illuminated by the views of the philosophers of science" (p. 530) also compounds the problem! Constructivism may be the currently preferred paradigm of science, psychology and science education, but empiricical positivism and rationalism seem to be alive and well in many classrooms. Moreover, constructivism is less than equivocal on conceptual change - Popper, Toulmin and Lakatos describe it as evolutionary while Kuhn's paradigm shift is clearly revolutionary.

Consideration of these practical and philosophical dilemmas led Driver and Easley (1978) to reinterpret misconceptions as 'alternative conceptions' and for Gilbert,
Osborne and Fensham (1982) to give credence to the notion of "children's science." The advent of these ideas negated behaviourism's simple fixes for student learning failures. The problem was that 'the problem' became more difficult: conceptual change was more complex than telling students the right answer, showing them a discrepant event or just providing better explanations. At last it was recognised that the student had to be provided with the ideas, the evidence, the time and the social conditions that would encourage them to reconstruct their private conceptions.

The student as scientist In attempting to understand conceptual change, the analogy between scientists as discoverers, and students as learners, has often been drawn (e.g., Piaget, 1962). One of the basic threads running through the original CCM (Posner et al., 1982) was that student learning and scientific discovery were analogous. This analogy appears limited for a number of important reasons:

Students are different from those great scientists of the past in ... age and intellectual capacity; repertoire of past experience ... previous relevant knowledge; previous knowledge in other areas which might provide analogies and metaphors for interpreting problem situations; the amount of time and effort ... to reflect on their own reasoning and thereby become aware of the essential features of their own (pre)conceptions. (Nussbaum & Novick, 1982, p. 187)

These student characteristics resemble important aspects of Posner et al.'s (1982) 'conceptual ecology.' Scientists, and students alike, depend on their conceptual ecologies to make sense of experience, however, scientists and school students have very different conceptual ecologies. Similarly, science as a research activity differs markedly from science as an educational enterprise (Horwood, 1988). Not only are there many differences between scientists and students as people, the environment, the language, the nature and the extent of the investigations differ in a whole host of ways. Therefore, Nussbaum and Novick argued that comparing students who spend only a few hours a week on science with full-time scientists is probably counterproductive. Duschl and Gitomer (1991) also argued that the 'scientist as discoverer' model was less than appropriate for the average secondary school science student.

The idea that major conceptual changes in students and scientists are comparable may be attributed to an over-simplistic image of the scientific enterprise and the over-emphasis given to Kuhn's description of scientific revolutions. It is often forgotten, especially in popular stories, that cutting edge science is neither glamorous nor easy. It is worth remembering Thomas Edison's adage that "genius is ninety-nine percent perspiration and one percent inspiration." Posner et al. (1982) captured this image by saying that science learning "involves much fumbling about, many false starts and mistakes, and frequent reversals of direction" (p. 223).

Piecemeal conceptual change Villani (1992) proposed that a productive analogy existed between Laudan's (1977) description of conceptual change in scientists and the learning of science by secondary and tertiary students. Laudan challenged Kuhn's
notions of "normal" and "revolutionary" science by asserting that normal science is not that normal, and revolutionary science is not so revolutionary. Using Laudan's theory, Villani suggested that scientists (and students) change parts of their theories, one at a time, and that in time these changes manifest themselves as outward changes in their research directions or in their theories: "in fact, minor changes gradually introduced into guiding assumptions may turn out to be very important ... a real conceptual change" (p. 228). This kind of scientists' behaviour is mimicked when students accrete items of new scientific theories while maintaining their preconceptions.

During a large part of the learning process, students are elaborating new academic models without leaving behind their spontaneous models, and it ought to be considered in many cases, a normal and rational behaviour. (Villani, 1992, p. 231)

Villani's model of conceptual change was thus rational, piecemeal and progressive. Duschl and Gitomer (1991) also argued that current perspectives on knowledge restructuring reflect the dichotomies espoused in Kuhn's (1970) 'normal' versus 'revolutionary' science and Lakatos' (1970) 'soft-core' and 'hard-core' changes to research programmes. Their thesis was that these dichotomies may well have spawned the weak/strong and weak/radical descriptions of knowledge restructuring. Consequently, the most prominent conceptual change theory, that of Posner et al. (whose authors admit a debt to Kuhn and Lakatos) was criticised for being too reliant on an epistemology that embraces a hierarchical model of knowledge justification. A model of conceptual change is hierarchical when it assumes that changes in central commitments to a theory of science bring simultaneous changes to other ontological, methodological and axiological commitments within the conceptual framework. (Duschl & Gitomer, 1991, p. 842)

Duschl and Gitomer preferred Laudan's (1984) view and rejected the notion that conceptual change was global or holistic by arguing that instead, change in science was piecemeal: "It is the characterisation of scientific change as a holistic process that is at issue" (Duschl & Gitomer, 1991, p. 842). This criticism appears somewhat harsh for Posner et al. acknowledged that some changes in conceptions were piecemeal. They stated that there are good reasons to suppose that for students, accommodation will be a gradual and piecemeal affair. ... for them, accommodation may be a process of taking an initial step towards a new conception by accepting some of its claims and then gradually modifying other ideas, as they more fully realise the meaning and implications of these new commitments. ... each new adjustment laying the groundwork for further adjustments but where the end result is a substantial reorganisation or change in one's central commitments. (Posner et al., 1982, p. 223; italics added)

What Posner et al. described in detail were the conditions required to accommodate a new conception. Dissatisfaction with the old conception may initiate examination of the new conception's intelligibility, plausibility and fruitfulness, but they were careful to point out that conceptual change is not a foregone conclusion and changes which do
occur are sometimes reversed at a later date. Posner et al. also added the qualification that "fundamental conceptual changes, termed accommodations, may involve changes in one's fundamental assumptions about the world" (p. 223). Seen in this light, Posner et al.'s conceptual change is less dramatic than Kuhn's revolutionary change and allows Duschl and Gitomer's and Villani's accreptive change.

By emphasising the piecemeal nature of conceptual change, Duschl and Gitomer made a valuable contribution to the debate by asking, "how do learners reform their understandings so that they become more scientific?" Briefly, Laudan's reticulated model of scientific knowledge justification abandoned the view that a concept's aims, theories and methods were hierarchical. Instead, aims, theories and methods share equal status and interact with each other in Laudan's (1984, p. 63) "Triadic Network of Justification" (see Figure 2). Thus, when scientists, teachers or students change the theories supporting a conception, concomitant changes to aims and methods are not automatic. If this is true, the implications for teaching are clear. Conceptual change teaching needs to target each of the three interdependent knowledge components shown in Figure 2. Curriculum design should include learning activities that equally address aims, methods and theories by focussing upon procedural as well as declarative knowledge items.

![Figure 2: Laudan's "Triadic Network of Justification" (1984, p. 63)](image)

*The Role of Preconceptions in Conceptual Change*

In 1987, White reminded science educators that the wave of research into alternative student conceptions could not of itself change inappropriate conceptions. The results of
qualitative research probing deep understandings could identify or point towards the origin of many intuitive student ideas, but more was needed. It was time, he observed, for a "shift from elucidating alternative conceptions to those unresolved problems of how to change conceptions" (White, 1987, p. 13) because teachers needed direction as to how to remediate their students' unscientific conceptions.

To comprehend the tenacity and force of student preconceptions (or prior conceptions), it is worth digressing to think about the origin of student preconceptions. Solomon (1987) argued that most knowledge is socially negotiated and socially confirmed through everyday discourse. This is particularly important in children as they try to make sense of their world. Personal ideas are tested against the ideas and opinions of others: "It is almost as though we do not understand what we think unless we can discuss it and receive back the effects it produces when our friends respond" (p. 63). The fact that children share their ideas and 'bounce' their theories off one another may well explain the consistency of preconceptions across populations and contexts.

Preconceptions in a student's conceptual ecology can help or hinder conceptual change: it all depends on how they are treated. Hashweh (1986) contends that even though many preconceptions are unscientific, they maintain their viability because students find that their intuitive theories explain the everyday phenomena to which they are applied. Moreover, the student has an observational base and well founded reasons (from their point of view) for thinking the way they do, and these conceptions do work for the student in a limited number of ways; albeit in ways that would horrify many scientists.

Preconceptions arise as a result of experience in interacting with the world. Through continuous use, these preconceptions become readily available for interpreting events and shaping expectations. ... they cannot be completely 'wrong', but are adequate for certain purposes and for interacting with a limited domain of the world. (Hashweh, 1986, p. 231)

Hashweh thus argued that once the persistence and nature of the student's preconceptions were understood, it was possible to selectively introduce new conceptions culminating in cognitive restructuring. He summarised his image of conceptual change in three steps: the old conception should be discarded or its use limited, a new conception should be accepted in its place, and the new conception should be available for application to future problems.

Hashweh proposed that conceptual change and conceptual stability involved both intrinsic student factors and extrinsic societal influences. Nussbaum and Novick supported this notion that affective influences were involved in cognition and advocated social learning activities that brought the students 'on-side.' Nevertheless, they recognised that social forces and challenging discussions were but a means "for making every student aware of his own preconceptions" ... invit[ing] a student to explain [a concept] in terms of his own preconceptions" (Nussbaum & Novick, 1982, p. 187).
Conceptual extension Hashweh reasoned that for some instances of conceptual change, the scientific position was really only a more general case of the alternative conception. For example, as a child matures, his/her notion of the volume of water in a glass extends to accommodate cross-sectional area as well as depth. Extension of a conception like this

show students that their preconceptions are not wrong but limited, and ... show that their preconceptions, in many cases, are indeed special cases of the postconceptions and [the scientific conception] could be derived from these preconceptions - these types of explanations ... are seldom provided although, in my opinion, are very important in fostering restructuring. (Hashweh, 1986, pp. 245-6)

Conceptual change does not necessarily require elimination of the prior conception, suitable extensions or qualifications can restructure the student's conceptions in a way that allows the students to see that their prior belief was not wrong, rather it was just limited or contained one or more inappropriate items. This type of change was evident in Dykstra (1992) 'class extension where students realised that the rest state was just a particular case of constant velocity. Gorsky and Finegold (1994) reported a parallel instance of this type of change. Whenever restructuring occurs, Hashweh advocates providing students with "opportunities to reinterpret past experiences after the new conception is accepted" (p. 246) enabling them to identify the changes they had made and to see the alternative and the scientific conceptions in their correct perspectives.

Concept substitution Grayson (1994) supports Hashweh's approach by showing that students' alternative science frameworks often contain some acceptable conceptions that are either incorrectly named, incorrectly applied, or are linked to one or more incorrect conceptions. Analysing the very common idea that current is consumed in an electrical circuit provides good reasons why students develop and maintain this conception.

After all, batteries go flat after a while. How can the current not be used up? Frequently, instruction stops here [the misconception is challenged], but I believe this is a dangerous state in which to leave a student. Because they have not really resolved the issue of what was wrong with their own preconceptions, students might not make the conceptual change to believing that current is not used up, or they might appear to accept the new ideas for a time and revert to their previous ideas some time later. ... This is the point where I introduce concept substitution. Students are told that they were right to say that something is 'used up', as evidenced by the fact that the batteries do go flat, but the 'something' that is used up is 'energy' and not current. ... In this approach the instructor introduces the correct physics term at the time that the apparent misconception arises, even though the term may not have been encountered before in the course. (Grayson, 1994, pp. 5-6)

In Hashweh's terms, concept substitution involves analysing the student's beliefs, identifying the part(s) of the conception that is acceptable and which is not. The correct item(s) is identified and acts as an 'anchoring conception' for building a more correct conception (similar to Clement. Brown & Zeitsman, 1989). This strategy also resembles Duit's (1993) continuous pathway which he used to evolve appropriate
conceptions out of preconceptions. Scott's (1992) scheme of 'conceptual pathways' may also employ this approach. Grayson (1994) continues,

I call this strategy 'concept substitution' because the instructor substitutes the concept that matches the students' intuitive ideas for the term they used incorrectly. The process allows students to embrace the accepted scientific concept without having to suspend their intuitions, intuitions are relabelled. [Concept substitution] builds on learners' existing ideas and extend them. (p. 2).

As concept substitution builds science out of intuition, canvassing student preconceptions is an essential prerequisite to this process. Making students' prior knowledge explicit (see White & Gunstone, 1992) provides a focus for instruction and avoids the 'broad-brush' approach which ignores many student alternative conceptions simply because they are in the minority. There has been a great deal of emphasis in the literature on identifying students' incorrect ideas, but much less discussion about the value of capitalising on students' correct ideas. Rather than seeing a student's answer as 'wrong', it is more productive to identify exactly what is wrong about it in order to decide how best to remediate the situation.

**Forms of Conceptual Change**

*A dichotomy* Most commentators represented conceptual change as consisting of two types; a weak form in which old and new ideas co-exist; and a strong form in which the scientific content and methods were accepted by the learner and "integrated in a coherent and effectual conceptual system" (Villani, 1992, p. 233). Dykstra (1992; Dykstra, Boyle & Monarch, 1992) referenced Carey's (1985) thesis that knowledge restructuring occurred in two ways, a *weak* and a *strong* form and supported Carey's view that only the latter passed as conceptual change.

The next two proposals, while part of this two-way classification of conceptual change, are sufficiently different to warrant individual treatment.

*Conceptual change or conflational change?* Concepts and conceptions are not the same things, therefore, conceptual change and conflational change ought to be different types of learning. White (1994a) introduced the notion of conflational change as an alternative to the current weak/strong and assimilation/accommodation dichotomies that have prevailed thus far. Conceptual change included anything new that a person learned about a particular concept such as new facts, "the adding of contexts, and understanding the bases of new groupings" (p. 118). Conflational change, however, included "major shifts, that typically involved detailed explanations of phenomena" (p. 118). This distinction characterised conceptual change as the weaker accretion process, subsumption or assimilation, while conflational change requires stronger, global or holistic changes to the learner's conceptions.
Conceptional change required competition between conceptions in the same way that Posner et al.'s. (1982) conceptual change was driven by dissatisfaction. Similarly, the success of conceptional change depended upon the comparative intelligibility, plausibility and fruitfulness of the competing conceptions. White emphasised the importance of students recognising the ways in which competing conceptions conflict with each other and promotes the value of teachers encouraging and guiding student so that they engage in metacognitive comparisons of competing beliefs and information. White's enthusiasm that "most of these issues should be resolvable through demonstration and logic" (p. 119) seems over-optimistic and over-simplistic in light of the weight of evidence regarding the resilience and robust nature of alternative conceptions. In fairness, however, he does advocate and describe detailed strategies that facilitate the generation of cognitive conflict and conceptual conflict (Fensham, Gunstone & White, 1994; White & Gunstone, 1992).

A taxonomy of conceptual change One of the difficulties facing researchers and teachers is how to unravel student conceptions. Systematic theory-driven approaches can account for the occurrence and structure of alternative student conceptions (Hewson & Hewson, 1988; Strike & Posner, 1992; Vosniadou, 1994). In order to explicate the structure of alternative student conceptions, Dykstra et al. (1992) analysed student discourses and student reasonings during problem solving to produce sets of individualised conceptual maps (which they say are not to be confused with concept maps).

The complexity and extent of students' verbal behaviours, especially given the number of terms they use and how they are related, make the conceptual maps, along with the computational tools used to help build them, an excellent way to manage and make sense of such information. Otherwise, it would be difficult to extract what students are thinking, except in very general terms (p. 632)

Typically, conceptual maps form rational sequences that identify changes to conceptions over time. The methodology for interpreting the maps was not explicitly described but appeared to be grounded in word associations, meanings and the frequency with which particular expressions were used. Dykstra et al. discussed two products that emerged as a result of interpreting the maps. First, they stated that "the maps organise and make explicit the essential content of students' knowledge which can be used to help select experiences intended to disequilibrate them" (1992, p. 633) leading to conceptual change. Second, sense making analyses of the sequences of student conceptual maps led to the creation of the taxonomy of conceptual change.

Dykstra argued that the reconceptualisation of say, motion from a "no force if not motion" to a "no net force if no acceleration" (see figure in Dykstra, 1992, p. 44; Dykstra et al., 1992, p. 624) situation required a sequence of at least three changes. First, a student's "initial conception" became a "refined initial conception" by which
students learned to discriminate or differentiate between different types of motion. Second, the conception was further refined by elaborating or enriching their experiences so that a "first version Newtonian conception" emerged. This "first version Newtonian conception", however, could only then be transformed into a "refined Newtonian conception" (Dykstra, 1992, p. 44) by students realising that the rest state was a particular case of constant velocity (compare Hashweh, 1986). Dykstra stated that the change from the "refined initial conception" to the "first version Newtonian conception" was conceptual change (p. 44); however, only the final transformation constituted strong restructuring or accommodation.

Based on this sequence, Dykstra proposed that conceptual change could be organised into a taxonomy containing three potential categories - differentiation, class extension and reconceptualisation (compare Hewson & Hewson, 1983). The three categories were the three changes that described the transformation of the "no force if not motion" conception into a "no net force if no acceleration" conception. For Dykstra and Carey, differentiation are the same change and Dykstra's class extension parallels Carey's notion of coalescence. Interestingly, differentiation when connected to class extension and reconceptualisation seems analogous to Ausubel's, progressive differentiation, superordinate learning (uniting separate concepts under a single higher order heading) and integrative reconciliation respectively (Novak, 1984).

Many alternative conceptions are aggregations of two or more concepts, for example, velocity and acceleration are undifferentiated within motion; electric current and electric energy are collapsed within electricity and hot and cold include both heat and temperature. Differentiation of a conception can be relatively straightforward as it only requires recognition that the alternative conception contained two or more separate parts (which are identified by the student). Class extensions occur when the phenomenon becomes more inclusive, for instance, the student not only recognises that deformations indicate a force but also nondeforming instances like a book on the table involves forces. "Students debate whether a force, which cannot be directly perceived, exist" (Dykstra et al., 1992, p. 639). Finally, "the force is inferred as a result of the logical necessity that similar phenomena should have similar explanations" (p. 640). Reconceptualisation, however, is a different matter. "In contrast to differentiation and class extension, conceptual change from 'motion implies force' to 'acceleration implies force' is a much more profound and conceptually difficult change" (Dykstra, 1992, p. 49). This is because reconceptualisation involves a change in abstraction level in which force is reinterpreted from an attribute into a relation. Dykstra et al. (1992) defined the abstract categories they used to describe students' conceptions as ontologies (i.e., states, processes, attributes and relations). Describing conceptual change in ontological terms, evokes comparison with Chi et
al.'s (1994) and Thagard's (1992a) tree switching. For Chi et al., changed ontology is clearly the strongest form of conceptual change.

Disequilibrium and dissatisfaction Dykstra insists that disequilibrium is central to conceptual change because students must appreciate that their alternative conceptions are incompatible with the scientific concept. Disequilibrium, however, requires more than mere exposure to a discrepant event; students need time and opportunity to experience the dissatisfaction that arises when the competing conceptions interact with each other.

Gorsky and Finegold (1994) observed that "cognitive dissonance, arising from the juxtaposition of explanatory frameworks, is often described only briefly, or even not at all" (p. 75). They studied seven discrepant events relating to motion forces and described the responses of nine students whose psychometric abilities ranged from average to excellent. Essentially, they found that the majority of commonly used discrepant events were of low to moderate value for generating disequilibrium. Two of the seven anomalies, though, produced extreme impacts. For their sixth item, when a student predicted that gravity was the only force acting on a book on a table or on a pendulum bob hanging by a string, a microcomputer simulated the book falling through the table without breaking the table or the bob falling without breaking the string! In the seventh item, when the student stated that for a book on a table the vertical forces were balanced while the book experienced a small horizontal motion force, the book accelerated instead of moving with constant velocity. The most able student was able to independently restructure his conception, the other eight needed teacher help before they could make sense of the computer presented discrepancies.

Most of the discrepant events used by Gorsky and Finegold appeared to have little impact on the students' explanatory frameworks because the students circumvented the dissonance by making minor adjustments to their explanations. According to Lakatos (1970), scientists do this when observation disagrees with theory - they save their theory by proposing a suitable set of auxiliary hypotheses. The authors put it like this: "Conceptual change came about by way of only mild disequilibrium without radical restructuring of current beliefs" (Gorsky & Finegold, 1994). This sort of change is "assimilation" (Posner et al.'s criteria) and probably would not have been allowed as conceptual change by Carey (1985, 1986), Vosniadou and Brewer (1987), Vosniadou (1994) or Chi et al. (1994). Gorsky and Finegold's assertion points up the depth of the problem with current conceptual change theories: different authors use different terminology for the same event or they use the same terms for apparently different events!
A Role for Motivational Factors in Conceptual Change

Cognition versus affect That conceptual change is a rational exercise has been stated explicitly by a number of researchers (Dykstra et al., 1992; Hashweh, 1986; Posner, et al., 1982; Strike & Posner, 1985; Villani, 1992). Others have implied that conceptual change is a rational activity in that they have only discussed cognitive factors (Carey, 1985; Chi, et al., 1994; Vosniadou & Brewer, 1987; Vosniadou, 1994; White, 1987) while a smaller group have acknowledged the presence of student interest and social factors without enlarging on these influences (e.g., Nussbaum, 1989; Nussbaum & Novick, 1982; Thagard, 1991). It can be claimed that the predominant conceptual change model depicts it as a rational activity that is influenced to a lesser degree by emotional and motivational factors (Gorsky & Finegold, 1994; Strike & Posner, 1992; Thagard, 1991; White, 1994b). Pintrich et al. (1992) took a stronger stance and claimed that affective issues play a significant role in mediating classroom conceptual change. They contend that the various models of conceptual change constitute "a continuum from rational (being driven solely by logic and scientific findings, a cold model) to irrational (being driven by personal interests, motivation, and social/historical processes, a hot model, often described as a naturalistic position)" (p. 170).

Motivational factors Pintrich et al. highlight a problem familiar to every classroom teacher: despite the best intentions of the teacher and the provision of excellent learning resources, many students who should learn, do not. The provision of ideal cognitive conditions cannot overcome student reluctance to learn when the student lacks motivation and therefore does not engage in the learning activities. "Three aspects of an individual's behaviour - choice of task, level of engagement, and willingness to persist at the task " (p. 168) are good motivational indicators and it is the student who decides whether or not to join in class activities. The failure of conceptually adept students to learn cannot always be explained in purely cognitive terms. Motivational and contextual factors such "as an individual's goals, intentions, purposes, expectations, or needs" (p. 168) also enter into the learning equation.

The force of Pintrich et al.'s argument was that situational influences interact with the students' personal characteristics to determine the degree of cognitive engagement of each student with the subject matter in the applied curriculum. Even though a considerable body of motivational research exists, Pintrich et al. state that "research on students' conceptual change has never explicitly examined the role of an individual's motivational beliefs" (p. 169).

The popular image of science is that scientists are committed to rational thought. This image depicts scientists as dispassionate pursuers of knowledge about the natural
world and its attendant phenomena, that they employ purposeful, objective methods as they observe, hypothesise, experiment and theorise. The authors metaphorically called this process "cold" (p. 170), and suggested that this image could be explained as being a positivist artifact of a realist ontology. However, not all science proceeds this way, for example, Milliken's determination of the mass of the electron, Flemings discovery of lysosome and Watson and Crick 'unravelling' DNA.

By focussing on the social and motivational aspects of classroom instruction, students' self-efficacy beliefs, different classroom contexts and varieties of teacher-student interactions were all shown to influence student learning (see also Wong, 1995).

The assumption that students approach their classroom learning with a rational goal of making sense of the information and coordinating it with their prior conceptions may not be accurate. Students may have social goals in the classroom context besides learning - such as making friends, finding a boyfriend or girlfriend, or impressing their peers - which can short circuit any in-depth intellectual engagement. (p. 173)

Similarly, positive attitudes may be more attributable to getting a good grade for vocational and other material rewards, or for bolstering ego rather than for cognitive reasons. Consequently, Pintrich et al. believe that there are serious limitations to a cognition only model of conceptual change. They reject the rational or cold model in favour of the irrational, hot description of conceptual change learning in school settings. "We take the constructivist position that the process of conceptual change is influenced by personal, motivational, social, and historical processes, thereby advocating a hot model of individual conceptual change" (p. 170).

Thagard (1991) also used the term 'hot' to describe the importance of self-interest factors in making decisions like giving up smoking. In Thagard's view, the 'hot' irrational influences complemented 'cold' rationalism. It is significant that Hewson (1982) and Strike and Posner (1982, 1992) recognised that motivational forces were useful adjuncts to rational conceptual change but did not explicate the social components of the learner's conceptual ecology. Indeed, motivation, interest, imagination, self-esteem and social influences (cooperation and peer pressure) need to be added to the list of factors that make up a learner's conceptual ecology (Posner, 1982; Strike & Posner, 1985, 1992).

Social construction of meaning The importance of the social element in learning was the focus of Solomon's (1987) paper. She persuasively argued that social interactions play a central role in the negotiation of meaning and that social forces must therefore, influence science conceptions. Solomon asserted that "sociological theory and classroom evidence suggest that in socially acquired knowledge exchange of meaning and consensus take the place of logical testing, and typification by context replaces abstraction and conceptualisation" (p. 78). She concluded her paper with this finding:
All aspects of this subject indicate that social influences are pervasive and strong. ... Our pupils are strong social beings for whom the teaching of a rigidly insulated science which makes no contact with the everyday context is simply not an option. Social influences of every kind permeate both the learning of science and its application. (p. 79)

**Affective-cognitive factors** Social-motivational factors were described and advocated by a number of prominent 'cognitive researchers. Dykstra's (1992) research identified the value of groups of students engaging in what he called "town meetings" (p. 48). Students were encouraged to discuss their different explanations for an experience in a social nonjudgmental context. Collectively, the students confronted and evaluated each explanation (see also Nussbaum & Novick, 1982, who provide detailed descriptions of a similar process). Dykstra's research showed that whenever the activities were capable of producing conceptual conflict, and the teacher resisted early intervention with the 'correct answer', students did become inventive and did work through the possibilities. In some of these cases, students achieved conceptual restructuring of the strong type (Gorsky & Finegold, 1994, report similar findings). Dykstra concluded that the pedagogic "challenge then is to find disequilibrating experience and then nurture the resulting thinking that leads to ideas which match the scientists' descriptions of the world" (Dykstra, 1992, p. 54).

Nussbaum (1989) argued that not even Kuhn, Toilem and Lakatos pictured conceptual change as a necessarily logical process. He went on to say that "we must therefore rely on something in addition to logic, we must initiate conceptual change in various additional ways including classroom group dynamics" (p. 537). The final phase of Nussbaum and Novick's (1982) teaching sequence about the particulate nature of gases harnessed the interest and enthusiasm of the class such that the group dynamics generated conceptual change for many of the students. Nussbaum (1989) concludes:

> My educational experience suggests that if a problem regarding a natural phenomenon is raised in a stimulating manner, and if it is then followed by a discussion of student beliefs and by an open debate, then even young children or those considered educationally disadvantaged would demonstrate genuine intellectual enthusiasm and good reasoning. Under peer pressure, the student's attempts to adapt the formulation of their beliefs could lay the basis for conceptual change. (p. 537)

**Trust and support** From a quite different perspective, White (1994b) raised the issue of affective influences in classroom conceptional change teaching. He argued that no teacher can expect to achieve conceptual or conceptional change without having the students 'on-side'.

> Certain conditions of trust must exist if lessons incorporating such conflicts are to succeed. The most crucial is that the students must trust the teacher to take their ideas and questions seriously ... students must trust the teacher to manage [the lesson] fairly ... and they must trust that conflict and confusion will be resolve in the end. ... the students must trust each other to be supportive (pp. 119-120)
Similarly, Gorsky and Finegold (1994) noted that "the need to reduce dissonance is a powerful human motivation" (1994, p. 87). Motivation fits well with their finding that "students' responses to anomaly were both rational and emotional" (p. 83, italics added). This supports White's assertion concerning student-teacher relationships - it is important when using discrepant events, and all teaching for that matter, that the students trust the teacher to not mislead them.

**Summary** The balance of reason indicates that conceptual change is neither wholly 'hot' nor 'cold.' The evidence depicts conceptual change as a rational cognitive process that draws essential support from social and motivational influences.

**Intellectual Development**

Each of the epistemological, ontological and motivational factors so far advanced as affecting conceptual learning also impact on the individual's intellectual status. Just as the CCM and Piaget's staged learning were described in hierarchical terms, intellectual development has been described using a nine-point scale (Perry, 1970). The idea that students may progress through nine positions subsumed under the four sequential headings of Dualism, Multiplism, Relativism and Commitment in Relativism, emerged from a study of undergraduates at Harvard and Radcliffe Liberal Arts Colleges between the years 1958-63. Perry and his colleagues surveyed and interviewed students at the close of each study year producing sets of interviews that were qualitatively rated by independent and reliable judges. The rated interviews yielded the nine discrete intellectual and ethical positions that were summarised under four headings.

**Dualism** Individuals at this level take an objectivist stance towards knowledge, that is, knowledge is a 'we-right-good vs other-wrong-bad' dichotomy within which the student defers to the Authority-teacher who is all-knowing. Truth is absolute and students expect to be told what is right, their task being to memorise and regurgitate that Truth. Uncertainties are resolved by obtaining the right answer. In Position 1 (Basic Duality) students see their world in polar black-and-white terms, they expect to be told what is right, and they succeed through obedience and hard work. By Position 2 (Multiplicity Pre-Legitimate) students recognise uncertainty as a ploy by Authority to force them to discover the right answer for themselves.

**Multiplicity** Diversity of opinion and uncertainty are found everywhere and are sanctioned by students to the point where they believe that everyone is entitled to his/her own opinion and that the opinion of novices and experts are equally valid. Position 3 (Multiplicity Subordinate) students rationalise uncertainty by believing that "Authority hasn't found The Answer yet"; consequently, they feel that they are graded on presentation, not accuracy. Students at Position 4 (Relativism Subordinate)
conceive of every opinion as equally valid and regard qualitative contextual reasonings as no more than special cases within multiplicity.

Relativism  To achieve this level, students must comprehend that knowledge is both relative and contextually bound. Insistence that students provide supporting evidence for their 'answers' and arguments challenges their previous Multiplist opinion that every stance is equally valid. These students concede that knowledge is relative and admit that they need to consciously analyse and evaluate each problem and event in context. The comprehension that truth is relative may, or may not, extend beyond the discipline in hand. Relativism's cost can be a loss of personal direction as all of the student's past certainties are dissolved. Those who survive this state of flux do so by realising the need to re-order their lives by introducing some form of commitment. Position 5 (Relativism Correlate, Competing, or Diffuse) is reached when the student intrinsically perceives that answers must be justified in context. Nevertheless, some problems still have agreed answers (e.g., physics) while others are much more open (e.g., literature, history). To gain Position 6 (Commitment Foreseen) commitment is felt to be a logical necessity if the student is to function effectively amidst the ever present relativistic turmoil.

Commitment in Relativism  The climax of intellectual development leads the student to responsibility. Radical restructuring of the way the student understands knowledge effectcetively thrusts the student into a new world. The issue now confronting the student is how to ethically re-establish his/her identity in this 'new' relativistic world. "Only then is the student able to understand that knowledge is constructed, not given; contextual, not absolute; mutable, not fixed. It is within relativism that ... the affirmation of personal identity and commitment evolves" (Belenky, Clinchy, Goldberger & Tarule, 1986, p. 10). Position 7 (Initial Commitment) "describes that state in a student's life when he has undertaken to decide on his own responsibility who he is, or who he will be, in some major area of his life" (Perry, 1970, p. 153). This affirmed commitment requires that the student in Position 8 (Orientation in Implications of Commitment) recognise the implications and tensions inherent in his/her commitment. Position 9 (Developing Commitments) becomes an on-going process of action and reflection in which equilibrium is established and maintained. The active engagement with pluralism, equilibration of commitment and maintenance of identity and ethics is dynamic.

Temporizing, Retreat and Escape  Completion of progress through the nine Positions is neither automatic nor fore-ordained. Students may suspend their progress and remain static in a Position for up to a year; this is Temporizing. Resumption of progress is common but not certain. A student may, for instance, find relativism too threatening and choose instead to Retreat to Multiplism or Dualism. Another response is Escape by
encapsulating oneself in a position like Multiplism or Relativism and resisting all opportunities to proceed. Perry observed that Escape was often accompanied by feelings of guilt and despair.

A diagrammatic summary of Perry’s scheme of intellectual and ethical development has been constructed by Finster (1989). That diagram is reproduced in Figure 3.

![Diagram of Perry's scheme](image)

**Figure 3:** A diagram of the Perry scheme focussing on the epistemological vector as the vertical axis. (from Finster, 1989, p. 659)

**Psychological Underpinnings for Perry's Theory of Intellectual Development**

Perry's psychological resources included Piaget's staged development, Kelly's personal construct theory, Kohlberg's description of moral development and epistemological references to Kuhn's progress of scientific revolutions. In particular, Perry acknowledged a debt to Piaget and recognised certain limitations in his and Piaget's theories.

In comparing our study with the work of Piaget, more is involved than particulars. We do depend heavily on his particular concepts of assimilation of an experience to extant structure and of accommodation of structure by transformations and recombinations ... Together with Piaget, moreover, we may be accused of suggesting, even when we do not affirm, some pretty large-sized generalisations about human development in our culture on the basis of a few, homogeneous and specialized subjects in one highly specialized setting. (Perry, 1970, p. 204)

Indeed, Perry and his colleagues saw their theory as picking up where Piaget left off by systematically describing adolescent mental development within formal operational thinking.
Piaget and his co-workers have not yet traced in detail the articulation of this particular [developmental] process at the level of late adolescence and early adulthood...

In deriving from the study of people beyond the age of 15, the scheme reflects processes not examined in Piagetian studies so far published. Positions 5 through 9 in our scheme describe in very general terms the course of orientation in this environment, or, to use Piaget's terms, the development of "equilibrium" in this [relativist] dimension.

One could look on our scheme, then, as adding an advanced "period" to Piaget's outline. But there are differences. While the first half of our scheme does reveal processes paralleling those of motoric, cognitive and moral "decentering" portrayed in each of Piaget's periods, the development of a personal style or equilibrium in commitment in the second half seems qualitatively different. (Perry, 1970, p. 204-5)

The realisation of intellectual and moral equilibrium thus requires reflection by the student on thinking, knowledge and its justification, and issues of personal and community responsibility. Pursuit of intellectual growth is predominantly cognitive through Positions 1-5; however, growth takes on a more ethical-personal orientation for Positions 6-9.

As well as sharing similarities with Piaget's staged development, Woods (1990, 1993) identified some striking parallels between Perry's scheme and Bloom's six levels of cognitive development. Woods (1990) reasoned (and Finster, 1991, agrees) that learning activities located at or just above the students' position on Perry's developmental continuum, should be most effective. Learning was hindered when the students and the teacher functioned at widely spaced positions. Most studies showed that commencing college students were at Positions 2-3 while most teachers were situated in the range, 6-9. This would, in effect, be like presenting pre-operational or concrete operational students with formal operational problems.

Finster specifically recommends challenging students within a supportive environment.

One must challenge the bipolar nature of dualistic thinking by presenting multipliant perspectives of an issue and letting [students] reconcile the inadequacy of the dualist position. Helping students wrestle with the inadequacy of their arguments provide the support necessary to assist them to meet the challenge of change.

However, presenting the pure dualist with a challenge to operate at the relativist level may represent an insurmountable challenge. (1991, p. 752)

In Finster's programme, cognitive development is optimised because his tasks and problems are intellectually compatible with and accessible to the student. Situating learning challenges at or just above students' expectations appear to have improved students' chemistry learning and to have accelerated their intellectual progress on Perry's scale.

*Intellectual Development in the Arts and Sciences*

Intellectual maturation along the Dualism-Commitment in Relativism continuum seemed to occur more readily in the humanities than in science and mathematics.
Finster argued that society and students expect the sciences, and chemistry in particular, to provide the 'right answer' to issues ranging from environmental problems through to the nuclear debate. In its authentic form, however, science is extremely pluralistic due to its dependence on diverse theories to explain nonobservable phenomena (Jung, 1994). The relativistic nature of chemistry is evident in the multiple theories for atomic and molecular structure, chemical bonding, kinetic theory, reaction rates and energetics, equilibrium and redox reactions. Maybe society's impatient demand for objectivist answers, the nature of research funding (it is easier to justify investigations with exact parameters) and the desire to popularise science has fostered the positivist image that scientists 'have' the answers. Perry's study showed that many students shared this view - several of his subjects asserted that they would resolve their discomfort with Multiplism and Relativism by transferring from literature and history to economics or science!

Finster (1991) and Allen (1981) proposed that reframing instruction in chemistry and biology around Perry's scheme has the potential to neutralise the Dualism that dominates curricula and student thinking in these disciplines. Speaking from biology's position, Allen (1981) lamented that

Many, if not most [students], find it difficult to examine evidence critically, to establish a line of reasoning, and to reach a conclusion or interpretation. The effort required often leads to impatience, frustration, or even antagonism. Students are frequently unable to accept the existence of more than one equally valid interpretation. They will expect the teacher to tell them the "correct answer" rather than try to establish for themselves a line of reasoning leading to the best interpretation. (p. 94)

This situation is particularly unfortunate when it is realised that more high achieving secondary students choose scientifically oriented courses than humanities at university (Tideman, 1995).

Could it be that the overtly positivistic way in which science is communicated and taught reinforces Dualism at the expense of intellectual growth towards Relativism? The alternative conceptions literature certainly attests that insufficient progress is being made in challenging student preconceptions. While various models of conceptual change learning have been advanced to address alternative conceptions, this approach may be ignoring a significant weakness in student knowledge, namely, the dominant student belief that knowledge is a right-wrong dichotomy. If students believe that there is a definitive answer to every problem, and they believe that they have that answer, surely restructuring will be inhibited. Conversely, if students believe that knowledge is relative and contextual, conceptual change may be easier to initiate but harder to complete.
A Tension Between the CCM and the Perry Scheme

Analysing and interpreting intellectual development using Perry's perspectives exposes a potential tension between Perry's scheme and the CCM's description of knowledge restructuring. Can a student relinquish an 'inferior' conception in favour of a 'superior' conception once he/she begins to believe that knowledge and solutions to problems are relative, that is, explanations are limited to specific contexts? If the student reduces conceptual competition (dissatisfaction) by reasoning that competing conceptions are but the 'correct' description of the phenomenon in different contexts, won't that student capture rather than exchange conceptions? An example may help. Motion can be described in three frames: Aristotelian (impetus), Newtonian and Relativistic. Newtonian and Relativistic motion are both scientific - with the context determining which is appropriate - but Aristotelian motion is unscientific. Many people who accept the scientific explanations of motion, experts included, default to Aristotelian explanations in everyday life. Based on everyday observations that thrown or batted balls naturally slow down, Strike & Posner (1992) explain why objects logically appear to need a force to keep them moving. From Perry's viewpoint, Aristotelian motion should survive if the knower is a relativist: he or she will believe that in non-scientific situations, motion is only maintained if a force is applied.

It is probably easiest to understand how a Dualist could change conceptions in the manner described by the CCM. But what about a Multiplist? How can a Multiplist experience dissatisfaction while believing that any and every opinion is as good as another? Posner et al. (1982) and Hewson (1981, 1982) argued that students must become dissatisfied with their conceptions in order for accommodation or conceptual exchange to occur. How can dissatisfaction arise when the student ascribes equal status to his/her opinion and the opinion of experts? A similar response may be expected from the Relativist, but for different reasons (as explained previously). Once a student perceives and believes that 'answers' are contextually bound; even though it may be easy to convince such a person of the flaws in a particular argument, it will be extremely difficult to convince that person of the need to relinquish that conception.

But how does a mature intellect handle competing conceptions? Commitment in relativism is achieved by consciously selecting the theory(ies) that will become the individual's modus operandi. The granting of primacy of operation to a theory or methodology does not, however, exclude other theories and methodologies; it simply relieves the individual of the need to evaluate every theory for every problem. When the primary theory is partly or wholly deficient, other theories or methodologies can and will be accessed.
The plurality of knowledge about a concept that worried Multiplists and Relativists and which has been resolved by those exhibiting Commitment in Relativism can be represented as an epistemological profile (Bachelard, 1968). As an illustration, Bachelard described the multiplicity of ways in which mass could be defined: mass extends from everyday qualitative notions of visual 'bigness' to empirical measures using scales, it can be further refined as Newton's dynamic mass \((F = ma)\), relativistic mass as a function of speed and mass in Dirac's propagation mechanics. Figure 4 describes an epistemological profile; the height of each column functions as an index of the frequency with which a person uses that conception to think about mass.

![Diagram](image)

**Figure 4: An individual's epistemological profile of mass (after Bachelard, 1968).**

Most recently, Driver et al. (1994) and Mortimer (1995) have suggested that Bachelard's epistemological profile may contribute to our understanding of conceptual change. Mortimer derived the notion of a 'conceptual profile' from Bachelard's 'epistemological profile' and posited that rather than suppressing or lowering the status of alternative conceptions, science instruction simply provides students with better knowledge options. Mortimer believes that enriching a student's "conceptual profile" by adding or strengthening scientific conceptions enhanced the student's problem solving repertoire. He argued that in learning a scientific concept, the student acquires "the concept at a specific profile level [or 'zone']" (p. 274) because students have conceptual profiles for most concepts about which they "know." Bachelard and Mortimer propose that students who need an explanation or problem solution, use the conception in their profiles that seems most applicable in that context. What appears to be conceptual change is just mobility between zones in the conceptual profile, the operant conception being determined by the problem's context, personal and social
influences. The notion of a conceptual profile resembles Perry's Relativism and Commitment in Relativism.

Mortimer appears to believe that conceptions within the conceptual profile remain static over time. On several occasions, he asserted that the status of an individual's conceptions did not change as a result of learning; for instance, he argued that

[the teaching process includes, therefore, the explicit use of alternative ideas, its criticism and the evaluation of its domain. Nevertheless it does not include the suppression of alternative ideas, neither does it raise or lower the status of a person's conception understood as "the extent to which the conception meets the three conditions (to be intelligible, plausible and fruitful) (Hewson & Thorley, 1989, p. 542). According to the [conceptual profile] we cannot lower or raise the plausibility or the fruitfulness of some conception, but only show in what domain it can be considered as plausible and fruitful. (1995, p. 276)]

This view that teaching does not alter the status of current conceptions is at odds with constructivism and the demonstrated capacity of conceptual change teaching to alter the status of students' conceptions (Hewson, 1982, Hewson & Hennessey, 1992). Conceptual change learning theory (and some practice), while agreeing that students can maintain several conceptions within their conceptual profile, does not support the idea that status remains static during learning. In fact, it would be an exceptional situation when a student's conceptions remained fixed during or following learning activities employing those conceptions. The experience of using a conception should alter the balance of information within the conception and how the student feels about the conception.

It would seem that an epistemological-conceptual profile could only operate in the fluid way described by Bachelard and Mortimer where the student's conceptual framework already contained multiple conceptions (i.e., multiple representations or models) of a phenomenon. Such students should, at the least, be Multiplists, but if they do "acquire consciousness not only of the new scientific concept but also of the relationships between the different levels of their conceptual profile, and when it is more convenient to use one or another of the levels" (Mortimer, 1995, p. 275), then, based on Perry's scheme, they will be Relativists. That students have conceptual profiles that aid learning and problem solving is tenable, but it is most likely that Multiplists will not be conscious of their profiles with only Relativists and those who have reached Commitment in Relativism being conscious and purposeful in their choice of a conception for a specific situation. The lack of multiple conceptions and awareness thereof amongst Dualists suggests that conceptual profiles do not play a significant role in learning by young or naïve students.

While Perry's scheme, Bachelard's epistemological profiles, the CCM, and the other models of knowledge restructuring discussed so far all make significant contributions to our understanding of learning, accommodations between these models are necessary.
if the major elements of each are to be reconciled. The concluding section of this chapter will compare the various conceptual change theories and attempt to make some sense of the alternative models.

**Summary and Critique of Conceptual Change Models**

A summary of the similarities and differences in the terms used by various authors to describe conceptual change learning is provided in Table 1 (like the table used by Dagher, 1994b, p. 607). The first seven authors (or groups of authors) use a simple dichotomy, the next three employ a continuum and the last group use accretion, piecemeal and evolution synonymously.

**Table 1**

*Summary of types of conceptual change proposed by various authors.*

<table>
<thead>
<tr>
<th>Author</th>
<th>Types of conceptual change learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuhn</td>
<td>Normal science</td>
</tr>
<tr>
<td></td>
<td>Revolutionary science</td>
</tr>
<tr>
<td></td>
<td>(Paradigm shift)</td>
</tr>
<tr>
<td>Lakatos</td>
<td>Soft core changes</td>
</tr>
<tr>
<td></td>
<td>Hard core changes</td>
</tr>
<tr>
<td>Posner et al. (1982)</td>
<td>Assimilation</td>
</tr>
<tr>
<td></td>
<td>Accommodation</td>
</tr>
<tr>
<td>Hewson &amp; Hewson</td>
<td>Conceptual capture</td>
</tr>
<tr>
<td></td>
<td>Conceptual exchange</td>
</tr>
<tr>
<td>Carey (1985)</td>
<td>Weak restructuring</td>
</tr>
<tr>
<td></td>
<td>Strong restructuring</td>
</tr>
<tr>
<td>Vosniadou (1994)</td>
<td>Weak restructuring</td>
</tr>
<tr>
<td>Vosniadou &amp; Brewer (1987)</td>
<td>Weak restructuring</td>
</tr>
<tr>
<td></td>
<td>Radical restructuring</td>
</tr>
<tr>
<td>White (1994)</td>
<td>Conceptual change</td>
</tr>
<tr>
<td></td>
<td>accretion, subsumption, assimilation</td>
</tr>
<tr>
<td></td>
<td>Conceptional change</td>
</tr>
<tr>
<td></td>
<td>global, holistic</td>
</tr>
<tr>
<td>Chi et al. (1994)</td>
<td>implied accretion</td>
</tr>
<tr>
<td></td>
<td>branch jumping</td>
</tr>
<tr>
<td></td>
<td>tree swapping</td>
</tr>
<tr>
<td>Dykstra (1992)</td>
<td>differentiation</td>
</tr>
<tr>
<td></td>
<td>class extension CONTINUUM</td>
</tr>
<tr>
<td></td>
<td>reconceptualisation</td>
</tr>
<tr>
<td>Thagard (1989, 1990, 1993)</td>
<td>1 2 3 4 5 6 7 8 9 adding an instance CONTINUUM tree switching</td>
</tr>
<tr>
<td></td>
<td>HOLISTIC Theory of Explanatory Coherence</td>
</tr>
<tr>
<td>Duschl &amp; Gitomer (1992); Laudan (1977, 1984); Villani (1992)</td>
<td>accretive, piecemeal, evolutionary conceptual change</td>
</tr>
</tbody>
</table>

So far, this chapter has described learning as knowledge restructuring (weak or strong/radical) or as conceptual change (capture/assimilation or exchange/accommodation). Although each commentator described learning changes as the personal construction of knowledge, the changes were informed from many
perspectives including epistemology, ontology, social-motivation and intellectual development. Moreover, several writers asked whether change occurred abruptly (revolution) or in a piecemeal way (evolution) and whether knowledge changes were rational ('cold') or irrational ('hot')? Significantly, there was agreement that knowledge changes do occur, that major changes are difficult to initiate and sustain, and even when one conception is succeeded by another, the prior conception does not become extinct and the knower may return temporarily or permanently to the prior conception.

Weak knowledge restructuring and conceptual capture were described as similar processes - frequent, non-traumatic learning in which new items of knowledge were added to the knower's conceptual framework. Similarly, strong/radical restructuring was like conceptual exchange because both were infrequent, traumatic events that affected the students' central commitments and presuppositions. Perry showed that such dramatic changes may also challenge the students' identity, sense of worth and direction. The major difference between Posner et al. and the Hewsons on one hand, and Carey, Vosniadou, Brewer, Chi et al. and Thagard on the other, was the explication of a viable and plausible mechanism for knowledge change during learning. The former group synthesised the CCM while in the main, the latter group sought a mechanism but lamented the absence of a model of conceptual change (like the CCM).

This difference is important because the CCM was explicated well before the work done by the second group of researchers. It is disappointing that neither Carey, Vosniadou, Brewer, Chi et al., nor Thagard discussed or critiqued the work of Posner and his colleagues. Incorporation of appropriate features of the CCM into their respective models could have enhanced their contribution to conceptual change teaching and learning. Strike and Posner (1992) reference the work of Carey and Vosniadou and Brewer but do not pursue those ideas. This is a decided weakness in each set of investigations. Thagard's work tends to stand alone (though he does discuss contributions from Carey, Chi, Vosniadou and Brewer) in that he proposed a model for strong knowledge restructuring, the Theory of Explanatory Coherence. The division between the two groups appears to present a science education - cognitive psychology dichotomy. Ten years ago, Carey (1986) proposed that a united effort was the best way to proceed, but this has not happened.

It is important to try to make sense of these schools of thought as each line of research promotes sensible outcomes. The low level of interaction between the research groups probably has several causes. The first cause may rest in philosophical and/or methodological differences. The CCM is mainly epistemological whereas the second group incorporate epistemological, ontological and developmental perspectives. A
second differences between the CCM and the second group of researchers concerns
the focus on age-related changes (Carey, Vosniadou and Brewer), and branch and tree
switching (Chi et al. and Thagard). This difference may be attributed to the nature of
the conceptions and the intellectual status of the students studied in each situation. The
developmental perspective dealt with young children who needed to learn new material
information and incorporate it in a meaningful way; whereas the intellectual
development continuum belonged to college students. Likewise, ontological changes
like tree switching are probably restricted to mature learners (e.g., Relativists) and to
process-oriented conceptions.

A third difference is the CCM's focus on an individual's dissatisfaction with a
conception or idea; however as indicated, dissatisfaction may really only be applicable
to Dualists. With Dualists and Multiplists, social and motivational forces are probably
significant and relatively independent of epistemology. But an increase in learner
sophistication (tending towards Relativism) should be accompanied by increased
concern with epistemology and ontology. If it is true that the significance of
explanatory coherence and ontological change increases and the importance of
dissatisfaction decreases as learner sophistication rises, this could explain some of the
differences between the two approaches.

Conclusion

This chapter set out to examine the research literature relating to Research Question 3
which asked: “Do the various theoretical perspectives on conceptual change learning
complement each other?” Based on the arguments presented in this chapter, the
superficial answer is no; however, it is possible to tease out compatible factors within
each perspective. Events like normal science, soft core changes, assimilation,
conceptual capture and weak restructuring are essentially the same and are reconciled
in Table 1. The not-so-obvious similarities and differences are described in the
detailed discussion about each type of conceptual change. Each component of
Research Question 3 (RQ3) also needs to be examined in light of the literature
reviewed in this chapter. A similar analysis of RQ3 and its components also will be
conducted Chapter 5h (following the discussions of the findings reported in Chapters
5b-5g).

The first component of RQ3 asked, "Is conceptual change always a rational-cognitive
process?" Pintrich et al. (1993) cogently argued that while motivational factors on
their own cannot produce conceptual change, social/motivational forces do influence
all classroom conceptual changes; that is, conceptual change is driven by both cold-
rational and hot-irrational forces. The second component of RQ3 asked, "Is
conceptual change learning global or local?" The answer to this question appears
equivocal: If a conceptual change involves tree-switching (swapping) (Chi et al., 1994; Thagard, 1993) then the conceptual effects should extend beyond the immediate topic; however, Perry (1970) and Mortimer (1995) point out that changes in one subject or conception often have no impact elsewhere. For the third component question, "Is conceptual change learning evolutionary or revolutionary?", the literature was similarly equivocal suggesting that both evolutionary and revolutionary changes occur depending on the student, the concept and the context.

The fourth component in RQ3, "What degrees of learning pass as conceptual change?" found that most theorists classified assimilation and conceptual capture as weak conceptual change. At one extreme, Strike and Posner (1992) disallowed as conceptual change, all changes short of a paradigm shift, whereas Thagard (1992a) and Hewson (1982) called the addition of even a new instance, conceptual change. Most other experts disqualified the addition of single instances as conceptual change but accepted assimilation and accommodation as weak or strong/radical restructuring of knowledge respectively. In response to component questions five and six, "Are conceptual status changes valid indicators of conceptual change learning?", and "Are other measures like modelling ability and intellectual development indicators of conceptual change?", the answer appears to be in the affirmative. Changes in modelling level (Grosslight et al., 1991) and intellectual position (Perry, 1970) certainly qualify as changes in epistemology and also probably involve ontological changes (tree-switching).

The last component of RQ3 asked "Is a multi-dimensional approach a better way to interpret conceptual change learning?" This review and the work of Treagust (1996) shows that all but a multi-dimensional interpretive framework will miss many vital aspects of student learning that are accepted as conceptual change. Various ways for describing the interactions between epistemological, ontological and motivational factors in conceptual change learning will be discussed in detail in Chapter 6. Thus far, the literature and this review has argued that a cognitive-rational model of conceptual change learning does exist (the CCM with its conditions for describing conceptual status) and a that multi-dimensional interpretive approaches should be adopted wherever possible. A multi-dimensional interpretive approach to conceptual change learning was used to interpret the data in the study of Year 11 chemistry students' learning about atoms, molecules and chemical bonds which is described in Chapter 5.
CHAPTER 3

REVIEW OF THE RELATED LITERATURE ON METAPHORS, ANALOGIES and MODELS

Overview

This review of the research literature on relational thought in science informs the investigations of Year 8-11 students' learning about atoms and molecules described in Chapters 4 and 5. Because chemistry deals with the nature and behaviour of entities that are unimaginably small, a consistent set of metaphors, analogies and models have been devised to describe physical and chemical process. Research Question 1 drew attention to relational thinking in chemistry by asking: "With which models of atoms and molecules are Western Australian pre-Year 11 chemistry students familiar; and what is the relative status of these models for these students?" Research Question 2 extended the inquiry by asking: "Do systematically presented metaphors and analogical models, and multiple models, contribute to conceptual change in learning about atoms, molecules and chemical bonds? The influence of metaphors, analogies and models cannot be adequately determined without first identifying their characteristics and operative modes. That is this chapter's role.

The chapter discusses the role of pedagogical metaphors, analogies and models from a theoretical and a practical perspective. Of necessity, this discussion has two foci: the viewpoint of teachers deciding to use metaphors, analogies and models, and the students whose understanding is challenged by representative imagery. Teacher-student understanding of a particular analogy can range from congruence to dissonance. Why is it that differing bodies of research respectively extol and condemn the use of analogies in teaching? Why do some analogies enhance student understanding while others generate alternative conceptions? The role of this literature review is to describe current knowledge relating to the use of metaphors, analogies and models in science education.

The review commences with a discussion of the nature of analogy and analogy's epistemological roots. Various generic models of analogical structure are examined and this leads into a consideration of schemes for classifying analogies. Next, the relationship between analogies and alternative conceptions raises issues concerning student familiarity with analogs, student mapping of analog-target attributes and analog-target limitations. The advantages of multiple analogies are highlighted and the frequency of analogy use in classrooms and textbooks is explored. The unrealised potential of analogies to create meaning initiates an analysis of teaching-with-analogies models and methods for training teachers and students in analogy use.
As the thesis is concerned with the influence of analogies and models on conceptual change, models and student modelling are reviewed and a typology of analogical models developed. The influence of analogical models on chemistry learning and the value of models in the development of scientific thinking is investigated. The chapter closes with a brief review of model usage in secondary science classrooms and summarises the recommendations that emerge from the literature.

The Nature Of Analogy

The Basis of Analogy

According to Goswami (1991), analogy is relational reasoning and Nagel (1974) defines analogy as "understanding the unfamiliar in terms of the familiar" (p. 107). Likewise, Gentner (1988) argues that analogy maps knowledge from a familiar analog domain to a less familiar target domain in order to transfer to the target, the set of analog relations that are applicable to the target. The power of an analogy resides in its parsimonious ability to denote ratio, similarity and correspondence. In harmony with recent research, the familiar instance will be called the analog (source, base) and the unfamiliar the target. Proposed likenesses between analog and target are called mappings and individual analog/target items that are mapped are called attributes. Glynn illustrated the relational aspects of an analogy (reproduced in Figure 5).

An abstract Representation of an Analogy and its Constituent Parts

<table>
<thead>
<tr>
<th>Superordinate Concept, Principle or Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog compared with</td>
</tr>
<tr>
<td>Feature compared with</td>
</tr>
<tr>
<td>1    compared with 1</td>
</tr>
<tr>
<td>2    compared with 2</td>
</tr>
<tr>
<td>3    compared with 3</td>
</tr>
<tr>
<td>n    compared with n</td>
</tr>
<tr>
<td>Camera</td>
</tr>
<tr>
<td>lens</td>
</tr>
<tr>
<td>inverted image</td>
</tr>
<tr>
<td>film</td>
</tr>
<tr>
<td>lens cap</td>
</tr>
<tr>
<td>focus</td>
</tr>
<tr>
<td>aperture</td>
</tr>
<tr>
<td>Human Eye</td>
</tr>
<tr>
<td>lens</td>
</tr>
<tr>
<td>inverted image</td>
</tr>
<tr>
<td>retina</td>
</tr>
<tr>
<td>eyelid</td>
</tr>
<tr>
<td>lens accommodation</td>
</tr>
<tr>
<td>pupil dilation</td>
</tr>
</tbody>
</table>

Figure 5: Schematic outline of an analogy and its constituent parts (adapted from Glynn, 1991, p. 195).
Initially, analogy was a mathematical term describing the equivalence of two ratios or proportions. It also expressed similarity or declared that two or more parallel relations were equivalent. This mathematical basis is reflected in Curtis and Reigeluth's (1984) description where they state that an analogy is any instance in which we use a statement of similarity. For example, the statement that an elephant is large, implies that when the subject changes to ant, the clause becomes, is small. Returning to the mathematical format, this analogy can be represented as:

\[ \text{elephant} : \text{large} :: \text{ant} : \text{small}. \]

Miller's (1979, p. 218) presentation of analogical relationships in mathematical form is at least as old as Aristotle (Pellegrino, 1985). For example,

\[ 3 : 4 :: 9 : 12, \text{ can be stated more generally as } x : y :: nx : ny. \]

In physics, the concept that water waves carry energy is well known, so if light also carries energy, then it is likely that light is also wavelike. This analogical relationship can be written as

transfers energy : water waves :: transfers energy : light waves.

Hesse (1963, p. 29) used a mathematical form to express the analogy between water, sound and light waves:

\[
\begin{array}{ccc}
\text{water waves} & \text{sound waves} & \text{light waves} \\
\text{water particles} & \text{air particles} & \text{aether particles}
\end{array}
\]

The above examples demonstrate that some analogies can be either a written statement or a mathematical statement of proportion.

Wherever analogies arise, they mostly occur as statements of structural or functional similarity. Metaphors and analogies have been used throughout the history of science and the arts and are accepted without question in literature. In fact, language and thinking may be thought of as records of metaphoric and analogical experiences (Lakoff & Johnson, 1980). Constructivist epistemologies posit that the only sense one can make of new experience is in relation to past experience and it must be explained in terms of prior knowledge (Curtis & Reigeluth, 1984). In fact, Farber (1950, p. 21) cites "analogies of experience" as one of Kant's four principles of pure reason.

At this juncture, it is worth extending the definition of analogy to include all the forms of likeness that are used in learning environments. In language and teaching, metaphors and similes perform like functions by stimulating recall of prior knowledge. Likewise, mental models (as thought experiments), physical models (e.g., model heart or DNA molecule) and scale models (solar system model) are used as analogies in science instruction (Osborne & Gilbert, 1980). Duit (1991a) asserts that the concepts underlying both metaphors and analogies are similar though noncongruent because analogies speak of explicit or literal comparisons which are basically true; while metaphors make implicit or nonliteral comparisons which are not true. Because
metaphors are plainly discordant, they effectively direct the hearer's thinking to generically different ideas and episodes and extract from those instances patterns and processes that apply to the subject of study. The frequent use of metaphors (Nagel, 1961, p. 108) "testifies to a pervasive human talent for finding resemblances between new experiences and familiar facts, so that what is novel is in consequence mastered by subsuming it under established distinctions."

The range, metaphor-analogy-model, will be taken as a continuum from most general to the most specific for this study. Extending the term analogy to cover a broad range of 'it is like' comparisons, stated or implied, is supported by Gentner (1983). An all inclusive approach is the only rational way to proceed in view of the diversity of metaphors, analogies and models used by teachers and textbooks.

Types of Analogies

Nagel (1961) broadly divided analogies into two types: substantive and formal. Substantive means the instance in which a familiar object, system or phenomenon is used as a model to explain a second situation. The familiar becomes a framework for the construction of a theory that elucidates and makes predictions about the new instance. For example, the kinetic theory of gases was formulated through an application of Newtonian physics to colliding elastic spheres such as billiard balls. Formal analogy is the description of a theory derived from abstract correspondences such as Maxwell saw between the mathematical description of gravity and the equations for conduction of heat. Of necessity, there needs to be an obvious similarity between the familiar case and the unknown for the initial link to be formed. Extending analogical mapping to learn something new requires imagination and critical reflection to ensure that the correct features and relations are realised without the inclusion of invalid matches.

Gentner (1988, pp. 74-76) also identified two analogical forms: "mere appearance matches" where one or more first-order attributes of the analog correspond with the target; and "true analogy" in which both first-order (material) and higher-order (causative) relations match. Solomon (1995) also divides analogies two-ways into "simple descriptive analogy (i.e., simile) and true inductive analogy" (p. 19). Shared higher-order relations constitute the systematicity principle on which Gentner's (1983) "structure-mapping theory" was grounded. Systematicity means that the analog-target similarities (material and causative) induce a coherent structural/functional relationship in the target. The set of systematic relations transfers the explanatory structure of the analog to the target. Like Gentner, Zook (1991) pointed out that first-order attributes promote analogy recognition, accessibility and recall but produce little growth in knowledge. Conversely, the systematic structure-mapping of true analogy enhances
inferential power but is difficult for unskilled learners to transact. Surface similarities
cue the learner to the analogical possibilities between the two domains, but it is the
systematic set of relations between the domains that transfers analog process
knowledge to the target. Novices are usually satisfied with 1:1 object mappings but
experts look for higher-level sets of process relations. The pattern of differences
between surface and systematic analogy resembles Chi et al.'s (1994) object versus
process thinking because higher order relations dominate both systematicity and
process-type knowledge. This 'analogy' to conceptual change is not surprising given
the power of true analogies to generate conceptual conflict and/or stimulate conceptual

Curtis and Reigeluth (1984) classified the analogies they found in textbooks by
distinguishing between the analogy's "condition" (p. 108), "relationship" (p. 103) and
depth (called "enriched or extended" p. 111). The condition of the analogy's subject
matter was classified as either concrete, abstract, or mixed concrete/abstract. Concrete
analogy resembles Nagel's substantive analogy. Relationship was divisible into two
categories - the mechanics of the relationship were either structural or functional. The
nature of the mapping classifies the analogy. A structural analogy example was 'a cell
is like a room' and a functional analogy example used a building's thermostat as an
analog for homeostatic temperature control. Mixed structural/functional analogies
contained both mapping side-by-side (e.g., a cell is like a factory: factory structures
and functions were used to elucidate cell structure and function). The depth criterion
focused on analogical detail, analogies being simple, enriched or extended. In a
simple analogy, the relationship between the analog and the target is obvious without
explanation (e.g., an artery is like a flexible pipe). Enrichment qualifies the analogy
by clearly stating the conditions under which the target is like the analog, such as how
and when the analogy is valid. An analogy is 'extended' when multiple enriched
analogs illustrate one target or one enriched analog informs multiple targets (Figure 6).

Are Analogies a Source of Alternative Conceptions?

Constructivism explains why people perceive the world about them in unpredictable
and individualistic ways (Tobin, 1993; Phillips, 1995). When an analogy is used to
elucidate an unfamiliar subject, the recipient's perception of the analog influences to
some degree his/her conclusions about the target (Weller, 1970). This is the dark side
of constructivism and analogy use because it is not possible to predict exactly how
another person will view the analogy. In the previous chapter, Strike and Posner
(1992) and Vosniadou (1994) provided explanations of how a person's conceptual
ecology and preconceptions generate alternative conceptions as the person tries to
make sense of new information. An analogy is new information and is thus subject to
thus subject to all the vagaries of individual preferences and differences. For this and other reasons, Glynn (1989) called analogy "a two-edged sword."

![Diagram of Simple Analogy, Enriched Analogy, and Extended Analogy](image)

Figure 6: Simple analogy plus three levels of enrichment for textual analogies (Curtis & Reigeluth, 1984, p. 111).

Zook (1991) grasped this issue and argued that students more easily map self-generated analogies than teacher-supplied analogies because their personal analogies are more familiar and easier to apply. On the other hand, students find it hard to generate or choose appropriate analogies for a given problem but are more likely to apply an analogy to a problem when the teacher supplies the analog. Gick and Holyoak (1983) demonstrated that many students needed to be cued to apply a suitable analogy even though the analogy was there for the using. The more obvious and familiar the analogy, the greater the chance a student will use it (Treagust et al., 1996). When analogies are wrongly applied or incorrectly mapped, alternative student conceptions are inevitable.

A case is recounted (Champagne, Gunstone & Klopfer, 1985) in which a science graduate used the water in pipes analogy to explain his conception of an electric current. He deduced that electrical resistance arose due to friction between the current in the wire and the insulation and concluded that if the insulation was broken, the current would leak out much like water leaks through a hole in a hose. Based on his analogy, the graduate asserted that much electrical engineering research was devoted to developing low friction insulation for wires.

**Student Familiarity with the Analog**

Continuing the constructivist thread, students can only map what they know. If the analog is intuitive or incomplete, these flaws will be transferred to some degree to the target. Gentner and Gentner (1983) found that student understanding of the hydraulic analog for batteries in an electric circuit was often incomplete or unscientific. They concluded "that an analogy is only useful to the extent that the desired relational
structure is present in the person's representation of the base domain" (p. 124). Alternatively, when a teacher demonstrated a simple known event like a pair of wheels changing direction when rolling from a hard to a soft surface, student success with this refraction analog was significantly improved (Harrison & Treagust, 1993). Similarly, Dupin and Johsua (1989) found that the continuous train analogy for conservation of current was more successful than other models because the students had a sound understanding of the analog model. Rather than assume that a student knew the water analog for electric current, Glynn (1989) went to considerable lengths to ensure that the student understood the aquarium water circuit analog before applying it to the electric circuit target.

**Student Mapping of Attributes**

Given a specific analogy, which analog attributes will an individual student map onto the target? Or, which combination of analog attributes will individual students map? There seems to be a dearth of evidence on this issue. Of the few studies that report empirical data Sandomir et al. (1993) showed that student mappings of the electron cloud metaphor were unreliable. Harrison (1992) found that the frequency of individual attribute mappings for the 'wheels' refraction analogy and the 'dominoes' analogy for heat conduction varied between students. Most of these attributes (written on a worksheet) were mere appearance matches. Will a specific analog attribute be mapped in the same way by a majority of students? McVey (1993) showed that mapping differences existed between both average and gifted students and within the gifted group.

Will students map the systematic attribute sets as surface similarities (simple structures) or as high-level systematicity (functions, relations and causes)? In Harrison's (1992) study, when the students were interviewed after completing their worksheet mappings, it transpired that most of the students had successfully mapped the systematicity of the analog onto the target even though their worksheet entries were predominantly surface similarities. This finding sits well with Gentner's (1988) proposition that access to the analogy's systematicity requires the presence of easily recognisable similarities. In fact, when this class of students was reinterviewed three months later, more than half of the students recalled the systematic structure of the 'wheels' analogy and were able to use this systematicity to solve previously unseen refraction problems (Treagust et al., 1996).

Will students confuse structures with functions? Goswami's (1991) reference to Piaget's work suggests they will. Students often provide correct answers to analogies of the form A:B :: C:. However, when asked to justify their reasoning, it emerged that some students did not arrive at their answer by logical analogy.
In view of Grosslight et al.'s (1991) three modelling levels, will the mappings be simple 1:1 correspondences (i.e., reality:reality) or will the mappings be sophisticated thinking tools? Given the permutations of student ability levels, knowledge bases, interests and values, it is predictable that the mappings in a heterogeneous class of students will be unpredictable. While recognising this possibility, Gentner (1983, 1988) seemed altogether too ambitious that her structure-mapping theory and the structure-mapping engine would produce reliable inferences from analog to target.

Analogy mappings consist of three types: positive analogy (shared attributes), neutral analogy and negative analogy (unshared attributes) (Hesse, 1963). Hesse and Gentner have developed rules and protocols that allow analogists and modellers to validly and reliably identify mappings. However, these processes are too demanding for most students and many teachers. Indeed, it is difficult to conceive that novice students will recognise the difference between shared, unshared and neutral attributes given that the target is unknown to them and given that their analog knowledge may be tenuous and/or unscientific. This situation makes a strong case for not leaving students to map anything more complex than a simple analogy or a straightforward enriched analogy in which the condition is quite unambiguous. Even the analogy "an atom is like a billiard ball" is open to question: is the likeness shape, material, texture, colour, or what? Likewise, students interpret the electron shell and electron cloud metaphors in all sorts of idiosyncratic ways (Harrison & Treagust, 1995).

The mapping problem is less acute for "within-domain analogies" (Thagard, 1992b, p. 538) where students use familiar problem solutions (e.g., type-examples) to solve new problems. "Cross-domain analogies", however, are an altogether different matter. The problem or phenomenon may be so new to the student that he/she has little idea where to start. The high level of unfamiliarity in this type of problem makes selection of an appropriate analogy improbable. How can the student analogise such a situation (about which he/she knows very little) to a familiar situation? If the teacher simply provides the bare analogy, how is the student to know whether the likenesses are structural, functional or stuctural/functional? It is much better if the teacher uses an explanatory analogy in which he/she says: "Do you all know how ....(analog).... works? Yes. Well, ....(analog).... is like ....(target).... because ....(list valid mappings and their type).... but ....(analog).... is unlike....(target).... because ....(list possible mappings which are in fact invalid).... Thus ....(analog).... is like ....(target)...." (based on Glyn, 1991). If the answer to "Do you all know how ....(analog).... works?" was "no", or "uncertain", the analogy should be abandoned or taught before proceeding (Harrison & Treagust, 1993). It is even better if the teacher develops the above analogy in interactive groups (Cosgrove, 1995) or in class discussion (Harrison, 1992).
The hazards involved in analogy use have caused many teachers to eschew analogy use in their classes (Treagust, Duit, Joslin & Lindauer, 1992). This stance does not necessarily improve their teaching because systematically applied analogies can enhance student understanding provided the teacher has an expert grasp of the target concept and critically scrutinises the mappings with the students. This approach has been found to be reliable for textual analogies (Hewitt, 1987) and in classrooms (Harrison, 1994; Harrison & Treagust, 1993, 1994). What teachers do need are effective teaching-with-analogies models and these will be described in a later section.

What Happens When Analogies Break Down?

In view of the widespread use of metaphors, Nagel (1961) observed that "little if any attention is generally paid to the limits within which such felt resemblances are valid" (p. 108). A similar caution is voiced by Weller (1970) who noted that "the only safeguards against being entrapped is to be particularly cautious when one uses an analogy, to be aware of its limitations, and to be constantly looking for dissimilarities" (p. 116). Weller identified another hazard in analogy use: an analogy can become so loved that the user becomes incapable of letting go. The result is a belief in perceived similarities that go beyond the evidence or reason. Many models and their analogies have been used as powerful tools of scientific discovery and often the model has so diffused the theory it generated that the model is spoken of as the reality. Weller points out that those who use models and analogies to develop theories must make a conscious effort to keep the tools separate from the product. This is particularly important with teacher-generated analogies because the student might retain the analogy and ignore the understanding it generates, or at the least, confuse the two. A case in point is the frequent use of the 'solar system' atom analogy/metaphor in secondary science textbooks (e.g., Duncan, 1977; Jones, Jones & Acaster, 1993)

Gee (1978) arrived at similar conclusions concerning Maxwell's use of analogies to mathematically describe Faraday's electric fields. Gee believed that drawing analogical arguments from models is inappropriate for general teaching. He warned of the dangers inherent in "erroneous inference by negative analogy or the reluctance to let go of some treasured and nurtured model" (p. 291). Gee recommended that teachers should always make the student aware that an analogy or model is but a representation of reality, not reality itself.

Experimental observations and reflections on analogy use sound the warning that indiscriminate or uncritical use of analogies can weaken understanding, or worse, construct alternative conceptions (Duit, 1991a). It is not just the wrong use by the teacher that needs attention; a conscious effort is needed to examine the inferences being made by the students. Thagard (1992b) warns that "students can be misled by
disanalogous features" of the analog and target and points out that teachers should "explicitly point out to students the places where the analogy breaks down" (both p. 542). As will be seen later, this is a particular strength of Glynn's (1989) teaching-with-analogies model because it consciously addresses these issues.

**Are Multiple Analogies Advantageous?**

Gentner and Gentner (1983) and Gick and Holyoak (1983) provide affirmative evidence that multiple analogies are cognitively superior to single analogies. The conservation of electric current in simple circuits is highly counter-intuitive for most students (Bullock 1979; Cosgrove, 1995; Dupin & Johsua, 1989; Glynn, 1989; Grayson, 1994; Hartel, 1982; Osborne & Freyberg, 1985). The array of analogies proposed to remediate this position is probably the largest in science education, yet the search for a truly effective analogy continues. Gentner and Gentner argue that no single analogy can resolve the problems students have with multiple batteries and resistors in series or parallels. Even though the moving crowd analogy enhanced understanding of series/parallel resistors, it was ineffectual for series/parallels batteries. The flowing water or reservoir analogy for batteries was useful with some students for solving batteries problems but was inapplicable to series/parallels resistors.

In a study of analogy recognition, only 29% of Gick and Holyoak's (1983) subjects solved Duncker's (1945) classic radiation problem using "The General" analogy. When the subjects received a hint directing them to the analogy, the number solving the problem rose to 80%. However, when the subjects were given two similar story analogies (with diagrams), 61% solved the problem before the hint and 94% after the hint. Gick and Holyoak believe that "two analogs ... can be mapped together to derive a more general schema; furthermore, any device that highlights the causally relevant correspondences will facilitate abstraction of a more optimal schema" (p. 32). These results with multiple analogies (including diagrams) may be transferable to the multiple analogical models that are used in senior secondary chemistry textbooks (e.g., Garnett, 1985, pp. 437-444; Pimentel, 1963, p. 32).

Bridging analogies are another case where multiple similar analogies (Brown & Clement, 1989; Clement, 1987) were superior to traditional approaches. Whereas Gick and Holyoak's analogies appeared to work side-by-side in constructing new schema, bridging analogies are clearly longitudinal. To establish the paired-force phenomenon, a familiar and unambiguous situation acted as a conceptual anchor (e.g., squeezing a spring compresses it). This was linked through analogous situations (the weight of a book bending a thin board or depressing a cushion) to a book sitting on a table. The multiple analogies led students to conclude that the book exerts a
downward force on the table, therefore the table provides an equilibrating force even though no distortion is seen. In their work with bridging-analogies, Brown and Clement found that in four applications of this technique, two cases of tutoring interviews succeeded in changing the students' conceptions from an unbalanced-force to a balanced-force conception for a book sitting on a table.

*Is Analogy Use Common?*

Tregast et al. (1992) investigated analogy use by seven teachers during 40 lessons in a large secondary school. Surprisingly, only six analogies were observed - three simple and three enriched analogies. These findings indicated that these teachers did not use analogies anywhere near as often as they claimed. Tregast et al. also found that the teachers frequently did not differentiate between analogies and examples. In the case of the enriched analogies, teachers discussed unshared as well as shared attributes with their students. Interviews with the teachers showed that they were aware that analogies generate understanding out of the students' prior knowledge and that a given student's conclusions regarding a particular analogy could not be taken for granted.

In her study of teacher explanations, Dagher (1995a) found a significantly higher level of analogy use. Sixteen analogies were found in 40 transcripts of lessons conducted by 20 teachers (novices to experts). The higher incidence of analogies in Dagher's study may be related to the lower mean age of her students (12-13 years) than in Tregast et al.'s study (16-17 years). The fact that Tregast et al. mostly observed physical science classes, while at least half of Dagher's analogies explicated biological science phenomena, raises the question of whether analogy use is content and/or context specific. Teachers may feel constrained to resort to analogies more often with younger students because a greater proportion of these students' prior knowledge is everyday rather than scientific.

All students are likely to encounter analogies in science textbooks. Curtis and Reigeluth (1984) developed their systematic analogy classification from a study of 216 analogies in 26 science textbooks, most of which were used by secondary students. Glynn's (1989, 1991) teaching-with-analogies model emerged from a survey of 43 content area textbooks, particularly Hewitt's (1987) exemplary use of analogies in *Conceptual Physics*. Thiele and Tregast (1994a) extended this research by identifying all the analogies in eight senior secondary chemistry textbooks. In-depth interviews with the authors of these eight textbooks probed the authors' reasons for including analogies in their explanations. Pictorial analogies predominated; 55% of all the analogies were pictorial to help students visualise abstract or non-observable phenomena like energy effects and atomic structure. Ensuring that the student is
familiar with the analog is crucial if satisfactory mappings are to follow. This issue is supported by Operation 2 in Glynn's teaching-with-analogies (TWA) model and by Harrison and Treagust (1993, 1994b).

Duit (1991a) and Glynn (1989) stress the need to map analogies in a valid and reliable way. For this reason, Thiele and Treagust (1994a) classified each of the 62 analogies using Curtis and Reigeluth's (1984) Level of Enrichment. "The use of simple analogies (23, 37%) was not uncommon although a substantial proportion of the analogies were either enriched (26, 42%) or extended (13, 21%)" (p. 786). Three authors stated a reluctance to place favoured classroom analogies in print because they could not monitor the students' mappings and conclusions. Most authors expected teachers to discuss in-text analogies with their students to remediate incorrect knowledge induction; however, there is a singular lack of evidence in the literature to support this expectation. Thiele and Treagust (1994a, p. 792) warn that "one of the difficulties with [analytical] visualisation is that students can over-internalise the analogy (such as the Bohr orbits)" to the extent that preoccupation with the analogy inhibits further conceptual development. This seems to be what Grosslight et al. (1991) call level 1 modelling in which the student treats the model as the reality.

Most textbook authors interviewed by Thiele & Treagust (1994a) felt that analogies were best suited to one-to-one interactions where they could negotiate with the students the extent and limitations of the analogy and occasionally push the analogy to outlandish limits to show that the analogy was not the intended end. This attitude makes the low reported incidence of analogies in classrooms from Treagust et al's study even more perplexing. If analogies are best suited to social settings, why are they apparently more common in textbooks? This remains a pressing issue for teachers, curriculum designers and textbook writers.

Are Self-generated Analogies Useful?

Analogies are common ingredients of human speech. It is not surprising that analogies find their way into classroom discourse as heuristic devices, teacher explanations and student communication. Fully recognising the conflict involved in the conservation of electric current (something is used up), Cosgrove (1995) described science-in-the-making whereby 14 year-old boys proposed, applied and modified their own analogies for electric current. Instead of teaching the scientific view, the teacher encouraged the students to make predictions, circuit test the predictions, and modify the analogy to fit the results. "The refinement of the student-generated analogy for electricity provided the students with a framework within which to reason" (p. 306) culminating in a scientifically acceptable model for current.
Wong (1993, p. 367) asked "can students use a series of self-generated analogies to bring about changes in their understanding of a given scientific phenomena ...?" Pre-service teachers were challenged to invent, apply, evaluate and modify their own analogies as heuristics in the development of scientific thinking. Wong concluded that searching for analogical explanations deepened the students' appreciation of the problem, motivated the students to ask personally relevant questions, and to recognise and attempt to resolve their prior conceptions. Unlike Cosgrove's approach, Wong did not intervene to circumvent alternative conceptions. In light of the alternative conceptions that can emerge when teachers do not guide analogy use, Wong asked, "is it ethical for teachers to encourage students to develop conceptions about scientific phenomena that are known to be incorrect?" (p. 378). As Cosgrove showed, individuals can engage in the personal construction of knowledge by analogy without necessarily abandoning alternative conceptions.

Reference has been made earlier to Zook's (1991) dilemma. Students map self-generated analogies more easily than they map teacher-supplied analogies. Conversely, students find it hard to choose appropriate analogies for a given problem but are more able to link a teacher supplied analogy to a problem. The problem again seems to be the assumption that analogies are mapped by students without teacher guidance. Sufficient has been said to demonstrate the fallacy of this assumption. Glynn (1989) and Harrison and Treagust (1993) have cogently shown that analogies do enhance student understanding provided the teacher supplies enough guidance to allow the students to correctly map the relational attributes. Cosgrove's and Wong's studies, however, show that the locus of learning control must remain with the students and that students need ample time to think through and tailor the analogy to their needs.

**Analogies Can Help Create Meaning**

In defence of an analogical, constructivist pedagogy, Oliveira and Cachupuz (1992, p. 1) suggest that analogies and metaphors "may help bridge theory and practice" and help students make sense of the world in which they live. They assert that the new ideas that students encounter in chemistry are foreign to their conceptual framework. If these ideas are integrated by analogy into a familiar pattern that is easily received, understanding is enhanced. Analogical learning is constructivist because the analogy assumes "a creative function when it stimulates the solution of existing problems" by recourse to common-place ideas. This position is supported by Duit (1991b) and by Sutula and Krajcik (1988, p. 11) who note that "cognitive psychologists agree that the use of analogies can influence meaningful learning by providing a link to previous learning." However, it is imperative, in making this nexus to prior knowledge, to
recognise when the preconception is itself valid and to consciously eliminate unsustainable mappings which might support alternative conceptions.

More needs to be said about the generative power of analogies. Analogies link theory to practice by positive analogy and this is the primary function of explanatory classroom analogies. Hesse (1963) and Gee (1978) point out that the heuristic power of analogies lies in the neutral analogy. Attributes that are neither positive nor negative stimulate scientific curiosity; analog-target mappings that cannot be immediately classified as valid or invalid suggest ideas that should be explored. Hesse puts it this way:

There will generally be some properties of the model about which we do not know whether they are positive or negative analogies, and these are the interesting properties, because, as I shall argue, they allow us to make new predictions. ... If gases are really like collections of billiard balls, except in regard to the known negative analogy, we may be able to make new predictions about the behaviour of gases. Of course, the predictions may be wrong, but then we shall be led to conclude that we have the wrong model. (pp. 9-10)

The 14 year-old boys in Cosgrove's (1995) study who adopted a coal-truck analogy for electric current mapped the positive analogy to a single-globe series circuit but could not immediately map the analogy to a two-globe series circuit. Cosgrove explains that "the students tested the utility of this [analogy], not by applying it to the critical circuit, but by leaping to question how it would apply to two lights in a series circuit" (Cosgrove, 1995, p. 299). This type of reasoning tends to resemble the sense in which analogy was used by scientists like Kepler, Huygens, Maxwell, Kekule and Lorenz.

The great value of neutral analogy is that it keeps the learner's options open. Positive and negative analogies represent the status quo, but neutral analogy is the window that keeps science alive, vibrant, and unpredictable by generating scientific discovery through analogy (Oppenheimer, 1955). Neutral analogy's heuristic power comes at a price, however, the potential for new alternative conceptions should not be underestimated because the status of any new relations predicted by neutral analogy is not immediately known. But this is what scientific thinking is about, and students need to be exposed to the possibilities offered by neutral analogy. Neutral analogy again reinforces the need for teachers to monitor their students' use of analogies and to critically scrutinise every student mapping. In the previous chapter, many authors (e.g., Hewson, 1982, Hashweh, 1986; Nussbaum & Novick, 1982, Thagard, 1992a; Tobin & Tippins, 1993) identified the central role of discourse and negotiation in meaningful learning. Understanding constructed by each individual reflects that person's unique perspectives and idiosyncrasies. If the constructed understanding is to be logical and socially congruent, while preserving the individual's character,
teaching should identify the essential concepts, fix those in place and allow the student to add his/her finishing touches.

Analogies are appealing in interactive contexts because they have the ability to develop conceptual patterns (Gentner, 1988) as well as transmit specific information. Therefore, appropriate instructional analogies have the potential to enhance student understanding in a stimulating and economical way. The next section examines what the literature has to say about the ways in which teachers can improve their analogy use.

Teaching-With-Analogies

Analogy Use in the Classroom

The science and science education literature contain many analogies that are proffered as ways for presenting difficult topics in science. Some are elegant and appealing, some are common and well known, while others appear to be quite esoteric and are probably unfamiliar to most students. Additionally, there are those analogies that are problematic (electric current is like water flowing in a pipe) because they often generate alternative conceptions (Champagne et al., 1985); however, for historical reasons they remain popular and are used frequently in science teaching. A representative sample of analogies is considered in this section.

Some simple analogies (Curtis & Reigeluth, 1984) are 1) a cell making a protein molecule is likened to tradesmen building a house (Biermann, 1988); 2) chemical reaction activation energy is compared to a hill (Hunter, Simpson & Stranks, 1976; Licata, 1988) or a high jump (Parry, Dietz, Tellefsen & Steiner, 1973); and 3) a polaroid filter is like a comb (Murphy & Smoot, 1982). Examples of enriched analogies are the supermarket-classification analogy (Australian Academy of Science, 1990) and the crowd-kinetic theory analogy (Coffman & Tanis, 1990).

There are very few analogies that are known to be truly effective for learning the target conception. For example, the teaching of electric circuits is fraught with problems (Dupin & Johsua, 1989; Glynn, 1989; Osborne and Freyberg, 1985). Electric current is frequently compared to the flow of water in pipes. Used in this sense, the analogy fails to model an electric circuit because domestic plumbing is not cyclic. Glynn (1989) modified this water analogy by using the circulation of water in an aquarium and its pump and filter as an analog of electric current. The analogy is compelling and is carefully developed to highlight invalid propositions and to derive maximum value from the shared attributes. Other investigators describe electric current as being like a continuous train on a circular track (Bullock, 1979; Dupin & Johsua, 1989).
Esoteric, unfamiliar analogies are those that are popular with their author but are hard to visualise and teach because the analog contains unfamiliar instances or ones that are conceptually too formal. Examples which appear to fit this category are "the ping-pong ball torture analogy for enzyme activity" (Helser, 1991) and "the shot gun-diffraction of light analogy" (Murphy & Smoot, 1982). Similarly, "a chess analogy - teaching the role of animals in ecosystems" (Kangas, 1990) requires expert knowledge of a board game that is unfamiliar to many students. While the analog-target matches are compelling, many students do not have the required background knowledge.

Students Need Experience in Analogical Use

Recognition that teachers and students often fail to maximise the value of an analogy raises the question of training students in analogical reasoning. Teaching students to use an analogy systematically has produced some encouraging results (Alexander, White, Haernsly, & Crimmins-Jeans, 1987). A controlled experiment with 36 average ability, fourth grade reading students, showed that those who received analogical training demonstrated enhanced capacity to complete verbal analogies of the form A:B::C:? In chemistry instruction, Friedel, Gabel and Samuel (1990) observed that students tended to use algorithms to solve problems rather than use the underlying chemical principles. The use of familiar, nonchemistry analogs as concept building tools were successful, especially where the students were trained in analogical mapping transfer. Too often, it is assumed that students can make valid and reliable links between the analog and the target; evidence suggests (Gick & Holyoak, 1983; Zook, 1991) that mapping is not automatic. Also, a systematic analysis of analogies may improve student understanding and reduce the incidence of alternative conceptions. In a similar manner, the quality of presentation of the analogy also affects comprehension of concepts as demonstrated by the study of Bean, Searles, Singer and Cowan (1990). In this study, biology students were provided with analogical study guides to augment lectures and text reading. When the analogy was enhanced by a visual representation of the analog, students' conceptual growth was increased.

Physical models of reality are similar to verbal analogies in that students need help in recognising analogical similarities (Osborne & Gilbert, 1980). The power of models and analogies to build concepts depends upon the student differentiating between the analogy and reality and in being able to integrate the ideas generated by the analogy into his/her mental framework. Based on research evidence to date, careful training and direction is likely to be beneficial in both of these aspects.

The assertion that "special teaching for [analogical] transfer seems to be indispensable" (Klaucr, 1989, p. 190), posits that analogical transfer skills are a composite of general
intelligence and expertise. Experts are more adept at analogical transfer because their skills have been honed by repeated practical experience and this skill should not be assumed in novices. Sutula and Krajcik (1988) found differences in students' ability to solve mole problems when analogies were used; one group was left to map the analog-target correspondence for themselves, while a parallel group had the similarities provided by the teacher who added the expert skills lacking in the students. It seems that identification and classification of analogical similarities and differences does need to be taught and this instruction should be repeated until each student is competent. This is a learning-to-learn issue that should be considered by teachers who use analogies.

A further matter in this issue of who benefits most from analogy use is the question of student cognitive levels. Whilst it has been shown that analogies enhance understanding by establishing links to previous knowledge, Sutula & Krajcik (1988) suggest that different strategies should be employed with different students. For instance, with students possessing "high non-verbal cognitive ability, more positive results are found by allowing the students to infer their own connections of new knowledge to prior knowledge" (p. 11). Overall, students with lower logical thinking skills derived greater relative advantage from analogies than did students with higher abilities. It is important to note, however, that these less able students needed teacher assistance to make the analogical connections. On the other hand, students operating at a high formal Piagetian level sometimes appeared to be disadvantaged by analogies because they more frequently constructed correct understanding of the target by direct means (Friedel, Gabel & Samuel, 1990; Gabel & Sherwood, 1980; Thiele & Treagust, 1991; Zeitoun, 1984). However, the delineation of analogical cognitive value based on Piagetian levels is not clearcut (Gabel & Sherwood, 1980). Analogies can be valuable to both concrete and formal reasoners, but for different reasons.

Systematic Presentation of Analogies

It has been established that students need help to correctly interpret analogies and that student learning is enhanced when teachers present analogies in a systematic way (Harrison & Treagust, 1993). The presentation issue is one of clarity, efficiency and economy. The chief proponents of improved presentation are Brown and Clement (1989), Clement (1987), Dupin and Johsua (1989), Gentner (1988), Glynn (1989), Treagust (1995) and Zeitoun (1984). Glynn's (TWA) Model will be considered last and in the greatest detail as it was important for this study - each analogy used by the Year 11 chemistry teacher (Chapter 5a) was presented following the operations of the TWA model.
Gentner's primary concern seemed to be with the need to establish some form of algorithm for use when analogies arise during instruction. Her interest was the need to identify enough surface similarities to initiate comparison of a problem situation to one that is well understood. This would arouse the analog-target's "systematicity" which would be particularly useful for transferring patterns and ideas of arrangement and function from the familiar to the unfamiliar. The Structure Mapping Engine's rules appear to be too mechanistic or algorithmic for classroom use. Many writers applaud the motivational aspect of analogy but Gentner's approach seems to stifle the originality and individuality that is the life-blood of relational thought. Over-reliance on structure mapping (Gentner, 1983, 1988) seems very much like the 'cold rationalism' for which Pintrich, et al. (1993) criticised Strike and Posner (1992) in the conceptual change debate. Analogies are mostly used in inter-personal and social settings where, as Dagha (1995) comments, "idiosyncrasies of ... analogies should be a source of celebration rather than one of concern, and the variations in the forms of expression are only suggestive of a spectrum of possibilities one would expect to encounter when observing classroom interactions" (p. 268). Unshared mappings also are dealt with in a cursory way and Gentner's logico-inductive processes do not seem to be accessible to secondary science students. Even the "structure mapping rules" (p. 65) may prove difficult for the average teacher to assimilate.

Bridging analogies (Brown & Clement, 1989; Clement, 1987) are more a set of analogical inter-relationships than a model for general pedagogical use. This concept of using an intermediate, more easily accepted analogy is a powerful way of bridging the gap between two distant domains that are analogical. While students may be incapable of connecting distant concepts, they may make the connection if this can be achieved through a number of smaller steps. This is what Clement means by a "bridging analogy". Instead of one large span, the bridge has many supports (mental resting points for the learners) along the way. The use of bridging analogies to represent instances of static equilibrant forces is illustrated in Figure 7.

In the case of a book placed on a table "76% of a sample of 112 students indicated that a table does not push up on a book lying at rest on it. ... 96% of these students believe that a spring does push up on one's hand when the hand is pushing down on it" (Clement, 1987, p. 86). The hand on the spring is used as an "anchoring example that draws out an anchoring intuition" (p. 86). From this anchor, the student is then shown the book sitting on a board supported at each end and the book bends the board. This is the bridging analogy. It can then be reasoned that the table must exert an upward force equal to the book's downward force because the table does not bend. If the students are reluctant to accept the concept of forces in equilibrium for the book on the table, a second bridging step is included (book sitting on foam).
Figure 7: Bridging analogies to link anchor concept to target concept. (from Clement, 1987, p. 87)

The analogical teaching model (Dupin & Johsua, 1989) contains five distinct steps. First, the analogy puts a new idea in a concrete, visualisable form, and the second stage performs a "descriptive function" (p. 210) by presenting the student with a plausible explanation comparing the new concept to old accepted ideas. Third, the analog must be less complicated that the target in the problem being investigated and fourth, the analog should simplify, not confuse. Finally, the time spent on the analog-target transfers must be economical. Dupin and Johsua centred their attention upon the continuous train analogy as a means for explaining the flow of electric current in a D.C. series circuit. This model, however, becomes more a set of criteria for analogy selection than as a presentation method. Nevertheless, such criteria have a place in teaching because each analogy should be assessed from these viewpoints before it is used in a class.

The "General Model of Analogical Teaching" or GMAT (Zeitoun, 1984) also has been proposed as a mechanism for logical presentation of analogies. This model goes further than those preceding it in addressing some of the problems observed in analogy use. It focuses upon the students' prior knowledge (but less so than Dupin and Johsua) and is strongly constructivist. It also asks the teacher to carefully consider the mode of presentation and has a reflective stage at its conclusion. Zeitoun's model contained nine stages, these being:

1. Measure some of the students' characteristics related to analogical learning in general.
2. Assess the prior knowledge of the students about the subject.
3. Analyse the learning material of the topic.
4. Judge the appropriateness of the analogy to be used.
5. Determine the characteristics of the analogy to be used.
6. Select the strategy of teaching and the medium of presenting the analogy.
7. Present the analogy to the students.
8. Evaluate the outcomes of using the analogy in teaching.
9. Revise the stages of the models. (Adapted from p. 118)

The strength of Zeitoun's model lies in the care taken in selecting the analogy, planning its presentation, purposeful in-class strategies and post-lesson evaluation.

The notable feature of all these models, however, is their lack of attention to the role of unshared attributes in generating alternative conceptions. The actual mapping process is also taken for granted in most cases, even though it is well known that students have difficulties in identifying the shared attributes. In contrast, Glynn (1989) developed his Teaching-With-Analogies (TWA) model as a six operations model which emphasised student familiarity with the analog, mapping both the shared and the unshared attributes, and providing the students with a concise conclusion.

The Teaching-With-Analogies Model

Glynn's (1989) TWA model appeared best suited for use in secondary science classrooms because it is comprehensive, concise and its actions are logically sequenced. Treagust (1989) modified Glynn's model by reversing operations 5 and 6. This placed the mapping and discussion of the shared and unshared attributes side-by-side in the belief that the proximity of both sets of mappings would better enable the student to see where the analogy broke down. It also meant that the concluding statement now closed the exercise. Harrison (1992) tutored an experienced teacher in the use of a modified TWA model [Figure 8(a)] and found that the teacher presented analogies systematically and the resultant student understanding was compatible with scientists' views. The six-operation modified-TWA model for providing inservice education for teachers was subsequently refined by Treagust (1995) as the FAR Guide [Figure 8(b)].

The modified TWA Model

1. Introduce the concept to be learned
2. Cue the students' memory to the analogous situation
3. Identify the features of the analog that are relevant
4. Map the similarities between the analog and the target concepts
5. Identify analog-target links where the analogy breaks down
6. Summarise, drawing conclusions about the target concept

(a) Modified TWA Model (Treagust, 1989; Harrison & Treagust, 1993)
The FAR Guide

Focus
Concept: Is it difficult, unfamiliar, abstract?
Students: What ideas do the students already have about the concept?
Analog: Is it something the students are familiar with?

Action
Likes: Discuss the features of the analog and the science concept.
      Draw similarities between them.
Unlikes: Discuss where the analog is unlike the science concept.

Reflection
Outcomes: Was the analog clear, useful, or confusing?
Improvements: Focus on the above in light of the outcomes

(b) The FAR Guide (Treagust, 1995; Treagust, Venville, Harrison, Stocklmayer & Thiele, 1993)

Figure 8: Two systematic models for teaching with analogies

Models and Student Modelling

Models and Analogies

This study has adopted the continuum: metaphor-analogy-model as representing most general to most specific. Justification for this position includes Duit's (1991a) opinion that metaphoric comparison is implicit while analogy is explicit. Some models are implicit, but most are explicit to the point where their concreteness suggests that they might even be called examples [the same may be said for literal similarity analogies (Gentner, 1988)]. Duit showed that different authors distribute models across the whole gamut of representational thought and this problem will be discussed later in this chapter.

The first part of this chapter showed that analogies are occasionally used by some teachers. It also showed that teachers, textbook authors and researchers have strong reservations about the value of analogies due to uncertainties concerning teachers' subject content knowledge, students' familiarity with the analog and students' ability to reliably map analogical attributes. While, many writers refer to the complicity of analogies in the formation of alternative conceptions, visits to classrooms and examinations of textbooks show that the same reservations are infrequently applied to models. Models are on constant display in most science classrooms and much school science content consists of conceptual models (Gilbert & Boulter, 1994; Glynn & Duit, 1995; Norman, 1983). The basic reason for this is supplied by Gilbert (1993).
Models play a crucial role in the practice of science. Their formation enables the scientist to reduce the complexity of a phenomenon such that some apparently key features can be concentrated on. They allow abstract theories to be represented in a more visualisable way so that predictions of behaviour can be made and tested. They are vital in the communication of the outcomes of science. If science education is about introducing students to the processes and outcomes of science, then models and modelling must be included in the curriculum. (p. 5)

Scientific Modelling

Modelling is an investigative process founded on analogical reasoning. Giordan (1991) views scientific modelling as constructivist thinking because high-level modelling fosters conceptual change that is clearly controlled by the learner. A model is a way to represent reality through an image that both describes the target's salient points and simplifies the situation; "schematically, a model is an answer to a question" (p. 326). By calling constructivist modelling the allosteric model of learning, Giordan seems to be referring to the ability of a visualised model to induce a Gestalt shift in the learner. Kuhn (1970) used Gestalt shifts to describe revolutionary science or what is now called strong or radical restructuring (conceptual exchange). For his examples, Giordan used water in pipes and a bicycle chain to model an electric current. These models, however, are presented in a form that would classify them as simple analogies (Curtis & Reigeluth, 1984). Indeed, this highlights the difficulty involved in differentiating between analogies and models. For this reason these, and many other models/analogies, are better called analogical models because they separately, or at the same time, satisfy both definitions.

Gee's (1978) approach to models is more that of a purist. He asserts that

To use a model correctly demands that (a) we do not use the device to argue by analogy ...; (b) we should not claim that a model can explain (... reality - whatever that is); (c) we must be prepared to drop a model once a theory is realised; and (d) we ought to note the valuable parallel which exists between the growth of a scientific theory (in which a model may be a heuristic tool) and the intellectual growth of the learner (for which a model is a pedagogical tool). (p. 287)

Gee recognised that Maxwell's model-based explanation of Faraday's electric fields was an analogy and that it was the "partial similarity between the laws of one science and those of another which makes each of them illustrate the other" (p. 288).

Zumdahl (1989) also draws attention to the power and the pitfalls of scientific models:

A model is considered successful if it explains the known behaviour in question and predicts correctly the results of future experiments. It is important to understand that a model can never be proved absolutely true. In fact, any model is an approximation by its very nature and is doomed to fail at some point. Models range from the simple to the extraordinarily
complex. We use simple models to predict approximate behavior and more complex models to account very precisely for observed quantitative behavior. (pp. 197-198).

This warning that all models fail somewhere heightens the applicability of analogy theory to models. Especially important is the issue of where the model breaks down. Just as only a minority of those writing about analogies drew attention to this trap, the same seems to be true of writers about models. This highlights the value of systematic presentations of analogies like the TWA model and the FAR Guide because they identify the dissimilarities between the analog and the target.

Each of these comments only deepens the problem of differentiating between analogies and models because of the indeterminate nature of their boundaries. Even the notion that analogy is often verbal, immaterial and mind-based does not clear the air because many theorists and researchers frequently talk about mental models (Gentner & Stevens, 1983). The overlap of analogy and model is further reinforced by the use of common language such as analog, target, mapping and attributes.

Chemistry in particular has subsumed models to the extent that removal of chemistry's analogies and models would leave very little of the subject matter intact. Farber (1950) argued that in the beginning, mythology, astronomy, agriculture and domestic activities provided the analogical basis for explaining physical and chemical changes. He showed how analogy has persistently influenced the growth of chemical knowledge in the work of Dalton, Baeyer, Van't Hoff, Pasteur, Kekule, and others. The periodic table is a classic conceptual model-analogy: "Mendeleyev forecast the existence of 21 elements that were not known at the time by comparing the properties of known elements around a gap" (Hunter et al., 1976, p. 117). The discovery of eka-silicon (germanium) by this method is an exemplary case of heuristic analogy.

Chemistry also has subsumed metaphoric language like 'electron shells', 'electron clouds' and 'the solar system atom' (Sandomir et al., 1993). Because of the preoccupation of this thesis with chemical modelling, in the sense that models are used to generate understanding by analogy, the term analogical model is the most appropriate descriptor for chemical models that will be discussed in the subsequent chapters.

**Analogue Models**

The ability of models to analogically transfer knowledge from a familiar analog to an unfamiliar target is itself modelled by Duit (1991a) and Gilbert (1993) (see Figure 9).

Very few authors discuss analogical models, Thiele & Treagust (1994a) do, and Black (1962) comes closest to defining an analogical model as it is used in this study.

An analog[ical] model is some material object, system or process designed to reproduce as faithfully as possible in some new medium the structure or web of relationships in an original. ... The analog[ical] model, like the scale model, is a symbolic representation of
some real or imaginary original, subject to rules of interpretation for making accurate inferences from the relevant features of the model. (p. 222).

Black insists that there are crucial differences between scale and analogue models. Scale models rely for their identity on proportionality, thus they convey geometry, shape and some of the original's superficial features.

On the other hand, the making of analogue models is guided by the more abstract aim of reproducing the structure of the original. An adequate analogue model will manifest a point-by-point correspondence between the relations it embodies and those embodied in the original: every incidence of a relation in the original must be echoed by a corresponding incidence of a correlated relation in the analogue model. To put the matter in another way, there must be rules for translating the terminology applicable to the model in such a way as to conserve truth value. Thus the dominating principle of the analogue model is what mathematicians call 'isomorphism.' (p. 222)

(a) Duit's model for an analogy (1991a, p.650)

(b) Gilbert's model of a model (1993, p. 6)

Figure 9: Analogical relationships between analog, model and target.
The relationship between scale models and analogical models therefore resembles Gentner's (1983) relationship between surface similarities (which promote access) and structure-mapping (which promote systematic inference). It is curious that the analogue model, which looks less like the original than the scale model, has higher-level communicative and heuristic power. Gilbert (1993) proposed four major roles for models in science education by arguing that:

1. Models are one of the main products of science.
2. Modelling is an element in scientific methodology.
3. Models are a major learning tool in science education.
4. Models are a major teaching tool in science education. (pp. 9-10)

In this sense, models are conceptual tools that are involved in every stage of the scientific enterprise, from initial hypotheses right through to the explanation of a phenomenon. Gilbert also points out that a particular model and its theory are not synonymous but interactively support each other. This of course provides the rationale for teaching models and modelling in secondary science; sense cannot be made of either science's content or reasoning processes unless students are immersed in the scientific culture.

Mayer (1992) argues that a "mechanical model" (actually an analogical model) contains at least four features that govern its role in knowledge and thought:

- **components** - the key parts of the system and their structural relation to other parts,
- **states of components** - the possible states of each component,
- **relations between state changes** - the "if-then" relations between a state change in one component and a state change in another component, and
- **principles** - fundamental natural laws that apply to the relations between state changes. (p. 231)

Analogical (or mechanical) models are capable of representing processes like the molecular kinetic model of ideal gas behaviour or collision theory model for reaction rates and chemical equilibrium. The importance of these models is their ability to transfer high-level holistic explanations of fundamental chemical changes. Models containing Mayer's four features explain phenomena using Gentner's (1983, 1988) systematicity principle and are especially useful in building conceptual models. Mayer points out that models are temporary human inventions (see also Smits & Finegold, 1995) and, as Weller (1970) and Grosslight et al. (1991) show respectively, models should not be preserved beyond their 'use-by-date' nor should they be allowed to replace reality (Zumdahl, 1989).
A Typology Of Models

What "truth" can we show with models of atoms and molecules? This question should never be far from us as we use models to help explain and predict chemical changes. A model cannot represent fully the thing modelled, and it may even mislead us if we imagine that the thing modelled must behave as predicted with the model. (Keenan, Kleinfelter, & Wood 1980, p. 188)

The use of the term "model" is a source of considerable semantic variation for science students and practitioners. What do we really mean when we say that two white balls separated by a black ball and interconnected by some springs is a useful model for carbon dioxide? What do we mean when we say that Le Chatelier's Principle is a good model (or algorithm?) for solving equilibrium problems? Or again, what do we mean when we use colliding balls in a kinetic theory apparatus to model ideal gas behaviour? Meanings for the term model are almost as varied as the array of models used in chemistry. The following nine categories constitute a composite definition that may be tendered for the concept of model, and is applicable to most science learning (Black, 1962; Gilbert, 1993; Gilbert & Osborne, 1980; Leatherdale, 1974).

Scale models of a building are used for planning purposes, scale models of a car guide advertisers and scale models of a boat are used for tank testing. While these models faithfully resemble the external proportions of the object modelled, they usually bear little or no resemblance to the object's internal structure (Black, 1962).

Analogical models are cases where one or more of the target's attributes are represented in the analog's concrete structure. Examples are ball-and-stick and space filling molecular models in chemistry and anatomical models in biology, e.g., a plastic human torso or model heart. Analogical models are constructed to reflect point-by-point correspondences between the analog and the target for the set of attributes that the model is designed to elucidate. The shared attributes, however, are intended more to reflect abstract patterns and relationships than proportions of magnitude (Black, 1962).

Mathematical models are cases where physical properties (e.g., density), physical changes and processes (e.g., k = PV, F = ma), and mathematical functions are represented in the form of an equation (e.g., ay = bx^2 + c). Graphs also can be used to represent equation relationships (e.g., Boyle's Law, reaction enthalpy changes, etc.) (Black, 1962).

Chemical formulae (e.g., CO_{2}) and chemical equations are symbolic models of compound composition and chemical reactions respectively. Chemical equations can represent reaction stoichiometry, thermodynamic and electron changes, reaction mechanics and equilibrium states (Pimental, 1963).
Theoretical models are used to analogically represent nonmaterial phenomena (e.g., magnetic lines of force and photons). Mental models of phenomena involving these entities may also belong to this category (Black, 1962).

A model or standard is something to be imitated. An example would be a model of a process that makes sense of an overall chemical or physical change (e.g., kinetic theory models for temperature, pressure and phase changes) (Pimental, 1963; Zumdahl, 1989).

Maps and diagrams that represent patterns, pathways and relationships. Examples are the periodic table, phylogenetic trees, weather maps, electrical circuit diagrams, process flow diagrams, metabolic pathways, nervous system connections, blood circulation, pedigrees, and food chains, webs and pyramids.

Simulations are highly sophisticated multiple models (e.g., an aircraft's structure and functions). Simulations allow novices to develop and fine tune skills without risking life and property. Researchers use simulations to model dangerous and socially unacceptable experiments such as deep sea, space and nuclear processes. Many simulations utilise 'virtual reality' experiences, nevertheless, they remain models because the events they model do not actually exist. Computer simulated chemical reactions hold promise in the teaching and learning of chemistry. Computer games are common examples of simulation-models.

Mental models "refer to a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning" (Vosniadou, 1994, p. 48). Mental models are intrinsic descriptions of objects and ideas that are unique to the knower and arise and evolve "through interaction with a target system" (Norman, 1983, p. 7). Mental models need not be technically accurate, but they must be functional and "people may state (and actually believe) that they believe one thing but act in quite a different manner" (Norman, 1983, p. 11).

Development of Models Through History

The concept that matter was composed of atoms began almost 2500 years ago with the Greek philosophers Democritus (B.C. 460) and Leucippus. Modern atomic theory, though, grew out of the work of John Dalton (1766-1844) and with the move from alchemy to a more systematic study of the elements and their behaviour (e.g., Lavoisier and Priestley), chemists were challenged to describe atoms and molecules. Early theories depicted atoms as spheres or balls; this idea was refined with Thomson's discovery of the electron and the emergence of his "plum-pudding" model of the atom. The discovery by Rutherford that atoms are almost all space and have a dense nucleus led to the "solar system" model. This model, however, was quickly displaced by the Bohr atom, and quantum mechanics generated an increasingly
abstract atomic model that required sophisticated mathematics for its description (after Planck, de Broglie, Schrödinger and Heisenberg).

Mathematicians such as Kline (1985) argue that despite the desire to produce mental or analogical models of abstract objects and processes, the belief that we can do so is a myth. This is because when dealing with space, mass, light, and gravity, the notion that there is an exact correspondence between mathematical descriptions and physical models is a retrograde step. He comments: "what is most relevant for us to see is that our models of atomic structure are not physical" correspondences with objects like atoms (Kline, 1985, p. 196). This is the basis of a dilemma: theoretical scientists enjoy startling the world with their discoveries and have a genuine desire to disseminate new ideas which often improve our world. However, while scientists achieve many of these advances through mathematical pathways, the teacher, who is the second last link in the education chain, is pressed to employ imperfect models and analogies that the theoretician deplores. Ironically, writers such as Kline use a wide range of analogies to transmit their own ideas to the average reader while criticising models and analogies as 'impure.'

Even a cursory glance at modern science textbooks reveals that they contain many analogies and analogical models. Probably nowhere is this more obvious than in chemistry textbooks (Thiele & Treagust, 1994a), chemistry laboratories and chemistry teacher explanations (Thiele & Treagust, 1994b). To introduce nonobservable entities like atoms and molecules to students, teachers and textbook writers are constrained to introduce analogies, analogical models and representational models like chemical formulae and chemical equations. Parallelling science's evolution of atomic models, teachers over the five years of secondary chemistry instruction often employ the historical succession of models in a spiral curriculum.

**Analogical Molecular Models in Chemistry**

Keenan et al. (1980) describe the four common molecular model types encountered in secondary chemistry classrooms. Not only do these authors discuss modelling with their readers, they also describe the shared and unshared attributes existent between each analog (the model) and its target (the molecule). An example of each model is shown in Figure 10.

**Ball-and-stick models.** These models provide simple 3-dimensional representation and the number of bonds to each atom is correctly shown and often, the models show the correct bond angle. These models are easy to make from proprietary sets and the double and triple bonds do show their nonrotatable nature in contrast to the fully rotatable single bond. Ball-and-stick models are similarly excellent for demonstrating isomerism. On the negative side, these models give an idea of "openness" and as
most balls are the same size, they imply that all atoms are the same size (which they are not). Double and triple bonds are represented by bent plastic or springs so that the single and multiple bonds appear to be structurally identical (which they are not). Further, ball-and-stick models cannot satisfactorily depict a benzene ring.

**Scale models or space filling models.** When constructed, these models roughly represent van der Waals and covalent radii. Bond angles and relative atomic sizes are depicted with adequate accuracy. The overall architecture of the molecule is well represented. This model's weakness lies in its inability to show bond numbers and bond type.

**Lewis structures (models of molecules).** These are 2-dimensional diagrams showing all the valence shell electrons for the interacting atoms and obey the octet rule for second row elements and the duet rule for hydrogen. Their advantage lies in ease of use and the ability to show all bonding electrons as well as allowing the student to 'work out' a satisfactory structure and deduce, in many cases, the molecule's shape. These diagrams are flawed in that they are only 2-dimensional and do not show bond type and fail to work in more complex cases.

![Ball-and-stick model of a water molecule](image1)
(a) Ball-and-stick model of a water molecule

![Space-filling model of a water molecule](image2)
(b) Space-filling model of a water molecule

![Lewis structure - electron dot models](image3)
(c) Lewis structure - electron dot models

![Lewis structural formula models](image4)
(d) Lewis structural formula models

*Figure 10: Four types of molecular models commonly used in secondary chemistry classrooms.*
Structural formula models. These models are derivation of Lewis structures with the addition of splayed and dotted bonds to depict in front of the plane and behind the plane orientations respectively. These structures allow 3-dimensional diagrams (e.g., tetrahedra) to be drawn on paper but cannot accurately show the bond angles nor can they distinguish bond type. Students need time to develop the visualisation skills needed to read these diagrams but they are quick and easy to draw on paper.

Zumdahl (1989) provided a convenient summary of the fundamental properties of models:

Models are human inventions, always based on an incomplete understanding of how nature works. A model does not equal reality.
Models are often wrong. This property derives from the first property. Models are based on speculation and are always oversimplifications.
Models tend to become more complicated as they age. As flaws are discovered in our models, we patch them by adding more assumptions.
It is very important to understand the assumptions inherent in a particular model before you use it to interpret observations or make predictions. Simple models usually involve very restrictive assumptions and can only be expected to yield qualitative information. If a model is to be used effectively, we must understand its strengths and weaknesses and ask only appropriate questions.
When a model is wrong, we often learn more than when it is right. If a model makes a wrong prediction, it usually means we do not understand some fundamental characteristics of nature. (p. 344)

The Value of Models

Student understanding of chemical phenomena utilise descriptions at three levels. Concrete observations and descriptions of chemical activities are easily made at a macroscopic level; however, the explanation of these phenomena requires an atomic/molecular approach (Lee et al., 1993). For instance, changes in volume, pressure and temperature of simple gases are wholly observable and describable using macroscopic dimensions. Charles’ Law, Boyle’s Law and their attendant mathematical statements were discovered and are still implemented at the macroscopic level. However, understanding and explaining these phenomena requires a model of particulate behaviour and the molecular kinetic theory provides an intelligible, plausible and fruitful particle explanation of macroscopic relations and changes. A similar situation applies to acids, bases and salts: macroscopic changes such as effervescence, dissolution and changes in indicator colours are easy to describe, but an understanding of molecules and ions in aqueous solution is essential if each phenomenon is to be properly accounted for. Carr (1984) argued that multiple models are needed to explain
acid-base phenomena. Similarly, collision theory explains at a particle level the macroscopic observations of reaction rates and chemical equilibrium.

Fensham (1994) points out that the most natural way to induct students into the study of chemistry is through a chemical reactions approach. All the same, whether students are introduced to chemistry via chemical reactions, a "conceptions of substances" method, or through the theory laden atomic structure approach (Fensham, 1994, pp. 15-16, 20-22), there comes a point beyond which the study of chemistry needs to be placed on a firmer intellectual base than merely describing changes in colour, phase and temperature. This was the issue that faced the likes of Priestley, Lavoisier and Dalton around 200 years ago. Without a cogent theory to underpin macroscopic observations, chemistry would have stagnated and would have remained the province of alchemists.

Given that chemistry deals with atoms, molecules and ions that are unimaginably small, changes at the particle level can only be explained by theories which, in their greater part, depend on inductive logic and a plethora of models. Models of particulate behaviour provided the essential scaffolding that supported and fostered the growth of chemical understanding; and topics dealing with atoms came to rely on a variety of models to explain their phenomena. Indeed, modern atomic models range all the way from solid, elastic balls (molecular kinetic theory), through diffuse structures that are mostly space (Rutherford and Bohr atoms), to the description of electron orbitals using quantum mechanics and wave equations.

How students cope with the models that must be introduced at some stage, is a dilemma that confronts every chemistry teacher. Rather than overwhelm students with multiple models for atoms and molecules at too early an age, most curricula employ a spiral approach in which new models progressively replace or are added to the models already familiar to the students. This approach often has an historical ring to it; the sequence of models roughly mirrors the succession of models developed over the past 200 years. But is the historical progression valid for novice chemists? Are the students to whom we introduce models capable of differentiating between the models and the reality they represent? First, 13-15 year-old school students differ from adult scientists in age, intellect and motivation. Second, past scientists encountered a new model only every few decades (or longer) whereas students strike new models weekly or monthly. It is arguable that the cognitive and intellectual capabilities of students cannot be likened to the experience and capabilities of mature scientists.

Grosslight et al.'s. (1991) study also casts doubt upon the student-as-scientist assumption. Modelling is a sophisticated intellectual skill. Modelling introduces more than just a way to represent an atom. Modelling invokes the philosophical
underpinning of the scientific method and models are devices for concreting scientific ideas (Mayer, 1992). Hypotheses and theories energise and support their attendant models (and vice versa); therefore the teaching of models conveys to students both content knowledge and the principles of scientific thought. But teenage students see the world in ways that often accentuate material attributes while scientific thought is dominated by processes (Chi et al., 1994). And therein lies a monumental pedagogical challenge: Models are not reality, they are an epistemology in their own right.

Like analogies, models are two-edged swords but models and science are also mutually interdependent. While some teachers claim that analogies can be avoided, they accept that models are indispensible to science. Fortunately, the teaching-with-analogies models are as easily applied to the teaching of models as they are to analogies. The TWA models and the FAR guide remind teachers to ensure that the analog/model is familiar, to map shared attributes systematically and to show students where each analog/model breaks down. Teachers who present analogies and models in a systematic but critical manner can enhance their students' conceptual understanding of science while avoiding many of the pitfalls.

**Modelling in Secondary Science Classes**

Gabel, Briner & Haines (1992) described three levels at which chemical concepts can be taught to, and learned by, secondary students. These were the **sensory** (macroscopic), the **atomic/molecular** (microscopic) and the **symbolic** (formulae and algorithms) levels. These authors agree with the previous argument that the presentation of atomic/molecular changes are both the most difficult to achieve in the classroom and the most important for scientific understanding of chemical processes. Gabel et al. advocated encouraging students to model chemical processes on a continuous basis and, as an economical means for achieving this, they propose inexpensive two-dimensional magnetic models for atoms. "Students should also be asked on numerous occasions to compare the particles in the standard with what is given in the problem until they link the sensory, atomic/molecular, and symbolic levels (p. 62). Bradley and Brand (1986) developed a similar approach called 'stamping out misconceptions' in which students regularly used rubber stamps to produce two-dimensional diagrams modelling physical conditions and chemical interactions. Both of these methods reported enhanced student visualisation of chemical processes. However, using coloured counters or balls to model atoms can have unexpected effects. Ingham (1991) found that as a result, a significant number of successful chemistry students believed that carbon atoms were black, hydrogen atoms were white and chlorine atoms were green. This finding simply reinforces the need for teachers (and textbook writers) to be conscious of how their students are mapping
analog/model attributes and to actively show where the analogical model breaks down (Fensham & Kass, 1988).

The fact that all analogical models break down somewhere is both a weakness and a necessity. It is a weakness because many teachers and most students fail to recognise where the analogy ceases; it is a necessity because to be useful, each analogical model needs to be wrong in some way otherwise it would be an example.

Learning to manipulate scientific models provides school students with a window into the world of science (Solomon, 1995): "Learning to model what happens through the use of sometimes complex scientific analogy is an active process involving considerable personal effort on the part of the pupil" (p. 16). Solomon's students were exposed to various analogical models resulting in 14-16 year-old students showing that they were "capable of doing more thoughtful and perceptive work than is often expected" (p. 22). Indeed, learning activities that are pitched slightly higher than a student's current intellectual level often result in advancement to that level (Finster, 1989). Many chemical phenomena can be modelled at a variety of levels of difficulty (e.g., atoms, bonding, organic molecules) and this provides teachers with the opportunity to challenge their students with a sequence of increasingly sophisticated models. If, for instance, the variety of atomic models are used in this way, it is likely that students will feel challenged, advance conceptually, and come to appreciate that conceptual models are but consensus decisions by a society of scientists. Progress of this nature requires that collectively, students and teachers avoid closure, that students are encouraged to explore alternative models, and that all parties remain aware that a given model is simply a best-fit representation that serves the learner and not the other way round.

Conclusions

This review has shown that metaphors, analogies and models are widely accepted as communicative and concept building tools in science education. As concept building tools in the physical sciences, the order of most common to least common use is models, analogies, metaphors. In chemistry, the distinction between models and analogies is often blurred and the category, analogical model, is most useful. Analogies and models can assist in articulating newly constructed theories and they can suggest questions for the refinement and extension of past theories. Similarly, analogies and models provide opportunities for the application of theories to concrete physical problems by suggesting points of correspondence between theory and practice. Finally, analogies and models help students understand the unknown in terms of familiar experiences and ideas and act as motivating influences when studying unfamiliar concepts.
But not every aspect of analogy use is positive. Abundant evidence has been tendered to show that in many learning environments, analogies have not realised their full potential. The main causes appear to be unfamiliarity with the analog, indiscriminate and invalid attribute mapping, confusing the analogy with reality, and misplaced attention to surface similarities rather than systematic relational structures. Furthermore, unchallenged invalid analog-target mappings can generate alternative student conceptions. Fortunately, teaching approaches do exist that promise to enhance the advantages while limiting the disadvantages of models and analogies.

The preceding analysis of instructional metaphors, analogies and models provides a theoretical framework for the investigations reported in Chapters 4 and 5. Chapter 4 is an interview-based survey of 48 Year 8-10 science students' knowledge about atoms and molecules and proposes answers to Research Question 1: "With which models of atoms and molecules are Western Australian pre-Year 11 students familiar; and what is the relative status of these models for these students?" Chapter 5 reports on a year-long study of Year 11 students' learning in chemistry and proposes answers to Research Question 2: "Do systematically presented metaphors and analogical models, and multiple models, contribute to conceptual change in learning about atoms, molecules and chemical bonds?"
Chapter 4
SECONDARY STUDENTS' MENTAL MODELS OF ATOMS AND MOLECULES

Introduction

The active role of constructivist learning processes in conceptual development has already been discussed. Everyday of their lives, students interact with the natural world, observe its features and talk to other people about their experiences and ideas. Out of these accumulated experiences, students develop rudimentary explanations or generalised mental models of many phenomena including life, astronomy, light, force and matter. These intuitive ideas or 'children's science' (Duit & Treagust, 1995; Gilbert, Osborne & Fensham, 1982; Gunstone, 1991) directly influence students' classroom learning, and because individual experiences are many and varied, the influence of this prior knowledge on learning varies from student to student. In the main, however, alternative student conceptions in science have been well documented (Driver et al, 1994; Pfundt & Duit, 1994). Nevertheless, student descriptions of scientific phenomena often are exemplified by their individuality and unique construction and this chapter describes research of this type concerning Year 8-10 students' conceptions of atoms and molecules.

This investigation was designed to provide base-line data for the subsequent study (reported in Chapter 5) of Year 11 students' learning about atoms, molecules and chemical bonds. The research described in this chapter was conducted in order to answer Research Question 1: "With which models of atoms and molecules are Western Australian pre-Year 11 chemistry students familiar; and what is the relative status of these models for these students?"

Studying Student Mental Models of Atoms and Molecules

This descriptive study of students' mental models of atoms and molecules is an investigation of how 48 students from Years 8-10 perceived atoms and molecules. Various students described atoms as being like a ball, a solar system, a plum, and even as a structure that is able to divide and reproduce like a cell. Teacher-initiated metaphors such as 'electron clouds' and 'electron shells', however, appeared to conjure in the minds of students quite different models to those intended by the teachers. Novice students (and some not so inexperienced) held a view of an electron cloud as a matrix within which the electrons were embedded like the water droplets in a cloud. This model is very similar to the conception that matter is continuous with atoms embedded in the parent substance (Rensstrom et al., 1990).
It appears that many students do not interpret teacher metaphors and analogies in the intended manner. Rather, they transfer attributes from the teachers' analog to the target (atoms and molecules) in a literal and undifferentiated sense. The need for care when using analogies in order to avoid the transference of unshared attributes to the target has been highlighted by Glynn (1991), Harrison and Treagust (1993) and reviewed by Duit (1991a).

Research into student conceptions of the particulate nature of matter has been conducted by Andersson (1990), Griffith and Preston (1989), Lee et al. (1993), Nussbaum and Novick (1982) and Scott (1992). These studies considered several intuitive student views: for instance, that matter is continuous without spaces between particles, that matter is not always conserved during chemical reactions and that atomic and molecular properties resemble the macroscopic properties of the substance. Sandomir et al. (1993) have probed student conceptions of the metaphor 'an atom is an electron cloud' and 'an atom is an electron shell' and showed that frequently students are unable to reliably identify where the metaphor (or analogy) breaks down.

The study reported in this chapter extends the research described above by examining the reasoning behind certain views of atoms and molecules held by students and investigates how students' mental models may assist or hamper further instruction in chemistry. The study also explores the variety of student models of atoms and molecules in order to inform the study described in Chapter 5.

Method

Subjects and Context

Forty-eight students, selected from Years 8, 9 and 10 at three large senior high schools (Years 8-12) in Western Australia, were the subjects for this study. None of the schools had a policy to restrict access to any student, and students in Years 8-10 are generally in non-streamed classes. Two of the schools were government senior high schools (one metropolitan, the other in a large country town) and the third was an exclusive metropolitan girls school. For all except the Year 8s in the country school, approximately half of the students in each class were unavailable due to excursions or being involved in other school end of academic year functions. Student willingness was the principal selection criterion. Given these self-selection criteria, it is likely that the students who were engaged in this study were representative of all but the weakest students in these year levels.

The distribution of subjects interviewed comprised: 13 students from Year 8, 18 from Year 9 and 17 from Year 10. Each student had studied at least one chemistry unit per year through Years 8-10 in the science curriculum and had encountered models of atoms and molecules during this teaching. As the interviews were conducted during
the last month of the second semester in November, students from the three grades had received one, two or three years of secondary science instruction respectively.

The Interview Protocol

The study itself used a semi-structured focused interview protocol (Appendix 3) of, on average, 20 minutes duration to probe student conceptions. In commencing each interview, the student was given a piece of aluminium foil and a block of iron and asked "what do you think these are made of?" In every interview, the student stated that the iron and the aluminium was either made of atoms or particles. When the students did not mention atoms after 4-5 probing questions, they were prompted with the term 'atom'. Next, every student was asked to think about his or her mental model of an atom and asked to draw this on a sheet of paper and describe the drawing. As most students drew or mentioned a ball or sphere, each student was given a 5 cm diameter polystyrene ball and a 5 cm diameter pom-pom (with a hard centre) and asked if either of these models shared any similarities with their diagram and description. The students were then shown the sheet containing six diagrams of "some of the ways atoms have been described" (Figure 11, diagrams 1-6). These diagrams were drawn by the author and were based on diagrams found in textbooks used in Australian schools or drawn by teachers. The free-hand quality of diagrams 4 and 5 may have appeared less attractive to some students, however, the diffuse nature of these two diagrams was intentional. Each student was asked to circle the diagram which best fitted his or her mental model of an atom and was then asked for the second and third best fit diagram (if possible) and to identify diagrams they didn't like. Often during this discussion the student introduced the terms nucleus, electron shell, electron cloud, electron movement, protons and neutrons. Each of these items was discussed at that point or, if not introduced by the student, the interviewer cued and asked each student about electron clouds and electron shells.

The discussion then moved to molecules and each student was given a space-filling and a ball-and-stick molecular model for H₂O [Figure 10(a)]. The student's preference for each of these models was explored and reasons sought for their choice. Finally, most students were asked to describe how far they thought the electron cloud extended out from the nucleus of the atom, where it started and where it finished. This estimation was based on the 5 cm diameter polystyrene ball representing the nucleus of an atom. During each interview, students either volunteered or were asked whether they thought all substances contained atoms (or not) and whether they thought scientists have actually seen atoms (or not).

Each interview was audio-taped and transcribed verbatim. The transcripts were combined with the students' drawings and formed the data corpus for analysis.
Figure 11: The set of six diagrams of atomic models shown to the students.

Analysis of Student Interviews

Initially, the student interviews were analysed and have been described in Harrison and Treagust (1994, 1995). This, and subsequent analyses of the data corpus, identified three categories under which the student responses could be analysed and the results classified. In all, each interview was read three times by the author. The first reading examined the students' conceptions of atomic shape, size and choice (as detailed in Figure 11) as well as determining their familiarity with electron shells and electron clouds. The second reading provided all of the other data tallies except for each student's Modelling Ability which, in most cases, was ascertained by a third reading of the transcripts.

First, the students' choices from the set of six diagrams in Figure 11 yielded two distinct criteria: students' preferred atomic models (subdivided into best, better and good) and models disliked by the students. Only the totals for each criterions' heading were computed and these are recorded in Table 2.

Second, student responses were organised under the 10 criteria of: Atoms, Size of Atoms, Composition of Matter, Living Atoms, Shape of Atoms, Texture of Atoms, Electron Shells, Electron Clouds, Molecular Models and Modelling Ability. These data are listed in Table 3. For two criteria (Shape of Atoms and Molecular Models)
the data totals exceed 48 because some students chose both models. For other criteria, the student's lack of knowledge, time shortage or the interview's direction meant that a particular question was not answered or was not asked. In these instances there are tallies for "Not asked, no response."

The assignment of each student as a level 1, 2 or 3 modeller needs explaining. Grosslight et al. (1993) formulated their three levels from interviews where students explicitly discussed their conception of models and they scored students as levels 1, 1/2, 2, 2/3 and 3. In this study, students who were not clear modellers at the higher level were scored at the lower level rather than deciding upon any mixed level scores (i.e., no levels 1/2 or 2/3). The interviews in this study focussed on atoms and molecules and the conclusions about students' modelling abilities were derived from students' comments about the various models rather than on modelling per se. Students often sought cues and endeavoured to provide responses they thought would please their teacher or the interviewer. It was felt that this less direct approach may possess high validity as it avoids asking interviewees direct questions about models.

Third, students' models of the size of the atom's electron cloud were analysed and evaluated. Students were shown a 5 cm diameter polystyrene ball and asked, "if the atom's nucleus was as large as this ball, at what distance from the nucleus do you think the electron cloud starts? ... stops?" Variability in the individual distance ranges defied simple classification. Each student's distance range was entered as a bar on the graph shown in Figure 12. A logarithmic vertical scale was needed to accommodate the breadth of student estimates and the individual estimates were ranked by size.

**Mental Models Held by Secondary School Chemistry Students**

**Sylvia**

Well an atom is made up of protons and neutrons and electrons and has a nucleus and has an electron cloud around it which has a certain amount of electrons depending on what sort of atom it is, um, the nucleus contains the protons and the neutrons and around it are the electrons and each of the different ones are positive and negative or neutral.  

[Year 10 student]

**Int.** 

Do you have any ideas about the shape of an atom?

**Jill**

Are they round, aren't they sort of rounded and they're really, really small and they are generally in groups, they are sort of joined together in groups .... a very, very small ball.

...Um, well, aren't atoms sort of soft on the outside and they've got a hard centre and so it'd be more like [the pompom model] but they're ... round and they're only hard in the middle, aren't they? I think.

**Int.** 

Can you draw an atom for me? Tell me what you're doing.
Jill: ... [drawing] ... ... Well that's the outside, and that's the middle, like the outside's the electron cloud, that's right, and the middle's like the centre and it's harder than the outside and it's got two other things in it ... some other things and they've got things inside of it.

Int.: You said that centre is hard?

Jill: Well not hard, but harder than the outside, the outsides are really soft.

[Year 8 student]

Students' Preferred Models of Atoms

The distribution of student responses to the six diagrams representing atoms in Figure 11 is given in Table 2. Each student preferred at least one diagram and some chose two or three diagrams as being acceptable and all found at least one diagram they disliked. Some students rejected two or more diagrams.

Table 2
Frequency of student preferences for the analogical models presented in Figure 11 (n=48)

<table>
<thead>
<tr>
<th>Classification</th>
<th>Best</th>
<th>Better</th>
<th>Good</th>
<th>Dislike</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Solar system model</td>
<td>5</td>
<td>12</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>2. Orbits model</td>
<td>22</td>
<td>9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3. Multiple orbits model</td>
<td>7</td>
<td>11</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>4. Orbitals model</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>5. Electron cloud model</td>
<td>8</td>
<td>7</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>6. Ball model</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Totals</td>
<td>48</td>
<td>43</td>
<td>18</td>
<td>48</td>
</tr>
</tbody>
</table>

Thirty-one students chose the orbits model (number 2, Figure 11) as their first or second choice. This diagram probably best represents the popular conception of an atom as used on television and in the print media. Twenty-four students rejected the orbitals model (number 4, Figure 11) compared to five who approved of it at any level; being Year 8-10 students, the orbitals model was most likely unacceptable due to its unfamiliarity. The number of students who disliked the electron cloud model (number 5, Figure 11) equalled the number who awarded this model their 'best' choice. It was notable that twice as many students approved of this model as rejected
it (16 = best + better + good, 8 = dislike). Overall, approximately the same number of students chose the solar system model as chose the electron cloud model (21 to 16 respectively). However, more than twice as many students disliked the electron cloud model than disliked the solar system model! Students who are less initiated into scientific representations may favour distinct, concrete models because such models resemble their everyday world objects. In other words, students visualise science concepts as possessing matter rather than process attributes (Chi et al., 1994). The solar system and the orbits model showed each subatomic particle as a separate entity and gave the electron paths a material flavour by drawing them as complete circles or ellipses. On the other hand, the electron cloud model was more diffuse and thus was less material from the students' viewpoint. The level of student approval for the electron cloud model in the interviews may have been artificially high. Some students may have chosen this representation because of the emphasis that teachers gave to electron clouds. Support for this notion is drawn from the observation that 50% (24/48) of all students and nearly 60% (24/41) of those who responded had heard of electron clouds (see Table 3).

Students' Descriptions of Their Mental Models of Atoms

The data collected from the students during the interviews produced some predictable and some unexpected responses. The notable unexpected responses were the assertion by a majority of the respondents that atoms are visible under a powerful microscope and the smaller, but significant, number of students who believed that atoms were alive and could reproduce. Each of the ten categories listed in Table 3 is discussed below.

Atoms

Atoms were not introduced by all the students at the start of the interview when the first question, "What do you think the aluminium foil and the iron block are made of?", was asked. However, when cued, each of these students stated that he/she was familiar with the concept 'atom'. While almost one third of the students needed to be cued, 12 of the 15 students in this group were from Year 8 and only one Year 9 and two Year 10 students needed a reminder. It is suggested that the Year 8 students' limited experience with atoms accounts for this observation.
<table>
<thead>
<tr>
<th>Criterion</th>
<th>Attribute</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms</td>
<td>Student volunteered the term atom</td>
<td>33</td>
<td>69%</td>
</tr>
<tr>
<td></td>
<td>Student was cued with the term atom</td>
<td>15</td>
<td>31%</td>
</tr>
<tr>
<td>Size of Atoms</td>
<td>Atoms are visible under a microscope</td>
<td>24</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Atoms too small to see</td>
<td>15</td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td>Not asked, no response</td>
<td>9</td>
<td>19%</td>
</tr>
<tr>
<td>Composition of Matter</td>
<td>All substances contain atoms</td>
<td>34</td>
<td>71%</td>
</tr>
<tr>
<td></td>
<td>Some substances made of other objects</td>
<td>7</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Not asked, no response</td>
<td>7</td>
<td>15%</td>
</tr>
<tr>
<td>Living Atoms</td>
<td>Atoms are inanimate</td>
<td>38</td>
<td>79%</td>
</tr>
<tr>
<td></td>
<td>Atoms are alive, grow and divide</td>
<td>10</td>
<td>21%</td>
</tr>
<tr>
<td>Shape of Atoms</td>
<td>Atoms are balls or spheres</td>
<td>29</td>
<td>55%</td>
</tr>
<tr>
<td></td>
<td>Simple diagram with nucleus and electrons</td>
<td>17</td>
<td>32%</td>
</tr>
<tr>
<td></td>
<td>Simple circle in a circle</td>
<td>7</td>
<td>13%</td>
</tr>
<tr>
<td>Texture of Atoms</td>
<td>Atoms most like a hard polystyrene sphere</td>
<td>26</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>Atoms like a pompom with hard centre</td>
<td>18</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>Not asked, no response</td>
<td>4</td>
<td>8%</td>
</tr>
<tr>
<td>Electron Shells</td>
<td>Aware of electron shells</td>
<td>13</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>Not aware of electron shells</td>
<td>29</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>Not asked, no response</td>
<td>6</td>
<td>13%</td>
</tr>
<tr>
<td>Electron Clouds</td>
<td>Aware of electron clouds</td>
<td>24</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Not aware of electron clouds</td>
<td>17</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>Not asked, no response</td>
<td>7</td>
<td>15%</td>
</tr>
<tr>
<td>Molecular Models</td>
<td>Prefer space-filling models</td>
<td>41</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>Prefer ball-and-stick models</td>
<td>13</td>
<td>24%</td>
</tr>
<tr>
<td>Modelling Ability</td>
<td>Level 1 modeller</td>
<td>28</td>
<td>58%</td>
</tr>
<tr>
<td></td>
<td>Level 2 modeller</td>
<td>20</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td>Level 3 modeller</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>
Size of Atoms

This criterion produced an unexpected finding. Although most students thought that atoms are like "a very, very small ball, incredibly small" [Jenny, Year 10], many believed that atoms could be seen using a powerful microscope. Of the 39 students who commented on this item, 62% believed that scientists could see or have seen atoms. Lee et al. (1993) found that Grade-6 students held similar unorthodox conceptions of the size of molecules. Even after the treatment group had been taught using revised instructional materials that addressed this alternative conception, students "still believed that they could see molecules with microscopes or 'magnifying lenses'" (p. 257).

If students think that scientists have seen atoms, then their attitude towards the diagrams generated by experts, the diagrams they see in textbooks, or in the classroom and on television, etc., is such that they may well view these diagrams as 'the real thing.' But there is an inherent problem for students with this perception: the diagrams are many and varied as indicated by Figure 11. If they believe that scientists have seen atoms, then which diagram (if any) is the real thing? It is worth noting that not every student expressed a second preference when examining Figure 11 (89% did) and only 38% made a third choice (only one student rated all six diagrams). Put another way, five students chose a single model and 30 chose two models (and 12 of these students chose diagrams 2 and 3 which are quite similar).

Whenever any of these models are used during instruction, it appears essential that teachers explain that each diagram is only an analogical model and that scientists have not seen individual atoms. Students need guidance to help them understand that each model contains some valid features along with many invalid features and, therefore, the unshared attributes should be identified for the students by the teacher.

Composition of Matter

The replies to the question, "Are all substances made up of atoms?", showed that 83% of the students who responded to this question acknowledged that all matter is composed of atoms. Five of the seven students who stated that materials were made of objects other than atoms asserted elsewhere in the interview that atoms are alive or are like cells. It is likely that the other objects which also make up matter in their cases were cells. Three of these seven students made unambiguous comments indicating that non-living things are composed of atoms but living things are made of plant and animal cells. This confusion is directly linked to the next criterion.
Living Atoms

This assertion was made by 10 (21%) of the 48 students interviewed. These students described atoms as "living", or "like cells", as behaving purposefully, and in two cases, able to reproduce! Nell, a Year 9 student, made this comment:

Int. What's this centre thing [diagram 2]?
Nell Nucleus.
Int. What are these little things around here [pointing to electrons]?
Nell They sort of like, um, shield ... for the nucleus.
Int. What do you understand by a shield?
Nell Like protects it, and it like helps it like, so once it is coming into two, break up, it's got something to shield them both.
Int. What breaks into two?
Nell The nucleus
Int. Why would it break into two?
Nell Oh, I dunno, like helps it to grow, in there ...
Int. So these can grow?
Nell Yea, like, not make the metal bigger or something, just like they break up so there's more of them.
Int. And what do these little ones do when they've broken up?
Nell They grow and they break into more.

Other students appeared to have confused the nucleus of the atom with the nucleus of a cell and one Year 8 student, Bob, actually drew a cell for an atom:

Int. Do you have a picture in your mind of what an atom might look like?
Bob ... [drawing] ... I always had the idea that an atom was like a cell of some sort, but we never really, we worked on it for about a week in class, and [it is] made up of extremely small cells ... Ah, ecto ... plasm ... I think it is and a cell membrane ... around this ... and everything is made up of billions of tiny atoms.

Later, Bob asserted that for an atom you could "compress it, stretch it, and you can always put it back to its original shape." But that wasn't all, on two further occasions, he returned to his atom/cell conception when discussing the six diagrams (Figure 11). The majority of Bob's transcript indicated that he was talking about
atoms but had integrated cell ideas into his mental model of atoms. Shelley, from the same Year 8 class, made very similar comments:

Int What do you think an atom looks like?

Shelley Well, you see them under a microscope, so I suppose it'd look like cells or something ...

Shelley [later] to split it easier, that's all, about splitting atoms.

Another student called the atom's nucleus its control centre, saying that the nucleus controlled the atom's activities. It is probably significant that all but two of the students who exhibited this alternative conception were taught the chemistry unit by a specialist biology teacher. A student from another school, however, also used this living or cell-like idea even though he was taught by a physical science specialist. It appears that teachers need to be vigilant in differentiating between the nucleus of a cell and its functions and the nucleus of an atom.

This biological influence also was evident when discussing electron shells. Where students indicated some familiarity with the electron shell idea, they were asked "what do you think of when we mention the term shell"? All the students who responded to this question saw a shell as acting as a form of protection and where examples were used, they were snail shells, beach shells, clam shells and egg shells. A typical response was from Kylie in Year 9:

Kylie That's the, ... right out there is the shell, and then ... that's [indicating] the nucleus.

Int Shell of what?

Kylie The shell of the atom.

Int What do you think the shell, when I say shell, what do you think of?

Kylie Apart from an egg shell, something, er, like a hard coating around the outside.

It thus seems inappropriate to use the 'electron shell' metaphor without explicitly defining the intended meaning, namely that of a level or position. The students interviewed were drawn from 11 different classes in three schools and although 27% of the students stated that they were familiar with the notion of electron shells, not one student used the idea in the intended chemical sense.

Shape of Atoms

Student drawings, and comments made during the interview, provided these data; the total exceeds 48 because several students chose two models. Students were deemed to hold a ball-like mental image if they drew a simple circle or described an atom as a
ball, a sphere or said that the atom was round and solid. It is intriguing that 55% of these students expressed the opinion that an atom was like a ball or sphere yet chose spatial diagrams from Figure 11 and showed little preference for the ball model depicted in diagram number 6. This uncritical acceptance of contrasting models suggests that understanding in this domain is quite superficial.

Texture of Atoms

Andersson's (1990) review and Lee et al.'s (1993) study showed that students believe that the properties of atoms and molecules resemble the substance's macroscopic properties. For example, Andersson found that students believed that particles were coloured and this same belief also was found in this student sample. Students told Lee et al. that water "molecules are frozen in ice, because they are solid together" (p. 261). To ascertain whether this also applied to texture, students in this study examined the hard polystyrene ball and the soft pompom with a hard centre which they were shown as models of atoms. Of the 44 students who expressed a preference, 54% believed atoms were hard and 38% believed they would be soft. One student chose both stating that the polystyrene ball represented the hard nucleus while the fluffy pompom represented the electrons [Natalie, Year 8]. Several students believed that the polystyrene ball was too regular for an atom, that the slightly irregular surface of the pompom better represented their image of the electrons surrounding the nucleus. Even though they preferred the polystyrene ball, two students stated that the balls represented atoms in different phases. Melissa from Year 9, reasoned this way:

Int. Do you think atoms are hard or soft?

Melissa ... they could be either.

Int. Sometimes hard, sometimes soft?

Melissa Yep ... it depends on what it's making really, whether it's a metal or a liquid.

Int. So we talked about a metal, what would you say?

Melissa Probably be hard.

Int. A liquid?

Melissa Probably be softer ...

Electron Shells

Slightly more than a quarter of the students (13) admitted familiarity with electron shells. When asked, "When I mention 'shell,' what do you think of?", most responded with a comment about sea-shells, clam-shells and egg-shells. These students held a consistent image in which they believed that atoms are protected by an outer shell. Similarly, Fensham and Kass (1988) report that some students think that
the "heavy line around" spheres used to represent atoms and ions in crystals "was 'a thick skin of the particular element (like aluminium foil'" (p. 7). Chi et al.'s (1994) ontological theory posits that when a student assigns a phenomenon such as an atom to a Matter 'tree', material features like volume and mass are attributed to it. For this characteristic, many students perceived atoms as concrete particles with discrete parts. It is not surprising, therefore, that they visualise electron shells in such a realistic way.

**Electron Clouds**

A number of the students spontaneously mentioned electron clouds during the interviews. Twenty-four students (50%) indicated some degree of familiarity with electron clouds while 17 students (35%) said that they were unfamiliar with this metaphor. Seven students were not asked or did not respond.

For example, James, who was in Year 10, introduced electron clouds early in the interview:

James  ... and around the nucleus is a thing called an electron cloud, and each electron spins around the nucleus and this makes the atom work, and the electrons are positively... no negatively charged and the neutrons are neutral ... and the protons are positively charged.

Int.  You called that an electron cloud. Why do you use that term?

James  Because um, ... it has no like solid structure, it's usually shaped ... it can be in all different types of shapes ... it's not solid.

Int.  What makes it into a cloud?

James  The electrons.

James, and a number of other students, described electron clouds in a manner that is appropriate for Years 8-10. However, a significant alternative conception was encountered in which other students described an electron shell as a matrix in which the electrons were embedded. Each student who demonstrated some familiarity with the electron cloud metaphor was asked, "When I say cloud, what do you think of?" Most replied, "clouds in the sky" and two students spoke of clouds of dust or clouds of smoke particles. When the 'clouds in the sky' idea was pursued, several students added that the electron cloud was like a cloud in the sky and the electrons were like the droplets of water in the cloud. Further discussion indicated that these students saw the cloud as a separate entity containing the electrons. This notion is similar to the conceptual category described by Renstrom et al. (1990) in which students visualise matter (say copper) as consisting of atoms embedded in a matrix of that substance (copper). For instance, Carol, in Year 9, said:
Int. Have you heard of the term an electron cloud?
Carol Yep, it's the stuff all the electrons are in I think.
Int. What's this stuff?
Carol It's er, I think it's a kind of substance ... holding them together or something.
Int. Can you see a cloud out there?
Carol Yep, lots of them.
Int. Ok, is that like what's being referred to when we say electron cloud?
Carol No, I don't think so, I think it's a cloud, tends to be more used to say that they're, the electrons, are all held together, like that's what they all are in.

Based on these data, as with the shell metaphor, the electron cloud metaphor (or analogy) needs to be explicitly defined before it is used with or by students. These metaphoric terms have many everyday meanings and it is therefore recommended that teachers qualify the sense in which they are transferring attributes from the analog to the atom. Gilbert, et al. (1982) and Sutton (1992, 1993) have shown that semantic differences between the students' and the teacher's meanings for commonly used terms in science are a source of alternative conceptions.

Molecular Models

Following the discussion of atomic structure, students were shown a space-filling (A) and a ball-and-stick (B) molecular model for water and asked to select the model they felt better represented a molecule of water (Figure 10). This choice was simpler than in Figure 11 and there was a strong preference for the space-filling molecular model. Forty-one students (76%) preferred the space-filling model while only 13 students (26%) favoured the ball-and-stick model. This total also exceeds 48 because several students expressed equal preference for both models.

Where students stated a reason for their choice it was almost always of the form used by Steve from Year 9:

Int. Which of these two models is the better for you - A [space-filling] or B [ball-and-stick]?
Steve A [why?] because they don't have spaces between them, they're all joined together.

Neil, from Year 10, put it this way

Neil That one, A [why?] well when they're a molecule, they're joined together, they share the electrons so that, to me, B, is not really joined together, it's more separated in B, these ones are separated and doesn't look together.
Int. The sticks represent bonds ...?

Neil It's not as convincing ... A's more convincing than B.

The strength of the student views suggests that the teaching approach of drawing structural diagrams of molecules on the blackboard is not satisfactory for students of this age. Of the 13 students who preferred the ball-and-stick models, not one student gave a convincing explanation of the model or strongly defended that representation. In contrast, more than 25% of the other group of students spoke strongly in favour of the space-filling model.

**Modelling Ability**

When the transcripts were reviewed to classify students into Grosslight et al.'s. (1993) modelling levels, a number of students were found to be transitional between levels. This was particularly evident when deciding between Levels 1 and 2. The results indicate that 28 students were Level 1 modellers and 20 were wholly or mostly Level 2. Even though one student was a mixed Level 2/3, this student was classified as a Level 2 modeller. When the descriptors of Grosslight et al.'s. classification are recalled, many of the difficulties that students had with atomic and molecular models become more understandable.

The majority of the 48 students were at or retained vestiges of Level 1. At this level students believe that there is a strong correlation between the model's structure and reality (in this case the atom). That 20 students (42%) were at or close to level 2 is encouraging. This demonstrates that a significant proportion of these students were beginning to differentiate between the model and reality. This intellectual growth should be accompanied by an increasing ability to recognise that overtly different models merely represent different aspects of the same phenomenon. If developed, this potential should allow these students to develop more scientifically acceptable mental models of scientific phenomena. The recommendation that teachers teach modelling skills should be extended to say that modelling instruction should be maintained throughout the science curriculum.

**Student's Mental Models of the Size of an Electron Cloud**

Forty-two students expressed an opinion about the relative size of an atom's electron cloud. Remembering that these distances were relative to a nucleus which was 5 cm in diameter, 33 students thought that the electrons commenced around 2-10 mm from the nucleus through to an outer limit of about 50 cm. For a hydrogen atom, the ratio of nuclear diameter to atomic diameter is approximately 1:10⁵. For a nucleus 5 cm in diameter, the electrons should start at about 5000 m. Only one student provided a realistic estimate; he said that the electrons would start "several kilometres away" and
would extend "to about three times that distance." Two more students described the electron cloud as sufficiently large but erred by stating that the electrons almost touched the nucleus. Three other students believed that the electrons touched the nucleus.

![Diagram showing student estimates of electron cloud size with logarithmic scale.](image)

*Figure 12: Distribution of student estimates of the size of an electron cloud. Vertical scale is logarithmic.*

The tight, compact atom described by most of these responses correlates well with the 29 students who asserted that the atom was 'like a ball'. Harrison and Treagust (1995) found that Year 11 chemistry students consistently drew atoms with large nuclei and close electron orbits. Even though the competent Year 11 students stated that the atom was mostly space, they did not convey this image in their diagrams.
Both data sets (Year 8-10 and Year 11) indicate that the majority of students have an image of an atom that does not take into account spatial dimensions. It must be pointed out that these findings are not surprising and are consistent with textbook models that do not show the proper scale.

**Concurrent Student Mental Models**

It was interesting to find that students do not always reveal what they really think in tests and examinations. Consider the comment from Carol, a Year 9 student:

**Int.** Why do you like diagram 1 [planetary model]?

**Carol** Cause, I see it on the, when the teacher represents atoms, you know, the electron configuration kind of thing, that's the usual way she pictures it, so that's the main kind of image that comes into my mind. If we've got a test or something, that's the easiest way for me to remember what it's like.

**Int.** You also said you liked diagram number 5 [hazy electron cloud model]. Why?

**Carol** Well, um, I think it's like the electrons would be in an atom. It wouldn't be that easy to remember it for a test or anything, but that's what I think that's what they would be like.

**Int.** Are you telling me that 1 is the best and then 5 is better, it sounds like, correct me if I'm wrong, it sounds like you're saying 5's more real but it's not good for tests?

**Carol** Yes. ... That's cause, um, I don't think electrons would be so like that [diagram 1], not totally ... [symmetrical?] yea. Yea, ... I couldn't think of the word [that's a reasonable word?] yea ... and this one's [5] a bit more random, yea cause I know that you, they're supposed to be um, have different spaces or something for each electron, like there's a nucleus and it [the electron] goes like that and comes out and the next one, um, but I still think that it'll still be more like that [diagram 5?] yea.

Carol's response could signal the beginning of a tolerance for multiple models; then again, it may simply be her way of reconciling disparate concepts. Indeed, it is well recognised that students are adept at tolerating the teacher's concept for the duration of the instruction while conserving their personal conceptions (Posner et al., 1982; Scott, 1992).

**Interpretations and Recommendations**

**Sources of Student's Alternative Conceptions**

Recent research into student conceptual frameworks has suggested an alternate source for student conceptions. Strike and Posner (1992) and Vosniadou (1994) propose that many alternative conceptions are actually generated during learning in the classroom as a product of the interaction between the students' preconceptions and
teacher-initiated instruction. Rather than students bringing well formulated theories to instruction, Strike and Posner assert that instead, students possess simple explanations or models of natural phenomena. While students' initial conceptions may not be well formulated and articulated, these models and simple explanations are nevertheless related to the students' conceptual ecology from which they emerged. Vosniadou (1994) calls these principles that organise student knowledge "naive framework theories" (p. 47) and asserts that these principles are grounded in ontological and epistemological presuppositions.

Thus, when rudimentary student ideas interact with teacher demonstrations, scientific language, laws and theories and the students' own experiences, students will try to reconcile their mental models (often referred to as conceptions or mental models by many authors) and ideas with the accepted scientific concepts. The outcome of this reconciliation can result in the science concept being distorted into an alternative conception. Hewson (1981, 1982) reasoned that when a student's prior conception is challenged by a scientific conception, and both conceptions achieve status of intelligibility and plausibility, the student will attempt to reconcile the competing conceptions. Hewson called this conceptual capture. Now if the competing conceptions are in fact incompatible, and the student fails to recognise this, then an alternative conception will result. With respect to mental models, Vosniadou puts it this way: "These various mental models ... can be explained as attempts on the part of the children to reconcile aspects of the model to which they are exposed through instruction with their initial model" (1994, pp. 62-3). Vosniadou calls these student constructions "synthetic models" (p. 53).

**Student Mental Models of Electron 'Clouds' and 'Shells'**

The generation of alternative conceptions during instruction may be what happened during the student interviews about atoms and molecules. The students may not have possessed clearly formulated nor well articulated mental models of electron shells and electron clouds. They would, however, already have mental models of shells and clouds and many would have heard this 'scientific' language used in teacher discourse. A simple reconciliation of the students' everyday image of a cloud with scientific concepts of atoms could have generated the 'water droplets in a cloud is like electrons in an electron cloud' analogy. A similar mechanism could account for the assignment of shells to atoms as protective devices, or on this occasion, the analogy being to snail and egg shells. If the alternative conceptions of 'clouds' and 'shells' were constructs of the interview, it demonstrates that students can generate alternative conceptions *in situ* from a technical discourse and if this can happen in an interview, it could happen in a classroom. Vosniadou (1994) and Renstrom et al. (1990) have
demonstrated that the set of categories of alternative conceptions in a domain is reasonably stable and that this was superficially evident in the interviews.

Models, Metacognition and the Nature of Science

The diversity of available atomic and molecular models provides an ideal context for metacognitive thought and discourse about the nature of science itself. Development of modelling and the systematic use of analogical models in chemistry may in the long-term generate a more sophisticated understanding of science. These possibilities are not limited to chemistry. Multiple models also are used to explain concepts in anatomy and physiology, light, electricity, genetics and geology, for example. Multiple models and analogies also have the capacity to ontologically redirect science learning away from a preoccupation with matter-centred explanations towards process-driven explanations (Chi et al., 1994). Some might say that all this does is intellectualise and marginalise science, but there is also a powerful case for saying that modelling, analogising and becoming process-driven makes science much more relevant to and more like everyday life.

Pre-Year 11 Students' Mental Models of Atoms and Molecules

Research Question 1, on which this study was based, asked: "With which models of atoms and molecules are Western Australian pre-Year 11 chemistry students familiar; and what is the relative status of these models for these students?" This investigation of the conceptions of atoms and molecules held by 48 Year 8-10 students provided ample evidence of the variety of scientific and alternative conceptions (see Table 3). Likewise, the range of Year 8-10 student ideas of what an atom looks like is presented in Table 2 and further details are found in the quotations and in-text comments. This study has demonstrated the scope of Year 8-10 students' scientific and alternative conceptions; however, apart from individual comments cited in the text, the study has said little about the status of individual student's conceptions. This will have to wait for Chapter 5. It seems reasonable therefore, to assume that many of these models of atoms, and some of the alternative conceptions, will be held by pre-Year 11 chemistry students.

Research Question 1 contained a number of subsidiary items and these will be considered in light of the outcomes reported in this chapter. The first subsidiary question asked, "What does an atom look like?" As mentioned in the previous paragraph, the range of student images of what an atom does and doesn't look like are summarised in Table 2. Most of the Year 8-10 students preferred a planetary-orbits image for their mental model of an atom; and the orbits-planetary model was more popular that the electron clouds model.
The second subsidiary question asked, "Do pre-Year 11 students use single or multiple models to describe atoms?" Interestingly, 43 of the 48 student chose a second best and 18 chose a third best model. These results are inflated because diagrams 1, 2 and 3 were quite similar (planetary, simple orbits and complex orbits models respectively). All the same, these data suggest that many pre-Year 11 students are familiar with a range of atomic models.

The third subsidiary question, "From the student's viewpoint, are these models real or representative?" was not answerable from the data collected in this investigation, this question will be answered in Chapter 5. The fourth and fifth subsidiary questions then asked, "What conceptions do pre-Year 11 students have of electrons, electron shells and electron clouds? and "Is an atom compact or spacious?" Nearly all the students were aware of electrons, but very few commented on electron arrangement and function. Just over half of the students were aware of electron clouds and just over a quarter had heard of electron shells. The plots in Figure 12 show that most pre-Year 11 students believe that the electrons are very close to the nucleus and this implies that they think that the atom is compact rather than spacious. It is concluded that Year 8-10 students have a limited knowledge of electrons, electron shells and electron clouds.

Subsidiary question six asked, "Do the properties of atoms and molecules resemble the material properties of the parent substance?" This reported alternative conception was evidenced by the students who suggested that liquid atoms are soft, solid atoms are hard, and atoms are the same colour as the parent substance. The final subsidiary question asked, "What idiosyncratic views do pre-Year 11 students have of atoms and molecules?" A significant group of students (20%) believed that as atoms have a nucleus, they are alive and can reproduce. The most widespread alternative conception (50%) was the assertion that atoms can and have been observed under a microscope. This has important implications for how students interpret the atomic diagrams provided in textbooks; it is likely that they will think that these are actual pictures of atoms!

**Conclusion**

This descriptive study of Year 8-10 students' mental models of atoms and molecules demonstrated that most students of this age prefer models of atoms and molecules that depict these entities as discrete, concrete structures. This conclusion was derived from observations that students' preferred an orbits model of the atom (similar to the solar system model), viewed electron shells and electron clouds as complete or semi-solid structures, and preferred space-filling molecular models. Indeed, many of the students interviewed appeared to believe that there was a significant correlation
between their mental image of an atom and reality. These outcomes should not be surprising given that many students of this age lack both experience with scientific modelling and the requisite intellectual maturity to successfully interpret multiple models.

This study also has illustrated the negative outcomes that arise when students are left to draw their own conclusions about analogical models. An implication from the study is the need for teachers to discuss with students their conceptions of scientific models, metaphors and analogies. These can be direct, content-specific discussions, or they can be metacognitive reflections on the nature of science itself. Listening to students can enhance science teaching if teachers take the time to carefully consider the mental models that the students either bring to instruction or construct during instruction. It also is recommended that science curricula include explicit instruction in scientific modelling and that analogies, metaphors and analogical models be presented in a systematic manner.

The common and idiosyncratic alternative student conceptions of atoms and molecules reported in this chapter provide a useful base-line for the model-based instruction described in Chapter 5. Chapter 5 investigates the effect of the systematic use of multiple metaphors, analogies and models on student understanding of atoms, molecules and chemical bonding. Therefore, the longitudinal case studies reported in Chapter 5 concentrate on answering Research Question 2, namely, "Do systematically presented metaphors and analogical models, and multiple models, contribute to conceptual change in learning about atoms, molecules and chemical bonds?"
CHAPTER 5
Evolving Conceptions of Atoms, Molecules and Bonds

Introduction

Chapter 4 described and discussed the variety of alternative conceptions of atoms and molecules that students may acquire during lower school science instruction (Years 8-10). It is therefore reasonable to assume that many pre-Year 11 chemistry students will hold synthetic mental models (Vosniadou, 1994) of atomic phenomena because their models combine varying degrees of scientific and alternative conceptions. This chapter describes the degree of conceptual restructuring of atomic phenomena that occurred when a Year 11 Chemistry teacher purposed to enhance his students' thinking and modelling skills by using metaphors, analogies and models in a systematic way. This aspect of the classroom research addresses Research Question 2 which asked, "Do systematically presented metaphors and analogical models, and multiple models, contribute to conceptual change in learning about atoms, molecules and chemical bonds?" In other words, the instructional aim was to conceptually exchange the students' synthetic mental models for more scientifically amenable conceptions.

The classroom research also sought answers to Research Question 3 which asked, "Do the various theoretical perspectives on conceptual change learning complement each other?" This was a higher-level question than Research Question 2 because it delved into the reasons for students capturing or exchanging conceptions during learning. By necessity, this question analysed three aspects of the students' knowledge: content knowledge including the metaphors, analogies and models used in their verbal and written explanations, modelling ability (Grosslight, et al., 1991) and intellectual position (Perry, 1970).

Chapter 5 is therefore divided into eight sub-chapters. The first of these, Chapter 5a, delineates the material and intellectual environment with particular reference to syllabus content and pedagogy; next, Chapters 5b-g contain six case studies detailing the discernible changes to each student's conceptual status, modelling level and intellectual position; and finally, Chapter 5h presents an overall analysis of the changes in each student's attitudes, thinking and knowledge. Included in Chapter 5h is a comprehensive table summarising the conceptual changes described in the six case studies. Wherever possible, each student's conceptions are discussed from as many theoretical perspectives on conceptual change as are appropriate to the individual case studies.
Chapter 5a

Context: The Year 11 Chemistry Class

Background and Contextual Factors

The study reported in this chapter was conducted in a Year 11 Chemistry class at a new independent secondary school situated in Perth, Western Australia. Year 11 courses comprise two semesters spread over four 10 week terms and, based on five 40 minute periods per week, contain approximately 120 hours of chemistry instruction. This class commenced with 12 students of varying ability - eight boys and four girls. Two students changed subjects during Term 2 leaving 10 students, seven boys and three girls.

The class was taught by the researcher/author who is an experienced chemistry teacher. The author also taught five of the boys in his physics class. Information was collected continuously over two semesters to provide a data base for the construction of a set of longitudinal case studies (Merriam, 1989; Patton, 1990). The accumulated information consisted of audiotaped and videotaped records of selected classes, all student pretests, tests, examinations and essays. An independent interview was conducted with each student a week before the Semester 2 Examination. Researcher notes and anecdotal comments also were collected throughout the year. All the information was combined to construct a chronological portfolio for each student. Analysis of the portfolios generated the data that are reported in each case study and the cases were interpreted in light of conceptual change theories to determine the degree of conceptual restructuring that occurred during the year (Carey, 1986, 1991; Chi et al., 1994; Duschl & Gitomer, 1991; Hewson, 1981, 1982; Hewson & Hewson, 1983, 1992; Hewson & Thorley, 1989; Posner et al., 1982; Strike and Posner, 1992; Thagard, 1992a; Vosniadou, 1994).

Additionally, each student’s modelling capability was assessed (Grosslight et al., 1991) and each student’s Intellectual Position (Perry, 1970) was estimated. All three assessments were combined to provide an overview of each student’s conceptual, modelling and intellectual development during the course of study. These conclusions provided the springboard for the meta-analysis of each student’s learning contained in the discussion at the end of each case study.

The Year 11 Chemistry Course

Most Western Australian chemistry students have studied three or four chemistry units during Years 8-10. While the Year 11 Chemistry course is a self-contained syllabus, it is for most students, the prerequisite for Year 12 Chemistry which culminates in a public, three-hour tertiary entrance examination. Chemistry is the most popular
physical science in Years 11 and 12 because it is regarded as a 'real' science without being too challenging. Chemistry tends to attract a reasonable number of girls, but boys often outnumber girls (Malone, de Laeter & Dekkers, 1993). The local chemistry course contains highly predictable quantitative and descriptive components. Many students master this component and believe that this improves their chances of achieving a high tertiary entrance score. Only a small proportion of students study pure chemistry at university; nevertheless, a significant fraction of each year's cohort take chemistry service units at tertiary level.

The Western Australian Chemistry Syllabus has a strong technical bent. As suggested, many students succeed using an algorithmic approach and many students successfully complete this chemistry course by memorising facts, formulae and equations. Still, most students find Chemistry 11 challenging and there are ample opportunities for students to conceptualise high-level chemical principles. The course program for the students described in these case studies is summarised in Appendix 4. A complete Year 11 syllabus is provided in Appendix 5. The Semester 1 course specifically set out to interest students in chemistry by exposing them to a wide range of chemical reactions and phenomena without delving too deeply into explanatory models. This approach is recommended by Fensham (1994). The applied curriculum contained a large practical component emphasising experimental chemistry.

Semester 1 commenced with the classification of matter, followed by units on the building blocks of matter, mole concept, chemical reactions, the gas laws, states of matter, kinetic theory and reaction rates. Admittedly, the kinetic theory unit depends on conceptual models; however, the units that explicitly employ atomic theory (e.g., bonding and organic chemistry) were programmed for Semester 2. That the particulate nature of matter was discussed during the opening three units will be evident from the comments made by the six students when answering the various questions put to them.

Year 11 Program and Sequence of Events

An overview of the teaching sequence which locates the analogical and modelling instruction and the data collection points is provided in Table 4. Only those events that are accessed in the case studies, or whose timing was important for understanding the interpretations, are included in this table. A copy of each pretest and relevant assessment instruments mentioned in the case studies is reproduced in the relevant appendix (as listed in Table 4).
Table 4

Year 11 Chemistry teaching sequence showing the relationship of analogical and modelling instruction to the course content and data collection points.

<table>
<thead>
<tr>
<th>Date</th>
<th>Teaching or learning activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 February</td>
<td>Pre-instruction diagram of an atom - selections from Figure 13, &quot;Some of the ways atoms have been described&quot;</td>
</tr>
<tr>
<td>25/28 February</td>
<td>Analogical models: Electron shells/clouds</td>
</tr>
<tr>
<td>4 March</td>
<td>Structure of matter test (Appendix 6)</td>
</tr>
<tr>
<td>29/30 March</td>
<td>Multiple models of atoms: Dalton, Thompson, Rutherford, Bohr (Appendix 7)</td>
</tr>
<tr>
<td>14 April</td>
<td>Term 1 examination</td>
</tr>
<tr>
<td>13 May</td>
<td>Kinetic theory pretest (Appendix 8)</td>
</tr>
<tr>
<td>17 May</td>
<td>Kinetic theory analogical models: colliding balls</td>
</tr>
<tr>
<td>30 May</td>
<td>Kinetic theory test</td>
</tr>
<tr>
<td>June 24</td>
<td>Semester 1 examination</td>
</tr>
<tr>
<td>27 July</td>
<td>Atomic structure and bonding pretest (Appendix 9)</td>
</tr>
<tr>
<td>1 August</td>
<td>Interactive discussion of atomic structure (students' address analogy)</td>
</tr>
<tr>
<td>12 August</td>
<td>Atomic structure and bonding test (Appendix 10)</td>
</tr>
<tr>
<td>12 October</td>
<td>Organic chemistry pretest (Appendix 11)</td>
</tr>
<tr>
<td>23 October</td>
<td>Organic chemistry worksheet (Appendix 12)</td>
</tr>
<tr>
<td>Oct/Nov</td>
<td>Extended experience with molecular models kits</td>
</tr>
<tr>
<td>1 November</td>
<td>Balloons and raft analogical models</td>
</tr>
<tr>
<td>11 November</td>
<td>Free-form essay</td>
</tr>
<tr>
<td>16 November</td>
<td>Interview (Interview protocol, Appendix 13)</td>
</tr>
<tr>
<td>23 November</td>
<td>Semester 2 examination</td>
</tr>
</tbody>
</table>

Metaphors, Analogies and Models Employed During Instruction

The Essential Nature of Models in Chemistry

Chemistry is an abstract science whose explanations employ metaphors, analogies and models to probably a greater degree than other sciences (Bent, 1984; Hardwicke, 1995a, 1995b). The submicroscopic nature of atoms and molecules requires that teachers provide their students with intelligible, plausible and fruitful analogical models to explain physical and chemical phenomena.
The specific purpose of this study was to gradually develop a set of atomic and molecular models which, when taught systematically (Glynn, 1991; Harrison & Treagust, 1993), would enhance the status of students' scientific conceptions of atoms and molecules while lowering the status of their pre-instructional mental models. The case studies will show that the six subjects commenced Year 11 with synthetic mental models wherein atoms were described as discrete concrete objects dominated by a substantial nucleus surrounded by close orderly electrons arranged in shells. Even though three of the students were initially familiar with electron clouds, this conceptual model was subordinate to the shells or orbits models during early descriptions and explanations. The systematic modelling instruction emphasised two strategies: the introduction and development of multiple models and the interactive discussion of each model's familiarity, plus its shared and unshared attributes.

Models such as chemical formulae and equations, ions and molecules, diagrammatic representations of solutions, colliding particles, graphs, reaction profiles, and flow diagrams permeated the instruction and practical work. It must be remembered that these models are the everyday language of chemistry and their implicit presence in each lesson is a 'given' in this thesis. Only explicit events are listed and discussed in detail. It is expected that the reader accepts that a model, once introduced, was regularly referenced in subsequent teaching and learning. Logistical and space limitations prevented the author from describing every event in which models were used.

**Systematic Use of Analogies and Models**

The differences between the students' pre-instructional synthetic models and scientists' conceptual models of atoms and molecules underlined the need to accomplish four remedial tasks during instruction. First, some students were unfamiliar with either the analog, the target or both; second they mapped certain analogies and models inappropriately and/or failed to recognise the point at which the analogy (model) broke down; third, they did not realise the need for multiple analogies (and models); and fourth, they confused the analog's (model's) representation with reality. Wherever possible, the teacher systematically presented each analogy/model in harmony with the modified TWA model (Harrison & Treagust, 1994) and the FAR Guide (Treagust et al., 1994).

The specific analogies and models that were presented in class are summarised in the following pages. Each analogical model used in class is described except for one very lengthy discourse (March 29/30) which is placed in Appendix 7. To establish the context, each analogical or modelling event is plotted on the time-line in Table 4. All students mentioned in the following accounts were class members. Six of these
students are described in the biographical sketches introducing each case study (Gina, Alex, Dan, Tim, Ken and Mary); the remaining four were Jon, Gary, Nat and Colin.

Students' Pre-instructional Diagram of an Atom 14/2/94

A simple pretest was administered in which the students were first asked to sketch an atom: "What do you think an atom would look like if you could see it?" Each student was given a copy of Figure 13 ("Some of the ways that atoms have been described") and asked to circle the diagrams they liked and to cross out the diagrams they disliked. If more than one diagram was circled or crossed out, the student was asked to rank the liked and disliked diagrams (e.g., 1 for best (worst), 2 for next best (not as bad), and so on).

Figure 13: Some of the ways atoms have been described.
During class discussion, Jon introduced the term 'electron cloud' and described it as a cloudy region within which electrons moved everywhere. This was the first time any student had introduced this idea. In reply, the fan-propeller analogy of electron motion (Bucat, 1983) explaining why an electron appears to be everywhere at once, was introduced. The fan analogy was demonstrated using the classroom ceiling fan and it was proposed that the three blades were like three electrons surrounding a nucleus (the fan's hub). The transcript sets the scene:

When the fan is stationary, you can see the three blades. This is a bit like the idea of three electrons surrounding the nucleus. When I turn the fan on, you can't see the individual electrons anymore ... they look like a semitransparent disc. [The fan was turned on at high speed] This suggests that when the electrons are moving quickly, then they blur into a disc and we think that the fan blades are everywhere at once. Can anyone see an individual blade and follow it with their eye? [No.] The electrons seem to be everywhere at once. Watch this [I was holding a crumpled paper ball], what happens if I throw the ball into the fan's disc, will it pass through? [Of three tries, the ball passed through once but was struck by a blade on the other two occasions.] This tells us that if the electrons are travelling at high speeds, and they are moving much faster than the blades of this fan, then the electrons are like, everywhere at once.

This analogy is OK to show that the electrons are like the fan blades ... everywhere at once. The fan blades are not like the electrons because the fan blades extend all the way from the hub which is like the nucleus to the outside of the circle. Each electron is an incredibly tiny particle that has almost no volume at all. Also, the electrons are moving many thousands of times faster than the fan blades. Is that alright? [Teacher]

Atoms are Mostly Space, Monday 28/2/94

Jon again referred to the arrangement of the electrons as a cloud and Gina described electron shells as containing respectively (moving out from the nucleus) 2, 8, 18, etc., electrons. The discussion then focused on whether an atom was mostly matter or space. First, Alex suggested that the atom was mostly space but reversed this opinion in subsequent discussion and (along with the others) chose the model that was mostly particles. A class vote resulted in six students choosing 'mostly full of particles' while four felt that the atom was 'mostly space.'

Mostly space = Gina, Ken, Dan, Tim
Mostly particles = Alex, Colin, Mary, Gary, Nat
Jon would not commit himself declaring "I don't have an idea."
Rutherford's experiment was briefly described (expanded later), and the Melbourne Cricket Ground (MCG) analogy was introduced (Bucat, 1983, p. 36; like Pimental, 1963, p. 88). Jon was again unconvinced and declared that he had real trouble visualising the size of the MCG even though he was an avid cricketer and had often seen the MCG during televised cricket matches. Ken remarked that he had never seen the MCG and was not interested in cricket (Ken is Vietnamese). Tim, another Vietnamese student, was happy with his impression of the MCG.

Multiple models, Tuesday 29 March

This discussion of atomic models arose during a physics lesson with the five boys who study both physics and chemistry. This, and the following discussion, are included because they are relevant to the conceptions held by four of the students who feature in the case studies (Ken, Alex, Tim and Dan). The discussion consumed all of this and part of the next lesson and pursued a range of topics including Democritus, Dalton, Lavoisier, Thompson, Rutherford and Bohr's atomic models and ideas. The students also introduced the solar system model which was discussed at length. The transcript of this and the next lesson (30 March) comprise Appendix 7.

Kinetic Theory Model, Wednesday 17 May

This class discussion centred on the notion of an ideal gas and the kinetic theory's assumptions (Garnett, 1985, p. 153). Using Nussbaum and Novick's (1982) activity, each student was asked to predict the spacing between particles in a liquid and a gas if the normal distance between solid particles was one unit. Dan, Nat and Tim gave ratios of around 1 : 10 : 1 000, Gina, 1 : 5 : 20; Alex, 1 : 2 : 100 and Ken 1 : 100 : 1 000 000. An example of ice, water and steam was used to show that 1 mol of each (18 g) would occupy 18 mL, 18 mL and 22 400 mL respectively giving an approximate cubic spacing of 1 : 1 : 10.

In light of the students' amazement and their prediction of vast distances between gas particles, the following analogy was introduced. "If an air molecule was as big as this table-tennis ball, how far away from it do you think the next air molecule will be?" The students were nonplussed, so, based on an O₂ or an N₂ molecule (3.0-3.5 Å), the inter-particle distance was calculated to be about 1.5 m. "So, if the molecules in the air in this room were as big as table-tennis balls, the air molecules would be between 1 and 2 metres apart. The distance will vary because they are continually moving and colliding with each other." The students were asked if "there are any ways in which the air particles are not like the table-tennis balls?" to which Dan responded, "they're not round like the table-tennis balls because they're joined, they're two atoms." Other differences were "different sizes" and "they're not orange" and "atoms haven't got shells, not a hard shell." The student's desks were about 1-1.5 m
apart, so five students were given table tennis balls to wave around in their hand as a model of air particle spacing and motion.

*Student's Address Analogy, Monday 1 August*

This lesson commenced with a review of the atomic analogies introduced in Term 1. Class-members were asked to describe their conception of an atom resulting in the proposition that electrons existed in shells and clouds.

*Electron shells* The class agreed that electrons resided in concentric shells or layers in which electrons were embedded. They proposed that the first shell contained 2 electrons, the second eight electrons and the third, 18 electrons. When asked to further describe shells, it appeared that the students imagined an orbit with two (or eight) electrons evenly spaced around the orbit. This diagram is common to many textbooks (e.g., Boden, 1962; Education Department of Western Australia, 1975; Jones, Jones & Acastor, 1993). Rather than visualising shells containing 1, 2, 3 electrons etc., depending on the element, the students maintained an image of 8 electrons evenly spaced around a circle.

*Electron clouds* The notion of an electron cloud was nowhere near as popular as the electron shell (probably because of its less discrete, more diffuse nature). When the students were asked to describe their electron cloud, Alex proposed a "fluffy spherical cloud, like a cloud in the sky, white and opaque." At this juncture the propeller/fan analogical model was repeated. The students indicated that they were satisfied with the analogy. In response to the question: "Can any of you remember the analogy I gave you last term to describe the size of a hydrogen atom?" [The Melbourne Cricket Ground (MCG) analogy], most students had forgotten the analogy and several suggested that the electron was as big as a football. Consequently, the analogy was reworked. "If we think about the MCG, you've all seen the MCG on TV haven't you?" Some said "yes", others were silent, therefore a discussion of the size of the MCG followed. Specific reference was made to the TV habit of providing a bird's-eye view of the arena showing its relative dimensions. "If we think of a hydrogen atom - how many particles make up a hydrogen atom?" Dan volunteered that it had an atomic number of one and Alex said that it had one proton and one electron.

OK, if the nucleus has one proton and there is one electron circling around it, what are their relative sizes? [Nat said the nucleus was as big as a ball.] Well, the nucleus would be better seen as a pea on the cricket pitch at the centre of the playing area. Where is the electron then if we think of the nucleus as a pea? [Alex: at the outside.] That's right, if the nucleus is like a pea on the cricket pitch, then the electron is about as big as a grain of sand at the outside of the seating area, at the outside of the building.  

[Teacher]
Ken again asked, "How big is the MCG?"

About 150 metres radius. On this scale, the electron is as big as a grain of sand and is about 150 metres from the pea-sized nucleus. All the rest is space. All atoms are nearly all space. Rutherford showed this when he shot $\alpha$-particles at a piece of gold foil. Gold foil is many atoms thick - 10-20 atoms thick and the $\alpha$-particles went straight through in most cases. A few were deflected by hitting the gold atoms side on and about one in a thousand came back because it had hit a gold atom's nucleus. Now gold atoms have a mass number of 197 and even then, it's mostly space. The mathematical relationship is that the radius of the atom's orbit is about 100 000 the diameter of the nucleus, the proton.

[Teacher]

This ratio was written on the whiteboard and a non-scale diagram drawn with these measurements on it.

Extending the analogy The notion that an atom is nearly all space was extended in the following manner:

So you can see that an atom is very large compared to the amount of matter in it. Another analogy that shows that atoms are nearly all space is what happens to a sun when it becomes a super nova and collapses down to a neutron star. Astronomers have now found hundreds of neutron stars that are the remains of collapsed stars. Think of our sun. It is about 1 500 000 km in diameter. That's humungous. But if it collapsed to a neutron star - which it isn't about to do - it would fit all the nuclei of the sun into a sphere about 15-20 km in diameter, from here to the city centre. That's possible because atoms are mostly space and that's why this analogy of the hydrogen atom using the MCG is useful. We can visualise the MCG and we know how big a grain of sand and a pea are. So atoms are mostly space and because the electrons go so fast - around the nucleus billions of times every second - they appear to be everywhere. That's why we use this idea of an electron cloud.

[Teacher]

Unfamiliarity with the analog Ken was still unhappy about the size of the MCG and one of the girls also indicated a lack of confidence with the analog. When this issue was canvassed, at least three students said that the MCG analogy lacked meaning for them. Consequently, the class set out to construct another analogy for a hydrogen atom based on the proximity of their homes to the school.

The student's address analogy The proposition was:

Let's make this more real for you. I want you to tell me where you live and tell me how far your house is from school and I'll use this 1:100 000 ratio to compare the hydrogen atom to your place. Let's start with ... Gina - where do
you live? [Marangaroo Dr] How far is that away [a couple of km?] Let's say 2 km - if the electron was 2 km from the nucleus which is here at school, then the proton in the nucleus would be about 2-3 cm in diameter say about the size of a ping-pong ball and the electron would be about 2 mm in diameter. Who lives further away [Dan] ... how far do you live from school Dan? [I'm not sure?] ... You're near Thomas Scott so that'd be about 5 km away. On this scale the proton in the nucleus would be ... 5 cm, about the size of a tennis ball and the electron about the size of a small pea.

[Teacher]

The process continued and an analogy was constructed for each student in the class based on where they lived. Each student was asked whether or not he/she was satisfied with their personalised analogy; no student indicated any dissatisfaction.

Fruitful application of the analogy Next, Ken asked "What if the nucleus was as big as me?" Based on the 1:100 000 ratio students proposed that the electron could be as far away as Kalgoorlie or Geraldton. Tim queried, what if the nucleus was a km? The class figured that the distance to the electron would be 100 000 km which someone claimed was about as far away as the moon. Tim continued, "what if the nucleus was as large as the earth?" The reply, "well what do you think?" Gina responded, "probably as far away as the nearest star." After some thought about orders of magnitude, it was suggested that Gina's idea was reasonable given that Proxima-Centauri is about 4.3 light years away!

Summary The student's address analogy not only helped each student conceive of the spaciousness of an atom, it proved useful in extending their knowledge because it led to meaningful analogies in other contexts. In Posner et al.'s (1982) terms, this analogy was probably Fruitful (IPF) because it suggested new questions and useful avenues of inquiry. Awareness of the need for analogies to be familiar transformed the Intelligible (I) (but implausible) MCG analogy into the Fruitful (IPF) student's address analogy.

Balloons Analogy, 1 November

Organic chemistry shapes are dominated by the tetrahedron. The students familiarised themselves with this structure using of Molymod® models and constructed most of the alkanes and their derivatives as they arose in the course. Concrete modelling proceeded to include alkenes, alkynes and their derivatives. Student-built models were especially useful for learning about isomers and IUPAC nomenclature. Many of the students found difficulty in understanding and explaining why molecules variously assumed tetrahedral, planar and linear shapes. The more able boys who were concurrently studying electricity in physics successfully related molecular shape to electron bond-pair repulsion but there was a need to model this phenomenon for the
rest of the class. The "balloons" analogical model employed by Hunter et al. (1976, p. 361) seemed a useful way to explain electron bond-pair repulsion.

(a) Four balloons forming a tetrahedral shape.

(b) Three balloons forming a planar shape

(c) Two balloons forming a linear shape

Figure 14: Balloons analogical model for organic molecular shapes.

This functional model began with four strongly inflated balloons with their necks tied together and hanging from the ceiling. The tied connections modelled methane's central carbon [see Figure 14(a)], the hydrogens were imagined to be at each balloon's distal end and the inflated balloons modelled the molecular orbitals (pneumatic pressure modelled electrostatic repulsion). The model was examined by the class and the students mapped these shared attributes. With the students' attention focused on
the tetrahedral structure, they were asked, "what sort of shape would the molecule have if there were only three bonds, ... you know, if one of the bonds was double instead of single ...". While the students thought or prepared their answer, one of the balloons was burst with a pin. The model popped into a planar shape with angles of about 120° each [Figure 14(b)]. The effect was dramatic; the students agreed that the this was the shape that minimised the inter-balloon pressure and this is what should happen when three bonds mutually repelled each other. Taking the analogical model further, they were then asked what shape should result if only two bonds were present. Again, before they could answer, another balloon was popped and the two remaining balloons assumed opposing positions [Figure 14(c)]. The students were visibly impressed with this demonstration.

*The raft analogy* The balloons model was followed by the raft analogical model designed to demonstrate the rotatability of single bonds and non-rotatability of double and triple bonds (Figure 15). The wooden balls modelled the carbon atoms while the wooden connecting rods modelled the bonds. This model was familiar because it mirrored the Molymod® models with which the students had been working. It was evident that one wooden ball could rotate relative to the other when there was a single "bond" connection but not when there were two connections - a 'double' bond. The idea of bond stability was further enhanced by floating both models in a dish of water. When set spinning, the single-bonded molecule continued to spin, the double-bonded molecule righted itself and remained in one position. Discussion of the shared and unshared attributes revealed that the students found the floating model challenging. The interviews later support this claim. Half of the class remembered the balloons analogy but only one student recalled the raft analogy.

![Diagram](image)

*Figure 15: The raft analogical model for rotatable and nonrotatable bonds*
Introduction to the Case Studies

This chapter is dominated by six longitudinal case studies and each case study describes one student's year-long conceptual development concerning atoms, molecules and bonds. Data were collected on ten students, eight cases studies were written and six are reported in this chapter. Four student cases are not reported here for the following reasons: Despite being a very capable student, Jon was anti-social and missed many classes. Due to the incompleteness of his portfolio, it was not possible to write a case study that fairly represented Jon's learning in the chosen topics. Colin had a chronic medical condition requiring medication that affected his ability to concentrate; consequently, he too missed many classes and what work he did complete was probably unrepresentative of his ability. Three students were of like ability and achievement; these were Mary, Nat and Gary. Length constraints in this thesis allowed the inclusion of but one of these students; therefore Mary's case was included. The author believes that the student case studies included in Chapter 5 resemble some of the students encountered in Year 11 chemistry classes in Western Australia. Nevertheless, the study did not set out to be representative, it simply studied and described what happened as six individual students learnt about atoms, molecules and bonding.

A total of seven episodes of analogical/modelling instruction, beginning 14/2/94, were included in the implemented curriculum. Apart from the comments embedded in the descriptions of each analogical model, no specific attempt was made to evaluate the efficacy of the analogies or models in the achieved curriculum. This was left to the six case studies. Each case study is introduced by a biographical sketch of that student. Of necessity, each sketch is a subjective description of the student from the teacher's perspective and contains subjective as well as empirical assessments. The biographical sketch leads straight into the bulk of the case study consisting of a detailed account and analysis of each student's progress through the year. For each student, only the teaching and learning activities described in Table 4 that provided positive or negative information about that student are discussed. Each case study then concludes with a detailed discussion comprising three perspectives: first, changes to the student's conceptual status throughout the year; second, an analysis of the student's modelling ability; and third, an evaluation of the student's intellectual status. These three factors are then combined to draw conclusions about changes to the student's conceptual framework.

Data Sources for the Case Studies

All of the student comments in the case studies were taken from audio- or video-taped conversations, from the students' written work, or from the teacher/researcher's notes.
The audio- and video-taped activities were transcribed verbatim by the teacher/researcher. All citations are verbatim and the vast majority of the students' spelling, syntactical and grammatical error were left uncorrected. Where a correction was made, it is enclosed in [ ] brackets. Qualifying comments were necessary, especially in the interview transcripts and from videotaped sequences to make sense of the dialogue. These too are enclosed in [ ] brackets.

During the last week of Semester 2, the students were asked to write an essay about organic molecules and their bonding. The students were allowed to refer to their notes and textbook and were given ample time to complete the task. This is called the 'free-form essay.' Two days later, each student was interviewed for about 30 minutes by one of two colleagues from the Science and Mathematics Education Centre. The semi-focussed interviews (Hook, 1981) (Appendix 13) contained set questions that were used as a springboard for probing the range of ideas about atoms, molecules and chemical bonds held by each student (White & Gunstone, 1992). The free-form essay and the interviews were complementary and provided sources triangulation (Patton, 1990). The free-form essay and the interview were designed to give the students an opportunity to metacognitively reflect (Gunstone, 1994) on their ideas about atoms, molecules and bonds in as non-judgmental an environment as possible. The interview and free-form essay preceded the final examination and were represented as revision activities. This was doubly useful because the students were serious about the activities and the thinking activity of the essay and interview discussion provided remedial feedback. Evidence in the case studies shows that students like Mary and Gina found the opportunity to discuss their ideas beneficial.

*Interpretation of Student Conceptual Status, Modelling Level and Intellectual Position*

Describing students' conceptual development necessitates evaluating student conceptual status. However, the student conceptual status construct is firmly rooted in the individual student's understanding of, and opinions about a particular concept. The interpretations of student conceptual status interspersed through these case studies (in terms of intelligibility, plausibility and fruitfulness) are the researcher's considered estimate of how each student felt about each conception based on his/her written and stated comments. The researcher recognises that interpretations of this nature are subject to the vagaries of time, place, personal differences and presuppositions. Predictions of conceptual status are predictions about mental models and Norman (1983) warned that interpretations of this kind are imprecise and unstable. This caveat was born in mind during the reading, interpretation and writing of each case study and its discussion. Nevertheless, Erickson's (1986) question "what is happening here?" provides the warrant for interpretive research of this nature.
Several conceptual change researchers believe that the student alone is capable of stating a conception's status. However, Norman also warned that students are unreliable evaluators of their mental models and Erickson pointed out how Malinowski was able to describe ideas his subjects could not articulate. The qualitative research literature is replete with studies that describe the ideas, opinions and conceptions of students and most of these interpretations have been derived from observations of the student and from comments the student made about events and instances. The constructivist paradigm recognises that knowledge is both individual and in a constant state of flux. Providing these limitations are kept foremost in the construction and reading of this thesis, the researcher's interpretations of conceptual status, modelling ability (Grosslight et al., 1991) and intellectual development position (Perry, 1970) should be considered as viable arguments.

For the sake of brevity in the case studies, each student's conceptual status is described using Hewson's (1981, 1982) terminology. When a conception was adjudged as intelligible to the student, that is, the conception made sense to the student, it is called Intelligible (I). If the conception was both intelligible and plausible to the student, that is, the conception made sense and was believable, it is described as Plausible (IP). Lastly, if the conception was intelligible, plausible and fruitful to the student, that is, it made sense, it was believable and it was useful in problem solving and/or it suggested new ideas, then it is called Fruitful (IPF). The hierarchical nature of intelligibility, plausibility and fruitfulness is described by Hewson and Hewson (1992, p. 60).

The ordering of the case studies is arbitrary. The more successful students are discussed first; however, it should not be concluded that the order is in any way an order of merit or suggestive that one student was 'better' than another.
Chapter 5b

Case Study 1 - Alex the Multiple Modeller

Biographical Sketch

Alex was one of the three most capable students in the class and throughout the year achieved the top score in the class on several tests, assignments and laboratory investigations. He completed the year's work with a strong A grade. Alex was very articulate and could craft a sound verbal or written argument when confident of his understanding. Throughout the year, Alex was a regular contributor to class discussions and though not as assertive as Dan or Tim, made more significant contributions to class knowledge by virtue of the fact that he thought through issues before making a comment. He was a committed student who completed all set work on time. Consequently, Alex's strong knowledge base, combined with his conceptual ability, explains his high level of achievement and sound understanding of chemical concepts. Despite being a high achiever, Alex was not as intellectually adventurous as several other students in the class and often reserved his comments until he was reasonably sure of his ideas. Near the end of the year, however, he attended a set of 'cramming seminars' and after being assured by the tutor that he could 'beat' the examination by learning a set of rules and algorithms, Alex withdrew from many class interactions and adopted a memorisation approach.

Alex's Mental Model of an Atom

Commencement of Semester 1 Alex's prior conception of an atom was revealed during an activity at the beginning of the year where he sketched the simple atom shown in Figure 16(a). This diagram is characterised by a very large nucleus and very close electrons. He provided an explanatory comment: "size - an atom is extremely small, smallest part of matter." Presumably, he meant the smallest independent unit of matter. The label "electron cloud" indicated that Alex was aware of this concept.

Next, from the set of eight common atomic representations (Figure 13), Alex preferred diagrams 2 and 6 (simple three-dimensional orbits and ball model) in that order; he also indicated that he disliked diagrams 8 and 7 (stationary electrons and enclosed atomic models). Against diagram 6, Alex wrote "the electrons would surround the nucleus like so" (arrow pointing towards diagram 6). It is unclear, however, whether he thought that the ball was just the nucleus or whether it represented the whole atom. Alex may have interpreted the swirling lines within the sphere (Figure 13, diagram 6) as electron 'paths.'

The structure of matter test This test was administered three weeks after the review of his prior understanding and Alex's responses indicated that he had mastered most of
the first month’s instruction. He demonstrated a sound understanding of the mole concept, the particulate nature of matter and correctly predicted that the atom was mostly space with the majority of its mass in the nucleus. In reply to the questions asking him to draw a fluorine atom of atomic number 9 and mass number 19, he sketched Figure 16(b) adding the rider that “the electrons were a great distance from the nucleus.” Alex drew the electrons in shells but labelled the surrounding region an "electron cloud." This suggests that he may not have fully differentiated electron shells and electron clouds. The fluorine atom diagram, Figure 16(b), shows the electrons at a greater distance from the nucleus than was the case in Figure 16(a). While this difference between the diagrams may not be significant, Alex's comments are useful; he recognised the need to qualify his diagram by naming and describing what he could not adequately draw (an electron cloud and the large distance between the nucleus and electrons).

(a) Semester 1 pretest: simple atom

(b) Term 1 Examination: fluorine atom

Figure 16: Diagrams of atoms drawn by Alex during Semester 1.
Models of atoms and molecules  At the end of Term 1, Alex provided another set of
exemplary answers during the end of term test. He was proficient with all forms of
chemical symbology - formulae, equations and notations of the type $^{16}_8$O. He
differentiated between atoms and molecules using this explanation:

Alex  An atom is the smallest particle of an element and a molecule is how the element
is found in its simplest form. ie atom - O, H, Fe, S, molecule - O₂, H₂, Fe, S₈.

[Term 1 Examination]

Early in Term 2, Alex responded to a kinetic theory pretest which solicited his
understanding of the arrangement of particles in solids, liquids and gases. One item
asked him to compare the "arrangement of the water (H₂O) molecules in water and
steam" at 100°C in a boiling kettle. Without drawing a diagram, Alex simply stated
that the water molecules "are moving rapidly and some turn into vapour." All he said
for the steam was that "they are more spread apart." Further on, he compared the
particles in a mixture of water and ice at 0°C. He stated that "the ice has a fixed shape,
water moves, ice is slightly more dense." He did not invoke the "elastic ball" model,
commonly employed for kinetic theory phenomena, even though he considered the ball
model more acceptable than six other models when selecting from Figure 13.

For the kinetic theory test, Alex was asked:

Quest. Explain in terms of the kinetic theory why the pressure in a car tyre increases on a
hot day.

Alex  Because the volume is fairly constant, as the gas wants to expand when heated -
explained by the fact that gas particles have collisions that are perfectly elastic
with each other, and with the sides of the container, because the gas particles
increase in kinetic energy when heated they move faster there will be more
collisions, thus the pressure increases because the volume is fixed.  [Kinetic
theory test]

Alex's mental model of a gas contained the propositions that gas particles are moving,
they collide elastically and their velocity is related to their energy content. He made no
comment about what he thought the particles looked like in a gas. For this description,
there seemed to be an emphasis on process rather than on matter entities. This change
will be discussed in more detail later.

Throughout Semester 1, Alex was able to correctly answer almost every test and
examination question that required him to interpret the meaning of chemical formulae
and symbolic expressions like $^{23}_{11}$Na. As indicated earlier, he was able to distinguish
between the terms atom and molecule. Interestingly, at no time during Semester 1 did
Alex ever state that all substances were composed of atoms.
After 16 weeks' instruction Alex wrote his first essay on atomic structure in the Semester 1 examination and that essay included a diagram of an atom [Figure 17(a)] which was very similar to diagram 8 in Figure 13. Diagram 8 was taken from the class textbook by Garnett (1985, p. 22). This diagram was entitled: "a model of the atom", and in the text was called "a diagrammatic representation of the structure of an atom" (p. 23). Prior to the formal instruction on atoms and molecules, Alex rejected this diagram as unsatisfactory.

(a) Alex's first essay diagram of an atom.

(b) Isotopes of hydrogen and deuterium.

*Figure 17: Diagrams of atoms and isotopes used in the Semester 1 Examination essay.*

In his essay he described an atom thus:

Alex ... a typical atom will have a nucleus with an electron 'cloud' swirling around it.

The nucleus contains the particles called protons and neutrons and the 'electron...
cloud' is made up of electrons that are moving very fast around the nucleus hence
the name cloud. The following is a theoretical diagram of an atom [Figure 17(a)].
The charge on the proton is 'plus one' and has a relative mass of 1 its symbol is
\[^1H\]. The electron has a negative charge and a mass of \(\frac{1}{2000}\) its symbol is \(e^-\). The
neutron ... has a charge of 0 and its relative mass is 1, its symbol is \(^1n\).

In this essay, Alex displayed a sound understanding of the terms atomic number, mass
number and isotopes, and could accurately predict the number of protons, neutrons
and electrons in a specific isotope or ion. Unlike several other students, Alex did not
use 'electron shells.' The tenor of his descriptions suggest that Alex's mental model
had conceptually matured to a level where the rapid motion of the electrons forming a
'cloud' dominated his thinking. Later in the essay, Alex discussed isotopes and
included in his explanation diagrams of hydrogen, \(^1H\), and deuterium, \(^2H\). These
diagrams are reproduced in Figure 17(b). Notice the difference between the
representations: Alex used two quite different models in the one essay suggesting that
he was not troubled by multiple representations.

*The atomic structure and bonding pretest* The pretest/worksheet commenced with this
question:

**Quest.** What do you think an atom looks like? If your idea of what an atom looks like
could be compared to an everyday object, say what that object is, and say how the
atom is like that object.

**Alex** An atom is an extremely small particle. It could be enlarged to look something
like a marble, the patterns in the marble comparable to the inside of the atom.
Size - an atom is extremely small, smallest part of matter.

[Atomic structure and bonding pretest]

When asked to describe how the chosen object (marble) was unlike an atom, he added:

**Alex** It is unlike a marble because there is nothing to represent the electrons in a
marble.

[Atomic structure and bonding pretest]

Further, when asked if all substances contained atoms, Alex provided the information
that was previously lacking.

**Alex** Yes, everything living or non-living is made of atoms. Atoms could be described
as the building blocks of life, the Lego of nature.

[Pretest]

His statement, "the building blocks of life, the Lego of nature" is an appropriate
metaphor. Lego® consists of about 20 different block sizes and shapes from which
children construct an almost infinite variety of structures and shapes. Lego's
comparison to the discrete set of elements from which all living things are built was a
useful analogy. The attributes shared by Lego® and atoms are obvious: different sized particles, different properties and different connections. Lego® is a model making tool and this may indicate that Alex recognised that atomic and molecular modelling was a legitimate way to describe chemical processes. Still, this final point cannot be definitively asserted and should remain an open question.

The third pretest item asked "Have you heard of the term 'electron shell'?" Alex responded with:

Alex  Yes. That the electrons are ordered in these shells, layer-by-layer around the nucleus, and the shell is surrounding the atom, and the electrons move within their shell.

[Atomic structure and bonding pretest]

From this comment, it appears that Alex may have visualised the 'electron shells' as concentric layers around the nucleus within which the electrons moved. If this is a fair representation of his view, he may hold the conception that the shells are like surfaces rather than regions and that the electrons lie on these surfaces. His lack of clarity (is this a problem with his conception or with his expression?) is evident when he said "the shell is surrounding the atom." These incongruous statements also may be due to the struggles that students go through as they try to use scientific terms while lacking the conceptual framework within which to use them in a consistent manner.

Alex was next asked, "Have you heard of the term 'electron cloud'?"

Alex  Yes ... that the electrons of an atom are swirling around it a[t] high velocities.

Surrounding the atom in a cloudlike manner.

[Atomic structure and bonding pretest]

This comment suggests that Alex had subsumed some scientifically desirable ideas about 'electron clouds' but still had not differentiated the 'shell' metaphor from the 'cloud' metaphor; that is, he had not reconciled the conflicts that arose when he used these two images side by side. It would appear that, for Alex, further conceptual differentiation of these metaphoric models was necessary (Carey, 1985; Novak, 1984).

The final pretest question asked Alex to estimate how near and how far electrons would range from an atom's nucleus if the nucleus was enlarged to 1 cm diameter.

Alex  About 250-300 m [closest] ... about 350-450 m [furthest]

[Atomic structure and bonding pretest]

Alex's description of the atom's spatial organisation is substantially correct and this is not often encountered in secondary students (see Chapter 4, p. 140). During the first test, 4 weeks into the course, Alex drew an atom [Figure 17(b)] and commented that "the electrons were a great distance from the nucleus." Alex drew compact diagrams
with large nuclei and close electrons even though he stated that the electrons exist at relatively vast distances from the nucleus. Alex was the only student who consistently added qualifying comments to his diagrams as the year progressed. It is conjectured that the MCG/student's address analogies were sensible for Alex and that he had conceptually exchanged (Hewson, 1981, 1982; Posner et al., 1982) his earlier generalised mental model for a more precise set of proportions. This may reflect Novick and Nussbaum's (1981) finding "that aspects of the particle model which are most in conflict with immediate perception present the greatest cognitive difficulty and are thus least internalised" (p. 187).

**Atomic structure and bonding test** First of all, Alex successfully sorted a set of 10 substances that were discrete atoms, covalent molecules, covalent networks, ions or metals and also displayed competence with electron configurations (shells only). In contrast, he did not recognise the error in the statement "When one molecule of copper (II) carbonate reacts ... it produced one molecule of copper (II) oxide ...". He wrongly accepted the use of the term 'molecules' for ionic copper compounds. He also had mixed success in predicting bonding types using elemental positions on the periodic table.

The atomic structure and bonding topic introduced the students to Lewis electron-dot diagrams. In three of the four situations where he was asked to interpret and describe bonding in a variety of compounds, Alex drew and explained ionic and covalent bonding using electron-dot diagrams. He constructed correct electron-dot diagram-models of $O_2$, MgS and $H_2O$ and he used his understanding of electron configurations to correctly explain the chemical reaction between magnesium and oxygen to produce magnesium oxide.

**Modelling in the Organic Chemistry Unit**

**Organic chemistry pretest** Carbon chemistry was the main unit of study during Term 4 and the unit was introduced using an organic chemistry pretest. Alex sketched a carbon atom [Figure 18(a)] and it is worth noting that this diagram resembled diagrams drawn by him a semester earlier (see diagrams in Figure 16). One hundred hours of instruction including two extended periods discussing the nature and structure of atoms produced little change in Alex's sketch of an atom. Alex still used the basic model that he brought from Year 10 and this model survived despite a number of analogies designed to stimulate conceptual change. The principal analogies used were the ceiling fan and the MCG/student address analogies described earlier. This finding reinforces the conclusion of many researchers that alternative student conceptions are robust and resilient to change (Andersson, 1990; Driver, 1989; Osborne & Freyberg, 1985). It also accords with Hewson's (1981, 1982) prediction that unless conceptual
competition causes the student to become dissatisfied with his/her prior conception, conceptual exchange will not occur.

A carbon atom consists of 6 protons, 6 neutrons and 6 electrons.

(a) Alex's first diagram of a carbon atom.

(b) Diagram of electron distribution in a molecule of H₂.

c) Electron dot diagram in a molecule of H₂.

Figure 18: Diagrams drawn by Alex during the organic chemistry unit.

With respect to molecular models, Alex indicated a strong preference for the space-filling type, "because it is more realistic." The final item on the pretest asked for a comment on the circled bonds in a structural diagram of ethene and ethyne. His response, "they describe or show how many bonds are present between the carbons", was a weaker answer than that given by several of his companions.

Free form essay The next task was the free form essay and this produced very interesting insights as to how Alex viewed and manipulated the various molecular models. Alex commenced with a definition of covalent bonding and drew two diagrams [Figure 18(b) and 18(c)] and added:

Alex ... over a period of time the electrons would be found between the two atoms [Figure 18(b)]. The atoms in a covalent bond share electrons so that each atom has a full outer shell e.g. [Figure 18(c)]. There are several ways that can be used to describe and draw covalently bonded substances.

1. Ball-and-stick method [Figure 19(a)]:

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2. Balloons: [Figure 19(b)] each balloon represents a hydrogen and the joint is the carbon.

(a) Ball-and-stick method

(b) Balloons model of methane

Figure 19: Balloon analogy for tetrahedral arrangement of bonds in methane.

Alex 3. Spring and ball: [Figure 20] Each ball represents a carbon or hydrogen, the springs show the bonding between them.

Figure 20: Alex's ball-and-spring model for ethane.

Figure 21: Alex's three diagram-models of ethyne
Alex These three are all models of molecules, the ball-and-stick method is too rigid and
doesn't show that the atom is mobile, the balloon method is too out of proportion, the hydrogens are huge compared to the carbon and the bonds. Some ways the atoms can be represented on paper are [Lewis structure —] [Figure 21] electron dots and this is a good representation of where the electrons are bonding to give a better idea of what is going on [Lewis structure] bonds as ‘—’. This shows the types of bonds between the atoms - each line represents two electrons being shared. These are both good methods of representing the bonding going on because they show you where the bonds are and give you clues why.

Alex I think the most appropriate of these is [Figure 22] ... method because it is one of the simplest ways of drawing the molecules and it also shows the position and nature of the bonds involved e.g. ...

![Figure 22: Alex's 'simplest' way to draw a molecule of propane.](image)

Free form essay

Throughout the essay, Alex's explanations for each model and what each represented included the advantages and in some cases, the weaknesses of the model type. He demonstrated an ability to move in a facile manner from one model to the other (Figure 23) and this understanding was similarly evident in the interview recorded at about the same time.

![Figure 23: Alex's multiple molecular models.](image)
The interview The conversation commenced with a discussion of atoms and when asked to sketch and describe an atom, Alex drew a small circle with a p+ in the circle.

Alex I'd draw it something like this, just a hydrogen ion.
Int. Alright yes, ... now this is p+ this is a proton?
Alex Yes.
Int. So is there anything else in the atom?
Alex Not in the hydrogen ion.
Int. What about another atom like carbon?
Alex Carbon ... draw it like this... .... six neutrons and six protons in the nucleus and there's six electrons in the cloud around it.
Int. Alright....
Alex And they're in shells ... one like that ... 
Int. Ok ... you understand that very well ... here are eight ways [Figure 13] of looking at atoms ... which is most like your image ... your model?
Alex That one [number 1] but I don't know ... I'd see it as a 3 dimensional sort of thing ... all around here more something like that or that [2 or 3].
Int. 2 or 3 are looking more 3-dimensional you're right ...
Alex They more, they go over them as well.
Int. That's right ... looking at your hydrogen, is there only a proton in the hydrogen?
Alex In a hydrogen ion there is.
Int. Oh, hydrogen ion, what about a hydrogen atom?
Alex There's an electron out there too. [Interview]

The interviewer then presented Andrew with, in order, ball-and-stick models of 1,2-dichloroethane, trans-1,2,-dichloroethene and ethyne. With little hesitation, Alex correctly named each compound and identified them as tetrahedral, planar and linear indicating a sound understanding of the structures represented by the models. The models were meaningful to Alex and for him, conveyed considerable information.

Int. Can you tell me the shape of that molecule?
Alex It's tetrahedral.
Int. And how do you work that out?
Alex There's three Hs or there's four on each and at 109.5 degrees for the bonds.
Int. Those balloons, did that help you work this out?
Alex Yea, it made itself into that shape ... That's the same, how they rotate around the [centre] they go the same no matter how you put it.
Int. It did do that, nice and this molecule, what do you call that?
Alex That's a ... ... a cis-1,2-ethene ... no trans ... cis is on the same side and they're across, there's two in the longest chain and it's a double bond and there's two chlorines and you label them 1,2, it's a 1,2 dichloroethene ... That one's ... this is
planar ... it's like in only two directions ... well it is really in a third direction, its
width but ...

Int. That's Ok what about this molecule?

Alex That would be ah, ethyne ...Oh, it would be just a straight line. [Why?] The
nature of the bonding ... in a triple bond there's nothing else to come off in
another direction, it's like a stronger bond, it doesn't move.

Int. Why does it want to have one hydrogen this way and another that?

Alex Because the hydrogens repel each other, that's why they're not near each other.

[Interview]

Alex's conception that the molecule's shape resulted from repulsions was correct even
though he mistakenly spoke of atoms repelling instead of bonds. This is indicative of
a stronger pre-occupation with objects (atoms) than with processes (regions of high
charge density). This suggests that at least some of Alex's molecular attributes were
still firmly rooted in the Matter ontological tree when they better belonged in the
Processes tree (Chi et al., 1994).

The interviewer then focussed on the similarities and differences between ball-and-
stick and space-filling molecular models.

Int. There are different ways of representing these molecules and there would be space-
filling models ... what you think about these models? Which made better sense
to you?

Alex I'd have to say that the ball-and-stick made better sense because you can see the
bonds, how would you make a triple bond with these [space-filling models]?

Int. Do you see any advantage in these space-filling models compared to the other one
in terms of your own understanding of molecules and what they look like?

Alex Yea, it does actually, this [space-filling] would probably better represent what one
of these looks like because the bonds don't really hang out like that, it's just a
cloud of electrons that goes up like that. [Interview]

The statement, "it's just a cloud of electrons" between the bonded atoms supports the
belief that Alex had grasped the nature and importance of electron clouds. The
interviewer then directed Alex's attention to the two-dimensional diagrams of the three-
dimensional structures.

Int. You're telling me that the space-filling represents something and the balls
represent other things better ... When you get a textbook and you see things like
this, what do the lines and the crosses and everything represent?

Alex This here ... [yes] that means it's coming out of the page like it's 3-D and that's
behind the page and that's in the page and that's part of the plane.

Int. And what are the lines?

Alex They represent the bonds.
Int. And what are the bonds?
Alex They're a pair of electrons or one line ... if there were two lines that means two pairs of electrons.
Int. Do you see anything advantageous between these two representations of lines over dots? Which do you find most easy?
Alex I like these ones better [structural diagrams with bonds as —], this shows the shape of the molecule and you can tell, I just did this in the essay, I said I prefer these ones, you can see the shape, which directions they are, and you can also see what type of bonds they are, single or double, you don't have to count up ... if you want to see how many electrons there are, you just say that's two, that's four.

[Interview]

These comments support the claim that Alex now possessed a scientifically acceptable understanding of molecular properties (for his age and course). The evidence supports the assertion that he understood that even though models were a powerful way to represent scientific phenomena, they had no independent existence.

*Semester 2 examination* The final facet of Alex's understanding of atoms and molecules was filled in by the Semester 2 Examination essay. He chose the third essay topic: "Discuss the nature of organic compounds and their role in our lives."

Alex described the differences between saturated and unsaturated aliphatic, and aromatic compounds in terms of their carbon-carbon bonding. Whereas most students commence with a description of specific members of each homologous series, Alex discussed the theory and then illustrated each group with examples. His answers, diagrams and models indicated that he was comfortable with his mental model of molecules and realised that their bonding determined their properties. He summarised his understanding thus:

Alex: The bonding within these hydrocarbons determine the nature of the compounds. Such as boiling point, state at room temperature, chemical reaction properties and shape of the molecules.

[Semester 2 Examination]

Despite his proficiency with multiple models, Alex used only one model throughout this essay; that is, Lewis structural diagrams. He did not mention the variety of appropriate models that could be used to represent the compounds he described. His exclusive use of one model suggests that Alex's conversion to the status of a consistent multiple modeller was not yet complete. In his defence, however, it can be argued that the context (limited space and time) may have led him to use the most efficient representation for the task in hand.
Discussion

Status of Alex's Conceptions

The preconception of an atom that Alex brought to Year 11 Chemistry contained a number of incongruities. His drawings showed a very large nucleus surrounded by close electrons situated in what he called an 'electron cloud.' The diagrams, however, showed the electrons in 'electron shells.' He declared that the "electrons were a great distance from the nucleus" and that atoms were "extremely small, smallest part of matter." From Figure 13, he chose diagrams showing electrons in discrete orbits and although he said he liked the ball model, never used it at appropriate times during the year (e.g., kinetic theory topic). The ball conception was mentioned only once when he likened an atom to a marble (an analogy he qualified by saying that the marble represented just the nucleus).

Each of these propositions were at least Intelligible (I); the only propositions that achieved a Plausible status (IP) were his beliefs that an atom had a central nucleus, was a component of all matter and was extremely small. For instance, electron clouds and electron shells were Intelligible (I) (he knew about and accepted the terms) but the way he confused them suggests that neither term was Plausible (IP). Undifferentiated ideas can hardly be classified as believable. The data suggest that Alex visualised atoms as submicroscopic discrete and static particles (IP). The scientific conception that atoms are dynamic, diffuse and spacious entities had little or no status for Alex at the start of the year. His conception of an atom appeared restricted to a single model (or two if the ball model is included).

By the end of Semester 1, Alex's mental model had matured and consisted of a more spacious orbits atom (still relatively compact) supported by a "swirling" electron cloud model and symbolic notations (e.g., \(^{16}\text{O}\)). Alex's use of three simultaneous representations of atoms in the Semester 1 Examination indicated a growing acceptance of the legitimacy of modelling and multiple models. At that time, three models were needed to adequately explain his conception and, early in Term 3, he added Lewis electron-dot diagram-models to his set of acceptable representations. Alex's conception of an electron cloud became more scientific, but he did not fully differentiate electron shells and electron clouds until late in the year. It is proposed that, by the close of Semester 1, the status of his mental model of an electron cloud had risen to Plausible (IP) because he regularly used it in a consistent way. While his mental model of an atom progressed little further during Semester 2, the status of his electron cloud conception came close to the scientific conception during the interview near the end of the year. For most of Semester 2, Alex correctly predicted the proportional extent of an atom's electron cloud. His end of year atom remained an
model of a static atom, of compact structure, with the electrons mostly arranged in discrete shells.

Modelling Ability

In the free-form essay and the interview, Alex used six different analogical models to describe the attributes of covalent organic molecules. More importantly, the way he used the ball-and-stick, space-filling, electron-dot, electron cloud/shell overlaps, 2-dimensional structural diagrams and the balloons model revealed that Alex viewed each representation as a purpose-built model. He believed that each model described a few of the many attributes of covalent molecules, and that collectively, these models adequately described a molecule. Alex's set of multiple mental models should be classified as Fruitful (IPF) because this conception allowed him to solve and explain the problems with which he was familiar. In Grosslight et al.'s (1991) terms, Alex saw models as representations or thinking tools; this classified him as a Level 2/3 modeller. As discussed previously, modelling level should be commensurate with conceptual status and intellectual ability if progress is genuine. In Alex's case, the three criteria seemed commensurable.

Intellectual Position

The free-form essay together with the interview provided compelling evidence that Alex's understanding had proceeded well beyond the Dualist Position (the belief that there is a right-wrong answer to every situation) through the Multiplist Position (many answers are available, but the puzzle is still to find the 'right' one) into Relativism (Perry, 1970). In the Relativist Position, the student appreciates that many phenomena in chemistry have no unambiguous solution and that multiple models (or multiple explanations) are necessary because chemists find that one model works best here, another there, and so on. Alex demonstrated an ability to choose from the range of available models, the one that best solved the problem in hand, and he was not troubled by the apparent contradictions that existed within and between models. In this sense, it is proposed that Alex had undergone an epistemological change which enabled him to see scientists' knowledge as 'best fit descriptions', rather than as positivist right-wrong dichotomies. It is also suggest that for Alex, the conceptual status of each available model rose and fell in light of the context and the descriptors accompanying each problem (Hewson & Hewson, 1992; Perry, 1970).

The language that Alex used to describe molecular models contained sufficient reference to molecular behaviour and processes, to support a claim that his understanding had changed ontologically. As Chi et al. (1994) pointed out, explanations that replace matter attributes with process attributes constitutes strong conceptual restructuring.
Summary

In spite of the weaknesses that persisted in Alex's mental model of an atom, he provided sufficient evidence for the way he understood and manipulated atomic and molecular models to support an assertion that he had exchanged his intuitive conceptions in favour of a more scientifically acceptable conception. This assertion is more sustainable with regard to molecules than it is in relation to atoms. In Alex's case, the combination of his interest in chemistry, confidence in his own ability and his sound work ethic provided the motivational basis for the conceptual addition and exchange that occurred during the year (Pintrich et al., 1993). The additions and changes were both epistemological and ontological because he added and changed actual knowledge items as well as changing the way he thought about them (especially electrons and bonds).
Chapter 5c

Case Study 2 - Gina the Relativist

Biographical Sketch

Gina was a very able chemistry student who eventually came top of the class despite her chronic shyness and withdrawing nature. She was one of three girls in this chemistry class, and of the three, was by far the most able science student. At the beginning of Year 11, Gina's performance on review activities revealed that her chemistry content knowledge was above average. Initially, Gina would neither volunteer an answer nor ask a question even though her content knowledge was strong and she was a very competent problem solver. With coaxing and positive feedback, her social reluctance declined; however, by the year's end, she was still reserved and inhibited by the assertive boys who dominated most class interactions. Gina would talk quite freely in a one-on-one situation but was content to sit back and let other students take the lead in group situations. The interview at the year's end was conducted by a female colleague from the Science and Mathematics Education Centre and in this situation, she was forthright and probably said more in that interview than she had said all year in class. The interview revealed another side to Gina: in a non-threatening environment she could be confident, articulate and willingly engaged in lengthy discussions about complex issues.

Gina's Mental Model of an Atom

Commencement of Semester 1 When asked to sketch her prior conception of an atom, Gina drew Figure 24(a). This atom was characterised by a very large nucleus and close electrons which she called an "electron shell." The diagram was accompanied by this comment:

Gina  An atom is so incredibly miniscule that it can't be seen with even the assistance of the highest powered microscope.

Next to the diagram, Gina wrote "10p 10n" yet showed only five electrons, all in the inner electron shell. When asked to choose her best fit model from the diagrams in Figure 13, Gina selected diagrams 2 and 3 (simple and complex three-dimensional orbit models respectively) and indicated a dislike of numbers 6 and 7 (the ball and enclosed atomic models respectively).

The structure of matter test Three weeks later the first chemistry test examined Gina's understanding of the particulate nature of matter and basic atomic concepts. She had mixed success with the mole concept questions but demonstrated a sound understanding of the basic components of an atom. In one response, she indicated that an atom was mostly space, that is, the nucleus was a very small part of the atom's
volume. Was Gina’s first diagram then, a model in which the proportions were not meant to be shared attributes? or had she by this time, modified her conception? Gina displayed a high level of competency in writing and interpreting chemical formulae and chemical equations.

(a) Semester 1 pretest: simple atom

(b) Term 1 Examination: fluorine atom

Figure 24: Diagrams of atoms drawn by Gina during Semester 1.

Models of atoms and molecules Gina’s next opportunity to describe an atom came when she was asked at the end of Term 1 to sketch a fluorine atom - atomic number 9, mass number 19. The diagram is reproduced in Figure 24(b) and new information was provided:

Gina The electrons are in shells yet they are only drawn stationary so they can be identified. They are in constant motion. [Term 1 Examination]
When asked, "What is the difference between an atom and a molecule?" Gina explained that:

Gina: An atom is a single particle whereas a molecule is multiple particles joined together. \( \bullet = \text{atom} \quad \bullet\bullet = \text{molecule}. \) [Term 1 Examination]

Early in Term 2, Gina completed a kinetic theory pretest in which she was asked to comment on the "arrangement of water molecules (H\(_2\)O) in water and steam" in a boiling kettle. She replied that water molecules are "close together but can freely move" while steam molecules "are wide apart." Later on, when asked to describe the differences between ice and water particles in a glass containing water and ice at 0°C, she observed that:

Gina: The water molecules are close together but movable. The ice molecules are very close together and packed so tightly that they are immobile. [Kinetic theory pretest]

Unlike several students, she did not draw diagrams for any of these situations.

Six weeks later, in her first essay on atomic structure, Gina produced Figure 24(c) and observed that "the electrons are not stationary, they are constantly moving." This qualification under the diagram reinforced the previously expressed model that Gina visualised an atom as comprising a nucleus made up of protons and neutrons which in turn is surrounded by moving electrons. She detailed the electron's mass, charge and function in the following way:

Gina: An electron is a negatively charged particle ... it is found outside the nucleus, floating, constantly whizzing around in an electron cloud. Although they are constantly moving, they are arranged in shells. An electron is the only part of an atom that leaves it. Electrons are gained or lost in an attempt to fill or empty electron shells so that each shell with electrons in it is filled to its potential. An atom to which this has occurred is called an ion. [Semester 1 Examination]

This was the first time that Gina discussed the "electron cloud" concept. Her explanation is interesting because she emphasised the dynamic ordered nature of electrons. Gina also conveyed a clear appreciation of the role of electrons in determining the chemical behaviour of the atom. Subsequent answers elucidated further aspects of her mental model of an atom: In another item she described the atomic nucleus:

Gina: ... the nucleus is a densely packed area and although it only consists of a tiny part of the atom's volume, it makes up most of its weight [Semester 1 Examination]

From the time the atom concept was first taught, Gina appeared to have a sound understanding of the ratios of protons, neutrons and electrons in both neutral and charged atoms, and in isotopes. Several pieces of evidence showed that she
understood and could manipulate symbolic expressions (models like chemical formulae) like $^{19}_8$F.

As Semester 1 progressed, Gina's description of an atom revealed several changes in her thinking: First, she drew an atom that was almost all nucleus and which contained no evidence that the electrons were moving. Second, she indicated that the nucleus was small and then went further by asserting that the nucleus contained most of the atom's mass in a very tiny volume. Third, she added electron clouds to her prior conception of electrons arranged in shells. The 'electron cloud' metaphor appears to have been added to the 'electron shell' metaphor because both models remained current. It is likely that Gina's knowledge restructuring was 'assimilation' (Posner et al, 1982) or "conceptual capture" (Hewson, 1981; 1982) in which extra information is added through weak restructuring (Carey, 1986; Vosniadou, 1994). Assimilation and conceptual capture occur when potentially incommensurable information is added to existing schema without generating dissatisfaction. Coexistent models like 'electron shells' and 'electron clouds can produce 'synthetic models' (Vosniadou, 1994) or alternative conceptions (Strike & Posner, 1992). Subsequent evidence shows that Gina did not construct synthetic models; indeed, she gradually moved towards a position in which electron clouds dominated her thinking.

Atomic structure and bonding pretest When Gina was asked to say what she thought the atom was like "compared to an everyday object", she responded with:

Gina  I think an atom has a dense 'structure' in the middle like a ball made up of tiny particles that are neutrons and protons - like a raspberry or blackberry. This inside structure is surrounded by electrons - tiny little particles much smaller than the nuclear components. They're not solid so they don't have a shape. It is sort of like a raspberry surrounded by hula hoops or like a plum in that there is a dense matter in the middle which is surrounded by much less dense area where the electrons are.

Quest  How is the object unlike the object you have chosen?

Gina  The area where the electrons [are] is not like the flesh of the fruit. They are tiny whirling things that move around (the hula hoops). The stone in the fruit is solid whereas the nucleus is not, it is made up of smaller particles grouped together.

[Atomic structure and bonding pretest]

This analogical model was unique to Gina. Other students used analogical models that could be attributed to books and teachers (e.g., marbles, balls, clouds and shells). A search did not identify any source from which this model could have been derived. It is therefore reasonable to conclude that this analogical model was constructed by Gina out of her knowledge and experience. Syntheses of this nature suggest that she was
comfortable with the notion that a model is a tool that can be manipulated in thinking and communication. Based on this evidence, it is proposed that Gina was probably approaching Level 2 on Grosslight et al.'s (1991) modelling scale.

Continuing, Gina responded to the query, "Are all substances made up of atoms?" by asserting that all substances, living and nonliving - everything is made up of elements which are made up of atoms. She expressed a clear conception of an electron shell:

Gina An electron shell is an area like a ring outside the nucleus. There are 'many' of them, not just one that surround the nucleus. In it are electrons. Each shell or area can only hold a limited amount of electrons. The amount generally increases as the shell move away from the nucleus.

[Atomic structure and bonding pretest]

Similarly, in response to a question asking had she heard of an electron cloud, she wrote that

Gina It is the area outside the nucleus where the electrons spin or in a sense the spinning electrons themselves forming a cloud.

[Atomic structure and bonding pretest]

The nature of this comment "the spinning electrons themselves forming a cloud" described an electron cloud as an 'ontological attribute' that arose from the electrons' activity. Gina's description characterised an electron cloud as an effect of the electrons' motion. In terms of Chi et al.'s (1994) conceptual change theory, Gina's electron cloud was a 'Constraint-Based Interaction', that is, a process with neither a beginning nor an ending like an electric current (pp. 31-32). Chi et al. assert that "conceptual change occurs when a concept has to be re-assigned to an ontologically distinct category." (p. 31). In Gina's early diagrams and comments, she drew and spoke about electrons as structures; here she described an electron cloud using process-oriented language. The beginnings of this transition were evident in her Semester 1 Examination comment when she wrote that an "electron is a negatively charged particle ... it is found outside the nucleus, floating, constantly whizzing around in an electron cloud." This evidence suggests that Gina was gradually restructuring her conception of electrons because the status of her 'electron cloud' conception was rising at the expense of the 'electron shell' conception (Hewson, 1982; Hewson & Thorley, 1989).

The pretest closed by asking, "If the nucleus of an atom was 1 cm in diameter, how far away would the nearest electron be?" Gina stated that it would be very far away, the closest being 100-200 metres and the farthest 500 metres or more. Gina's proportions were compatible with the desired Year 11 chemistry conception.
**Atomic structure and bonding test** Gina provided a perfect response when asked to sort 10 atomic, covalent molecular, covalent network, ionic and metallic substances - only Alex matched her performance. She also produced perfect answers to the questions about electron configurations (shells only) and interpretations of atomic notation (e.g., $^{16}\text{O}$) and the periodic table.

The remaining questions tested Gina's understanding of bonding situations by asking her to draw Lewis electron-dot diagrams for four molecular and ionic situations. While a number of errors appeared in these questions, she accurately drew the Lewis electron-dot diagrams and on two separate occasions pointed out that the dots, circles and Xs were all "electrons that are the same only different representations to show separate atoms." The models' parts suggested that the electrons were different, but Gina recognised and explained that the items depicted by the dots, circles and Xs were in fact the same, identical electrons. This explanation indicated that she had identified shared and unshared attributes of the analogical model.

Finally, Gina volunteered a conceptual understanding of a molecule as being a discrete entity not to be confused with an empirical formula like NaCl (an ionic lattice). She rejected the statement "one molecule of copper (II) carbonate reacts with two molecules of HCl", reasoning that

Gina There is one fundamental error that occurs twice. CuCO\text{$_3$} is an ionically bonded substance as is CuO. Therefore these substances cannot exist as molecules, rather they are ions that are very close together - the product formula CO\text{$_2$} does represent molecules.

[Atomic structure and bonding test]

All this evidence bolsters the conclusion that, by this time, Gina had begun to consistently think of formulae, equations and atomic notations as symbolic representations or models. On at least one occasion, she had identified the metaphor's shared and unshared attributes and was regularly using the term 'representation' in her explanations.

**Modelling in the Organic Chemistry Unit**

**Organic chemistry pretest** By the 24th week of instruction, the various atomic and molecular models were used interchangeably by Gina in the organic chemistry topic. First of all, the pretest required her to reflect on the structure of an atom by drawing a carbon atom: the result is shown in Figure 25(a). Under this diagram, Gina wrote:

Gina It has 6 electrons and a valency of ±4 depending on the electronegativity of the chemicals it is bonded to ...

[Organic chemistry pretest]
Figure 25: Atomic models employed by Gina during the organic chemistry topic.

Next, Gina was shown two diagrams, one of a space-filling model, and the other a ball-and-stick model of methane. In answering the question, "Which of these models do you think is the better representation?" Gina circled the space-filling model and explained:

Gina: In normal molecules they don't have sticks bonding them. They have electrons moving between the nuclei. Therefore the atoms are close and electrons overlap and are better represented as closely bonded. [Organic chemistry pretest]

Again, Gina described electrons in terms of what they do - "electrons moving between the nuclei. Therefore the atoms are close and electrons overlap." This description
reinforces the interpretation that Gina’s mental model of an atom, and of electrons in particular, had ontologically moved from the Matter tree to the Processes tree.

This audit of bonds and their meaning was extended by the next question which asked Gina to describe the circled portions of a ball-and-stick molecular model of ethene and ethyne (the C—H, C=C and C≡C bonds were circled). Her comments were as follows:

Gina  A single bond. Only one electron is joining the two atoms. A double bond, two electrons are moving between the two atoms. A triple bond, three electrons are 'joining' between the two C's. [Organic chemistry pretest]

This error of underestimating the numbers of bonding electrons introduces a note of caution when assessing the strength of Gina’s (and for that matter, any student’s) conceptions. When student conceptions are in their formative stage, there is a certain degree of flux and the student can easily revert to his/her prior conceptions (Posner et al., 1982). This is where Hashweh’s (1986) recommendation that teachers should encourage students to metacognitively identify the changes that have taken place to their conceptions is valuable. Explicit changes to conceptions can be identified and reinforced, thus inhibiting regress.

**Organic chemistry worksheet** Two weeks later the students responded to a worksheet related to the intervening instruction. A significant proportion of the fortnight’s work was devoted to modelling using ball-and-stick, space-filling and Lewis electron-dot and structural diagrams for a range of alkanes, alkenes and alkynes. The students had practised naming many compounds using IUPAC nomenclature. When asked to describe bonding in hydrocarbons, Gina proceeded as follows:

Gina  1. Single bonds - are rotational two electrons between them, sigma bonds give a tetrahedral formation [Diagram - Figure 26(a)]

     2. Double - not rotational shares 4 electrons in a planar formation - sigma + pi. [diagram - Figure 26(b)]

     3. Triple - not rotational, shares 6 electrons, linear formation- sigma & pi [Diagram - Figure 26(c)] [Organic chemistry worksheet]

Gina also drew a second diagram of a carbon atom - see Figure 25(b). Her appended comments were essentially the same as for Figure 25(a). She then correctly named two of the three model molecules (ball-and-stick forms). Subsequently, the exercise asked Gina to critically compare and contrast the three ball-and-stick models with the molecules they represented.
(a) Single $C-C$ bond

(b) Double $C=C$ bond.

(c) Triple $C≡C$ bond.

Figure 26: Gina's diagrams of single, double and triple bonds.

Quest. Are these models accurate representations of the atoms and their bonds? Explain.

Gina No. Real compounds don't have sticks joining them, they share electrons. This makes them much closer than the models make them appear.

Quest. In what way(s) are the hydrogen, carbon and chlorine atomic models LIKE actual atoms?

Gina The angles of the bonds are the same.
The amount of bonds possible is the same.
The rotating ability is the same.

Quest. In what way(s) are the hydrogen, carbon and chlorine atomic models UNLIKE actual atoms?

Gina They are too far away.
They are not different coloured balls.
The sizes are different (chlorine > hydrogen). [Organic chemistry worksheet]

This mapping exercise yielded only superficial likes and unlikes. Gina did not delve into issues such as the propriety of representing atoms (or were they nuclei?) as solid balls; nor did she critique the use of identical sticks for s and p bonds. In view of her previous assertion that sticks were unrepresentative, it was expected that she might
have more to say about the bond being a region of electron cloud overlap. That she listed superficial likes and unlikes is nevertheless useful: Gentner and Gentner (1983) posit that unless a learner quickly and without difficulty recognises "surface features" of an analogy, the analogy, for that person, does not work. It may simply be that the limited response space (three lines) solicited terse responses.

*Free-form essay* Excerpts from the free-form essay show that while Gina had assimilated many of the year's relevant chemical ideas, deficiencies were evident in her understanding such as incorrect numbers of bonds in several structural formulae. In describing Lewis structures as a useful way to depict covalent bonding, she wrote:

Gina  ... each carbon shares an electron with the other carbon. This increases the number of electrons in each atom by one. This bonded pair physically holds the atoms together by electrostatic attraction between the shared electrons and the carbon nuclei. As shown in the diagram [Figure 27] the shared electrons are located between the two nuclei so that the distance for both nuclei for each electron is equal.

![Diagram of a C—C bond](image)

*Figure 27: Lewis electron-dot diagram-models of a C—C bond.*

These static models suggest, and Gina's further descriptions conveyed the image, that for her, the electrons were static between the sharing atoms even though she had earlier described them as moving. Nevertheless, she had a reasonable conception of bonding in terms of electrostatic attraction (but she did not mention like charge repulsions). She continued discussing models adding that:

Gina  People cannot see actual nuclei and electrons so they devise ways to represent the various molecules so people gained a basic idea of what a molecule is like.

*Free form essay*

In terms of understanding the nature of, and changes to Gina's conceptions, this statement is crucial. This identifies Gina as, at the least, a Level 2 modeller because she rejected the notion of reality in the model and she explicitly declared that the
purpose behind constructing the model determined its structural and/or functional attributes. According to Grosslight et al.'s (1991) scale, her comments contain hints of Level 3 attributes. This premise is reinforced by the way she proceeded to write about how and why people use models.

Gina: Three-dimensionally, people use models comprising of balls & sticks to represent atoms and electrons. There are two main ways of doing this, either using a ball-and-stick model, or a space-filling model [Figure 28]. The most accurate of the two is the space-filling model because in reality atoms share electrons which makes them almost become part of the other they are so close. Two dimensionally, there are two other methods, the most common being a structural formula and an electron-dot model [Figure 28]. It is difficult to pick the best of these, certainly, the second of the two, structural models, is best as it shows the shape of the molecule and also shows the fact that they are single bonds. The second one shows the electron orientation better. Each different representation shows a different aspect of the molecule, if you looked at each together, you would discover most of the properties of these hydrocarbon bonds. [Free-form essay].

Notice her statement, "in reality atoms share electrons which makes them almost become part of the other." Gina clearly differentiates reality from the model and nearly all her discussion centres on the how and the why of model use. Reread her closing comment: "if you looked at each together, you would discover most of the properties of these hydrocarbon bonds." This is genuine multiple modelling. Gina used four models in this description and declared that all were useful, but contextually, each had its place. There was a definite flavour of use and purpose in these comments.

For a 16 year-old student, this is sophisticated thinking. It is difficult, though, to know just what she meant by electron-dot diagrams "shows the electron orientation better." Had she accidentally transposed the models? Structural formulae of the type she is discussing show bond orientation better; Lewis electron-dot models show the electron distribution better. Gina may just be mistaken; however, the clarity of the surrounding comments suggest that this may be no more than an expressive slip.

Gina then devoted a page and a half of the essay to pictorial and word descriptions of single, double and triple bonds. She made no reference here to any of the analogies and analogical models employed in the lessons several days earlier (raft and balloons analogy, s and p bond models). She did discuss, in detail, the combustion of various hydrocarbons and her conception of the information contained in balanced combustion equations. This description indicates that she may have seen these equations as another form of model.
Figure 28: Gina’s diagrams representing methane (re-drawn for clarity).

Gina  As you can see, in all cases [alkane, \( \text{C}_n\text{H}_{2n+2} \); alkene, \( \text{C}_n\text{H}_{2n} \); alkyne, \( \text{C}_n\text{H}_{2n-2} \)] the number of carbon dioxide produced is equal to the number of carbons in the hydrocarbon molecule. The number of waters produced is equal to half the number of hydrogen in the hydrocarbon molecule, because for each hydrogen in the hydrocarbon molecule there is two hydrogens needed for each water. The number of oxygens needed is three times the number of waters over two. This is because some is needed for the carbon dioxide \((2n)\) and number of waters . . . [Free form essay]

While Gina’s conclusions were not mathematically exact, it is important to recognise that she was able to generalise a mathematical model from the combustion equations.

Interview The final data source, the semi-focussed interview, commenced with a discussion of Gina’s end of year conception of an atom [here Gina drew Figure 25(c)].

Gina  Sort of like nucleus thing, with protons and neutrons in it, and sort of electrons around the outside, that are always whizzing around, sort of thing, in different shells and stuff.

The nucleus, the electrons are whizzing around these shells, that’s really tight [the nucleus], and [the electrons] is like really far out.

The [nucleus] it’s really tightly bound, it contains the main weight of it, and it’s like, it’s a really small part of it and it contains protons and neutrons.  [Interview]
When Gina was asked to again select her favoured diagram from Figure 13, she chose number 4 (orbitals model) as her best representation of an atom (she had now learned about s and p orbitals). Her second choice was number 2 (her first choice at the beginning of the year). The next part of the interview involved examining first, ball-and-stick models for 1,2-dichloroethane, trans-1,2-dichloroethene and ethyne and second, space-filling models of the same three compounds (using Molymod models). In turn, Gina described each molecule's shape (tetrahedral, planar and linear) and then explained the various structures in the following way:

Gina Because the bonds between the ... what do you call it ... between the carbons and the hydrogens, they're trying to be as far out as possible ... the hydrogens, they go as far as possible. [Interview]

During this interview, Gina re-expressed the opinion she gave in the essay, that she preferred the space-filling to the ball-and-stick models. When asked why she felt the space-filling model was more appropriate, she replied:

Gina Cause um, real molecules don't have these sticks sticking out, they're really close together, they're sort of real close together, joined up, except these ones can't show the bonds very well. There aren't sticks in real molecules, they're just to represent the um, bonds but they're not really there normally, they're really jammed up together cause they share electrons, so they're really close and they don't have this great big stick stuck in the middle. [Interview]

When asked to identify problems with space-filling models, she argued that:

Gina They don't show the bonds very well ... and these ones [ball-and-stick] do, in between them, how they're supposed to be spread out.

Int. Do you think that either of these models types accurately describe the molecule?

Gina Not perfectly, they both show different things.

Int. Did Mr Harrison use any other models to explain these shapes?

Gina Um, ... he used balloons (laughing) ...

Int. What about these balloons?

Gina Um, that was there was four balloons, and they started off being ...

Int. What did the balloons represent?

Gina There was four balloons tied together and the centre was tied, it was meant to represent a carbon atom and the tips of the balloons were meant to be the electrons and the um round bit was meant to be ... inaudible ... and then when he popped one um, balloon they, it was tetrahedral sort of shape and when one balloon went they all automatically sort of went to a planar sort of shape, and then when the he
let the other one off it went sort of automatically linear as they were trying to go as far apart as possible.

Int: Did that help you understand about molecules a bit?

Gina: Yea, the sort of shape, like yea. [Interview]

Finally, Gina indicated that she did not hold a totally static view for bonding-pair electrons. When asked what she understood about the pairs of dots between atoms in Lewis electron-dot diagrams for the same three organic compounds, she replied:

Gina: Well, they're bonding them, they're moving, but they're staying in that sort of area where they're held by the two sort of forces. [Interview]

*Semester 2 examination* Gina's second essay on atoms in the end of year examination included this description:

Gina: Surrounding the nucleus are electrons. These do not have any real shape, they are understood to be like electrical impulses which have a charge of negative 1. Electrons are constantly spinning around the nucleus so the area they occupy is known as an electron cloud. Despite these electron clouds seeming non-structured, electrons keep within certain invisible boundaries known as shells. These shells too are divided into subshells and electrons stick to their particular region. Atoms are incredibly small, so small that they have never been observed through any microscope. Despite this, the amount of atoms and their relative size is crucial to chemistry and so chemists have devised numerous ways to describe them. [Final examination essay]

The models Gina used in describing atoms included detailed word pictures of subatomic particles and their arrangement, isotopes (plus symbolic representation), moles, bonding (covalent, ionic, metallic), Lewis diagrams and 2-D structural diagrams.

**Discussion**

*Status of Gina's Conceptions*

Gina’s preconception of an atom was typically that held by middle school science students. Her initial atom was a static submicroscopic particle dominated by a relatively large nucleus surrounded by close electron shells containing electrons which revolved around the nucleus. Atoms were particles out of which all objects were made. No functions were attributed to either atoms or their electrons other than 'being there' and making molecules. The status of this initial conception could be described as Plausible (IP) (Hewson, 1981, 1982; Posner et al., 1982) because when asked, these were Gina’s beliefs about atoms. Gina did not use her initial conception to solve
problems or generate questions, for this reason it did not reach Fruitful (IPF) status. No status could be assigned to the scientific conception because it was substantially unknown to Gina.

The first discernible changes to Gina's mental model were her assertions that atoms were mostly space and the electrons are constantly moving; this however, resulted in but a minor change to her diagrams [Figure 24(b)]. The status of her scientific conception of electrons was enhanced during Semester 1, such that she presented a Intelligible (I) description of a dynamic electron cloud for the Semester 1 Examination. The evidence suggests that the 'electron cloud' conception had begun to replace the 'electron shell' conception in her mental model of an atom (conceptual exchange). All the reader can detect is the rise in status of the 'electron cloud' conception and the apparent disappearance of the 'electron shell' conception. The status of the static electron shell model declined as the status of the dynamic electron cloud model rose. Likewise, the 'large nucleus, close electrons' conception appears to have yielded to the 'dense nucleus, spacious atom' conception.

Consolidation of the diffuse electron cloud conception was evident during Term 3. By this time, Gina's mental model of an atom's electrons could be described as tiny little particles, not solid (so they don't have a shape) with each shell or area only holding a limited number of electrons and the rapidly moving whirling and spinning electrons creating a cloud. At this juncture, Gina's mental model contained sufficient scientific attributes to sustain an assertion that this conception was fully Plausible (IP).

During Term 4, the organic chemistry pretest, free-form essay and interview data established that Gina could use her conception of atoms and 'electron clouds' to explain bonding and, in the case of hydrocarbons, molecular shapes. It is conjectured that Gina's mental model had grown in status and was approaching Fruitful (IPF) status. Interestingly, she retained the term 'electron shell(s)' but this conception was apparently subordinate to her diffuse 'electron cloud' conception.

This case study suggests that Gina did not undergo an 'apocalyptic' or revolutionary conceptual change, rather, her conceptions changed gradually and incrementally (Duschl & Gitomer, 1991).

Modelling Ability and Intellectual Development

Over the course of the year, Gina utilised a series of atomic and molecular models to explain chemical phenomena. The only situation in which she maintained a single model was in tests and examinations. In all other instances, she employed two or more simultaneous models indicating that she was not troubled by multiple representations. At the commencement of the year, Gina chose diagrams 2 and 3 in Figure 13. Diagrams 2 and 3 were quite similar and resembled Gina's sketch [Figure
24(a)]. Later in the year, though, she concurrently used electron-dot, space-filling, ball-and-stick and structural diagrams to describe molecules. By Semester 2, Gina was able to critique groups of analogical models on the basis of their use and purpose. Using Grosslight et al.'s (1991) criteria, by the year's end, Gina was a Level 2/3 modeller.

From Perry's (1970) perspective, the sophistication of Gina's later explanations suggest that she had advanced from a Position of Multiplism (Position 4: Relativism Subordinate) at the start of the year to Relativism (Position 6: Commitment Foreseen) at the year's close. When the year started, Gina tolerated multiple representations but her use of a single representation for tests and examinations suggested that she saw that model as 'right.' However, the free-form essay and the interview revealed that she had become comfortable with multiple models. Still, the way she used different models indicated that she understood the context-specific nature of each model. The models thus served her thinking and she did not feel constrained to nominate a definitive correct model for atoms or molecules (except when drawing an atom in a test).

Changes in Perry Position status should be concomitant with changes in modelling ability and conceptions held (and status of those conceptions) because these three epistemological/ontological measures rely on similar attributes of intellect, thinking about reality (ontology) and conceptual structure respectively. From these combined perspectives, it is asserted that Gina restructured her conceptions of atoms, electrons and molecules during Year 11. Gina's conceptual change should thus be characterised as evolutionary or incremental.

Issues of gender and opportunity Gina's case illustrates the very real difficulties experienced by girls in science classes that are dominated by assertive boys. The content knowledge of several of the boys was inferior to Gina's, and her conceptions were superior to theirs; yet two boys (e.g., Tim and Dan) managed to monopolise many learning opportunities at Gina's (and the other girls') expense. It is conjectured that Gina's intellectual growth was hampered by reduced opportunities for her to discuss her understandings with other capable students. Solomon (1987) insists that most knowledge is socially negotiated and confirmed, that "it is almost as though we do not understand what we think unless we can discuss it and receive back the effects it produces when our friends respond" (p. 63). The progress achieved by, for example, Andrew, David and Kim seemed to be positively correlated with their high level of argument and discussion about conceptual matters.
Summary

Intellectually, Gina and Alex were mostly equivalent and there was a discernible rivalry between them for the top position in the class. Gina succeeded with the higher grade but Alex demonstrated superior intellectual development according to Grosslight et al.'s (1991) levels and Perry's (1970) positions. The discernible difference between these two students was that Alex consistently discussed his conceptions publicly whereas Gina did not. Transcripts and notes show that Alex verbalised a significant number of factual and conceptual errors in both chemistry and physics over the year. Gina did not make verbal mistakes because she rarely expressed her thoughts. This raises several questions: Did Alex's open discussion of his conceptions give him a significant advantage over Gina? Could Gina have achieved greater conceptual growth and conceptual change if she had had similar opportunities to discuss her conceptions, make mistakes and socially reconstruct her thinking (Solomon, 1987)? The evidence pattern suggests that this may be the case. All the same, because the case studies did not focus on this possibility, it must be admitted that the data collected concerning this issue are too 'thin' to support definitive interpretations. This issue should be pursued in other studies.

Gina also studied Human Biology and that teacher reported that she was probably the best student he had taught over the past three or four years. Gina's social behaviour in that class resembled her behaviour in Chemistry. Some students who fail to interact with others do so because of emotional and psychological reasons. There did not seem to be any evidence to suggest that Gina was disturbed or willingly uncooperative. Amongst her friends, and in other classes lacking assertive individuals, she was quietly friendly and a regular contributor. It may just be the case that Gina preferred to take a low profile in the class, that she could not act assertively, and that she was comfortable with her achievement and level of engagement. The incremental, evolutionary nature of Gina's conceptual development, improved modelling ability and intellectual development was compatible with her cooperative learning style.
Chapter 5d

Case Study 3 - Dan the Naive Rationalist

Biographical Sketch

Three of the students in this class shared an Asian heritage and Dan, a 15 year-old, was one of these three. Prior to coming to Australia at the beginning of Year 11, he had been educated in Singapore; consequently he had been educated in and was a fluent speaker of English. Singapore's curriculum has a Western orientation (culminating in a Cambridge-style O-level examination). Therefore, many of the courses Dan had studied to the end of Year 10 were suitable prerequisites for those he commenced in Western Australia. His physical science background was sound and his in-class responses indicated that his prior learning may have emphasised content over process and encouraged the rote learning of facts. Nevertheless, his practical skills were at least as well developed as the rest of the class. Dan possessed an outgoing personality and was always one of the first to respond to a question or to offer an opinion. When unsure of himself or conceptually challenged, he was a tenacious arguer and at times waylaid the class with his questions. He was quite articulate, made his points in an assertive manner, and held robust opinions on the majority of the preparatory chemistry course concepts. Dan vigorously defended his conceptions and was on many occasions the most vocal student in group discussions. The negative side of his assertiveness was his dominance of class discussions to the detriment of the more reserved students like Gina, Mary and Gary. His commitment to learning was of a high calibre; all homework was completed in depth and on time and he remained 'on-task' for the majority of each lesson. Dan was the third high achieving student in this class (along with Gina and Alex) and completed the year with a lower A grade.

Dan's Mental Model of an Atom

Commencement of Semester 1 In the first week of Term 1, Dan drew a diagram of his preconception of an atom. Dan's diagram [Figure 29(a)], entitled "what I think an atom looks like", included a caption stating that "an atom is very, very small." Like the majority of student diagrams drawn at this time, Dan's atom has a relatively large nucleus and two full electron shells. In a subsequent lesson, Dan declared that an atom was "a bit like a ball ... because it's round and they bounce off of the walls of their container." At the time he drew Figure 29(a), Dan also chose from Figure 13 the diagram(s) that best fitted his mental model of an atom. He selected, in order, diagrams 1 and 3 (two-dimensional planetary and three-dimensional orbits models) and rejected diagrams 4 and 6 (orbitals and ball models). In view of Dan's concurrent
An atom is very very small.

(a) Diagram drawn in Week 1, Term 1.

This is Fluorine atom
- P stands for proton
- N stands for neutron
- @ stands for electrons

The electrons are revolving around the nucleus very fast and the nucleus is very tightly bound together.

(b) Diagram of a fluorine atom.

(c) Diagram of an atom drawn during the Semester 1 Examination.

Figure 29: The set of diagrams drawn by Dan during Semester 1.
statement that an atom was like a ball, consideration must be given to the possibility that his 'ball' description was a functional generalisation with little reference to the atom's structure. The proposition that Dan tolerated multiple models should also be considered.

The structure of matter test Dan's knowledge of macroscopic properties, the mole concept and atomic structure was satisfactory but not outstanding. He was one of the few students to answer the multiple choice question about the spaciousness of an atom incorrectly (see Appendix 6). He chose one of the distracters rather than a conceptually wrong answer. Dan also was proficient in writing and interpreting chemical formula. The status of his atomic conception was reinforced by the diagram he drew for this test [Figure 29(b)]. Dan drew a fluorine atom whose nucleus contained nine protons and 10 neutrons, surrounded by nine electrons, two close and seven in a simple orbit labelled an "electron cloud." The fact that these seven electrons were drawn on several overlapping orbits hints at diffuseness. He also wrote that:

Dan  This is a fluorine atom ... the electrons are whizzing around the nucleus very fast. 
And the nucleus is very tightly bound together. [Structure of matter test]

The electron cloud concept was present in Dan's conceptual framework. However, the fact that he drew electron orbits that looked more like electron shells, coupled with the observation that he ignored the electron cloud model in Figure 13, suggested that his mental model of an electron cloud was embryonic. Dan knew the term, but his conception may have been a synthetic model (Vosniadou, 1994) consisting of an incorrectly labelled (Grayson, 1994; Hashweh, 1986) model of an electron shell.

Models of atoms and molecules The end of Term 1 Test supplied further information about Dan's conception of atoms and introduced his conception of molecules. He wrote that:

Dan  An atom is a simple particle of an element while a molecule is two or more atoms of an element joined together in a constant proportion. [Term 1 Examination]

Dan stated that the ball model was an acceptable description of gas particle behaviour; however, he did not use this explanation on the kinetic theory worksheet that preceded the kinetic theory topic early in Term 2. When asked to compare the air particles in a conical flask with a balloon over its mouth, before and after heating, he wrote:

Dan  The air in flask A is 'smaller' than the air in flask B because flask B was heated, the molecules in the air become further apart thus 'bigger'. The air has expanded because it was heated. The molecules are further apart than in flask A. [Kinetic theory worksheet]
At no time did Dan explicitly mention inter-particle collisions. At the end of the topic test he described the change in pressure in a car tyre on a hot day thus:

Dan  The pressure inside the tyre is measured by the particles of air in the tyre hitting the sides of the tyre. As the temperature goes up on a hot day, then particles inside the tyre get more energy and increase their velocity. Because of the increase in velocity, they hit the tyre more frequently and with more strength, thus the pressure in the tyre goes up.  [Kinetic theory pretest]

Both explanations indicated that Dan understood that gas particles were moving rapidly. In spite of ample opportunities to do so, he did not suggest that either solid or liquid particles were also moving.

Dan wrote his first atoms essay for the Semester I Examination. The intervening instruction had explicitly addressed the concept that atoms are nearly all space using a detailed discussion of Rutherford's experiment, by exploring the MCG/student's address analogy. Despite this instruction, he again drew a compact atom with a large nucleus and close electrons. [Figure 29(c)]. Several extracts from this essay illustrate aspects of Dan's mental model.

Dan  In an atom there are a few parts. They are the nucleus which contains 99.9% of the mass and the electron cloud. In the nucleus, there contain two types of particle, namely the proton and the neutron. The proton has a positive charge and the neutron has no charge. ... The other particle is the electron which resides in the electron cloud. This particle carries a negative charge and "counter-effects" the proton with its positive charge.

A normal atom has no charge because the protons and the electrons cancel out each other. Atoms or molecules can occur with a positive or a negative charge. This happens when the atom or molecule loses or gains an electron. If the atom or molecule is negatively charged by 2, e.g. 2-, then the atom or molecule has two more electrons than the number of protons. If the atom or molecule is positively charged by 2, e.g. 2+, the number of electrons is less than the number of protons by 2.  [Semester I Examination]

Throughout the essay, Dan demonstrated competence in the use of symbolic notations for atomic number, mass number, number of protons, neutrons and electrons, and charge. The actual notation that he used was $^{12}_{6}X$ with charges added where necessary. He explained that it was incorrect to refer to "a molecule of sodium chloride because it is actually Na$^{+}$Cl$^{-}$; nevertheless, he did not indicate that NaCl was an infinite lattice rather than a discrete two ion unit.
**Atomic structure and bonding pretest** The first question of the pencil-and-paper pretest asked: "What do you think an atom looks like? If your idea of what an atom looks like could be compared to an everyday object, say what that object is and say how the atom is like that object," Dan provided the following concise response:

Dan I think that an atom looks like a ball, probably a basketball or a marble. The atom is comparable to a marble as they are both round and relatively small.  
[Atomic structure and bonding pretest]

His answer to the next question, "How is the atom unlike the object you have chosen?" qualified the previous comment:

Dan The atom is thousands of times smaller than the marble. And the marble does not have electrons going round it.  
[Atomic structure and bonding pretest]

This comment suggests that Dan may have visualised only the nucleus as ball-like because he stated that the marble was not encircled by electrons whilst all his diagrams (Figure 29) showed electrons encircling the nucleus. Did Dan visualise the electrons as constituting part of the atom or were they peripheral? The pretest analogy favoured this latter view; however, his essay description and the diagrams in Figure 29 support the former view that an atom consisted of a nucleus plus electron shells/cloud. An alternative interpretation is that, at this time, Dan did not have a firmly conceptualised mental model of an atom. His drawings and written comments describe a mental model consisting of the unreconciled assimilation product of two competing conceptions (ball and orbits models). Dan may not have experienced any dissatisfaction between the two conceptions because he was not strongly committed to either conception, he had not tried to reconcile his mental models, or he restricted each model to different contexts in a way that prevented them clashing.

Dan's mental models at this time may have been the product of prior, uncritical conceptual capture (Hewson, 1981, 1982) which Vosniadou (1994) calls a synthetic model. Alternatively, Dan had ceased to view models as reality but was not yet competent in the selective use of multiple models. He may have used the conflicting representations (ball and orbits models) with the intent that each analog would model different attributes of atomic phenomena; however, he seemed insufficiently cognisant of his mental constructions to be aware of the need to explicitly state why he was using a particular model. This perspective suggests that as a model user, he was a transitional Level 1/2 modeller (Grosslight, et al, 1991).

Dan next stated: "Yes, all substances are made up of atoms", and indicated an understanding that atoms come in different sizes and exhibit a variety of chemical and physical properties. Further probing of this model revealed familiarity with the
concepts 'electron shell' and 'electron cloud.' These conceptions are best represented by these excerpts:

Dan  [electron shell] means the electrons surrounding the nucleus. It naturally has layers like a covering shell. The first layer has two electrons, then 8 then 18 and so on. An electron shell is one layer.

[electr

[electron cloud] means the electrons surrounding the nucleus irregardless of layers. They are moving so fast as to be like a 'cloud.'

[Atomic structure and bonding pretest]

The electron shell portion of this response could be characterised as a rote answer, but the electron cloud description sounds much more original. His statement, "it naturally has layers like a covering shell", demonstrated that this alternative conception was unscientific (see Chapter 4, pp. 131-132). In the Semester 1 Examination essay he spoke of "the electron which resides in the electron cloud." Thus, on two separate occasions Dan spoke of electron shells and clouds as real objects rather than as abstract constructions.

The final question asked Dan to describe his mental model of the spatial arrangement of an atom's nucleus and electrons. If the nucleus was imagined to be a 1 cm diameter ball, Dan believed that the electrons would range from 200-300 m to 300-400 m. This proportion is acceptable for a simple atom and it appears that Dan had restructured his atomic proportions. Like the majority of the class, however, these proportions did not impact on the diagrams they drew at this time or later.

Atomic structure and bonding test  Dan correctly sorted nine out of 10 substances that consisted of atoms, covalent molecules, covalent networks and ionic or metallic lattices. He wrote correct electron configurations for all the elements or ions presented but had limited success in predicting a compound's bonding given the position of its elements on the periodic table. His answers were consistent with his previous test responses in the way he used symbolic models of the type $^{16}_{8}$F to predict numbers of protons, electrons, neutrons and ionic charge.

Subsequent written responses revealed that Dan was competent in the use of symbolic models such as Lewis electron-dot diagrams and the diagrammatic equations that are used to describe electron transfers/sharings during reactions. He drew correct Lewis electron-dot diagram-models for oxygen and water, but predicted that MgS was a covalent molecule. He also failed to recognise the error in the statement "one molecule of copper (II) carbonate ... one molecule of copper (II) oxide."

The final question on the atomic structure test asked Dan to carefully describe the bonding in all substances involved in the reaction when magnesium ribbon burns in
air. While this answer was acceptable, it was again a technical rather than a perceptive explanation of the bonding models involved in this process.

**Modelling in the Organic Chemistry Unit**

*Organic chemistry pretest* After 24 weeks, the final Year 11 topic, organic chemistry, commenced. This unit of study was prefaced by a pretest in which student conceptions of 'organic', 'hydrocarbon' and the carbon atom were sought. Figure 30(a) contains the pretest carbon atom drawn by Dan. This diagram is again technically correct but maintains earlier proportional distortions. Diagrams like this are analogical models and it is unreasonable to expect every atomic attribute to be represented. Seeing, however, that Dan added explanatory comments, the fact that he omitted qualifying the atomic model's proportions suggests that the spacious atomic model did not have high status.

Pretest item 5 contained space-filling and a ball-and-stick diagrams for methane. When asked, Dan preferred the space-filling model justifying his choice by saying "because it shows that they are joined together." In view of his familiarity with these models, there is a paucity of fact and explanation in this response. Chapter 4 (p. 139) showed that Year 8-10 students provided more substantial responses to this question. To be fair, in his response to item 6 (a ball-and-stick model of ethene), Dan described the single C-H bond 'sticks' as "these are the joining forces." This indicated that he interpreted the 'stick' structure as a non-material force, that is, as a function, process or effect. Unambiguous evidence that he understood a force to be non-material is contained in parallel data collected during his physics lessons.

*Organic chemistry worksheet* Two weeks later, Dan worked through a set of questions and problems using IUPAC nomenclature and analogical mappings. He was asked to examine some ball-and-stick models and respond to the query, "Are these models accurate representations of the atoms and their bonds?"

Dan  No because they are not moving and the actual nucleus and electrons and protons are not present.  

[Organic worksheet]

When next asked, "In what ways are the hydrogen, carbon and chlorine atomic models in cis-1,2-dichloropropene LIKE actual atoms?", all he wrote was "correct number of holes to join up." The question continued with "in what ways are the ... atomic models UNLIKE actual atoms?"

Dan  cannot see nucleus, protons and electrons ... not moving ...wrong colours, wrong size.  

[Organic worksheet]

Similar questions probed how "the carbon-carbon and carbon-hydrogen bonds were LIKE actual atoms?" and "UNLIKE actual atoms?"  

202
A carbon atom has 6 protons and 6 electrons and 6 neutrons. 
It has an ability to lose 4 and gain 4 electrons.

(a) Diagram of a carbon atom drawn for the organic pretest.

(b) Diagram of a carbon atom drawn for the organic worksheet.

(c) Atom drawn during the interview.

Figure 30: Diagrams of atoms drawn by Dan during the organic chemistry unit

Dan [LIKE] because you can actually see the types of bonds ... they are at the right angles.

[UNLIKE] not moving ... actually joined, not free to move. 
[Organic worksheet]
These superficial responses suggest that Dan believed that analogical models should contain most of the items found in the object modelled (e.g., nucleus, protons and electrons). Dan seemed to expect a 1:1 correspondence of items between the model and reality. These expectations are typical of Level 1 modellers (Grosslight et al., 1991).

Non-perceptive answers like this are atypical for a student whose all-year average was just under 80%. Dan's work habits were characterised by a continuous quest for excellence as far as his grade was concerned. The indications were that he was not prepared to search for understanding, his goal was technical excellence (expressed as high marks). Pintrich et al. (1993) provide an explanation for Dan's behaviour.

It is important to note that interest and value beliefs are assumed to be personal characteristics that students bring to different tasks, not features of the task itself. ... Utility value concerns the student's instrumental judgments about the potential usefulness of the content or task for helping him or her to achieve some goal (e.g., getting into college, getting a job). ... the importance of the task refers to the student's perception of the salience or significance of the content or task to the individual. (p. 183)

Dan's parents had sent him to Western Australia to gain entrance to the state's most prestigious university. Dan was highly focussed on this task and because these worksheet questions did not represent the question style used in tests and examinations, he did not appear to take the questions seriously.

Dan's diagram of a carbon atom, drawn for the organic chemistry worksheet, is shown in Figure 30(b) and there are no significant differences between Figures 30(a) and 30(b). Indeed, the atoms shown in Figures 29 (early in the year) and 30 (late in the year) are conceptually similar. The lack of changes in Dan's atom diagrams adds supports the preceeding comments.

**Free-form essay** Four weeks later at the conclusion of the organic chemistry unit, Dan wrote a free-form essay and was later interviewed. The free-form essay yielded modelling information that was lacking to this point.

Dan  
A covalent bond is a bond in which electrons are shared between two atoms. The two atoms are held together by an electrostatic attraction between the shared electrons and the nuclei of the atoms. A covalent bond can be presented like

\[ \text{H}^+ + \text{H} \rightarrow \text{H}_2 \]

the bonding electrons are arranged in between the nuclei of the atoms. They spend most of their time there. The bond above is called a single covalent bond because
one electron from each atom is shared making two electrons. We can have double 
or triple bonds. [Free-form essay]

Previously, Dan had talked about atoms being held together by forces but this was the 
first time that he explained that "the two atoms are held together by an electrostatic 
atraction between shared electrons and the nuclei." In view of the fact that most of 
Dan's previous comments had a technical emphasis, this statement was a significant 
improvement on his earlier explanations.

Dan then described the many possible ways for representing a methane molecule; to 
this end he employed the series of diagrammatic models shown in Figure 31.

(a) Space-filling model. (b) Ball-and-stick model. (c) Electron-dot model.

(d) Structural formula model. (e) Lewis structural diagram-model.

Figure 31: Series of analogical models for methane representing Dan's mental 
models of methane.

Dan These are different methods and they are good for different occasions. The 
structural formula would be good if you needed to see the types of bonds which 
space-filling model doesn't show. The variation of structural formula ... would 
show shape too. I think the best is the ball-and-stick model where I can see the
bonds and shape. The electron-dot diagram would be useful to see how electrons are placed.

These comments revealed that Dan recognised that multiple models provided legitimate ways to represent molecules and that each analogical model represented a limited set of shared attributes. His preference for the ball-and-stick diagram ("I can see the bonds and shape") was a distinct change from his pretest assertion that space-filling models were better.

Dan continued discussing alkanes, alkenes and alkynes and mentioned single, double and triple bonds (C—C, C=C and C≡C) without explaining that these bonding representations were models. Diagrams representing Dan's three-dimensional models of ethane, ethene and ethyne are shown in Figure 32.

(a) Ethane 
(b) Ethene 
(c) Ethyne

Figure 32: Analogical models of bonding in ethane, ethene and ethyne used by Dan to represent his mental models.

The interview  This probe provided further insights into Dan's thinking as well as enhancing a number of Dan's earlier statements. The interviewer invited Dan to draw and describe his mental model of an atom. The diagram is found in Figure 30(c) and on this occasion and he described the atom this way:

Dan  ... yes, it has a nucleus, kind of like this, ah, I'm not sure of the shape, nearly round probably and it has an electron cloud going around where the electrons are ... mostly everywhere but there is quite a big distance between them, like there are a few layers of the electrons [alright] ... and the protons and the neutrons are in the centre and most of the mass ... the electrons are really light and are like the exact opposite charge of the protons.

Int. Which do you think is the best, ah, picture of an atom?

Dan  Probably this, number 1 ... this one here because like they're going around so fast you can't see them, you can sort of picture them going around like that ... These
are mostly like stationary ones, just the split second when it stops there, ... so I say this one.

Int. Is there any other one there that is a good representation?

Dan. Um, this one, 3 ... that's the best one for shells and subshells. [Interview]

Dan also indicated that he disliked diagrams 4 and 6 (ball and orbitals model) in Figure 13. The set of preferred and rejected models was identical to his response in Week 1 of Term 1. With respect to Figure 13, nothing had changed. Dan's conception of an electron cloud, however, had significantly improved towards the scientific model but the diagrams he drew [compare Figures 29(a) and 30(c)], liked and disliked, revealed little change in the status of his conception of an atom.

The interviewer then directed Dan's attention to the set of Molymod models of alkanes and alkenes (each containing two chlorines) and a molecule of ethyne. Each compound was represented as a ball-and-stick and a space-filling model. First, Dan was invited to name 1,2-dichloroethane, which he named correctly at his second attempt. The subsequent discussion focussed on this molecule:

Int. How would you describe its shape?

Dan Say, like it's mostly like two tetrahedrons ... joined together, like it would be like two CH₄s ... like take one off there and one off there and sort of just join them like that.

Int. Ok ... why does it have that particular shape?

Dan Ah, because these [bonds] are like they're like electrons and the like charges repel so this is the maximum distance form where they can get like the further away from each other cause like this, the same between there and there and there and there and they go to opposite ends, but this could be too close to this one so it evens up. [Interview]

This explanation completed Dan's description of bonds and molecular shapes as being due to forces, attractions between the bonding electrons and the nuclei, and repulsions between the adjacent bonding electrons. He was then shown the models of trans-1,2-dichloroethene which he again successfully named at his second attempt. The discussion continued:

Int. How's this molecule different from the previous one?

Dan It has a double bond here meaning it can't turn [rotate around the C=C bond] ... that way, it can't turn, that means it has double bond there and this is only in one plane, it's not three dimensional. [Interview]
Dan could not explain the non-rotatability of the double bond even though during instruction he had seen and handled two analogical models designed to explicate this phenomenon. Moreover, Dan had a basic understanding of s and p bonds and their orientation between the double bonded carbons. He had described s and p bonds during his free-form essay. The interviewer then cued Dan to the balloon analogy:

**Int.** Mr Harrison had those balloons, did that help you understand?

**Dan** It shows you how they are all evenly spaced out like if you put them two together they sort of bounce off so that's like the two electrons repelling each other at an equal distance from each other but it doesn't look like it, it just shows how they repel each other and how the shape ... like three dimensional pyramid ... it's electrical.

**Int.** So that gives you a good understanding, a reason for why molecules have these shapes?

**Dan** Just like, just the most basic one, methane, that one and probably that's where you can see it's three dimensional, you can see the actual spacing of ... but for this one, it doesn't really help, no, no, ... just this type [referring to alkane model]

**Int.** When you burst one of those balloons, things changed didn't they?

**Dan** Yea ... when he burst it, it became like, it became evenly spaced, like more on one, on one plane.  

[Interview]

Dan experienced difficulties when he tried to describe the bond angles for each model because he insisted that the alkene bond separations were 180° and then claimed that they were 109°, when in fact they are 120°. Twice during the interview Dan had to be cued - about the balloons analogy and about the linearity of alkynes. Even though Dan was adept at providing correct answers in tests and examinations, his ability to correlate known facts with analogical models was deficient. This suggests that his mental model was neither as well formulated nor as sophisticated as Gina's and Alex's.

The final phase of the interview compared and contrasted ball-and-stick models with space-filling models for 1,2-dichloroethane, trans-1,2-dichloroethene and ethyne. Dan correctly identified the spatial orientations of these three molecules as tetrahedral, planar and linear respectively. Dan expressed his model preference using these words:

**Dan** Probably this one ... the ball-and-stick because in the ball-and-stick you can actually see the double bond, in [the space-filling model] it's just one bond there, you can't see that, but here you can see the double bond or a triple bond.
Int. Are there any features of this space-filling model that might be better than the other model?

Dan In [ball-and-stick], it's too far away but in [space-filling] it looks more realistic, it's more compact, whereas [ball-and-stick] is bigger and doesn't look that real ... and in [space-filling] you can actually compare the size, I mean it looks more normal than this one.

Int. The thing is scientists and you and I don't know what these molecules really look like, it's ...

Dan A best idea. [Interview]

Finally, the discussion moved to the printed diagrams of the above three molecules in Lewis diagrams - electron-dot form, two dimensional structures and three dimensional structures (Appendix 13). When queried about what the $\rightarrow$, $=$ and $=$ represented, Dan pointed out that these symbols represent electrons shared between the adjacent atoms; that the bond was a product of the atoms repelling each other while being attracted to the shared electrons. Dan did not offer any illustrative examples and when the interviewer again cued the balloons analogy, he responded with

Dan Yes, it's much easier to have something to look at, cause it, on the book, it's just one plane, you can't see what happens, but after the balloon thing, you could see just how it actually fits up. [Interview]

Semester 2 examination The entire year's work was examined, reviewing all the items discussed thus far. Dan again demonstrated his ability to describe atoms, molecules and ions in both inorganic and organic contexts using structural and electron-dot diagrams. The formal essay offered a choice of three topics and Dan chose to write about the question asking him to "Discuss the concept of atoms, bonding, molecules and ions."

This essay was comprehensive with respect to subatomic particles, their organisation within the atom and the use of atomic notation. Unlike previous occasions, Dan drew four diagrams comprising models based on simple orbits, electron shells, electron orbitals and electron clouds (Figure 33). The standard diagram was now accompanied by three additional representations indicating that Dan recognised that a series of appropriate atomic models was superior to a single, definitive diagram. Consider also, his comments about the structure of electron shells:

Dan The electrons reside in electron shells. The innermost shell can carry 2 followed by 8 and 18 ... There are also subshells. These are shells above the K shell. The L shell consists of one s subshell and 3 hourglass shaped subshells in the x-y-z plane. [Semester 2 Examination]
Figure 33: Dan's diagrams of simple orbits, electron shells, electron orbitals and electron clouds.

Although many of Dan's answers still emphasised factual content, his diagrams and some comments indicate that he had broadened his ideas. All the same, unless he was pressed (e.g., in the interview) Dan was reluctant to discuss models in anything other than textbook or teacher terms.

Discussion

Status of Dan's Conceptions

Dan's beginning conception of an atom was dominated by the orbits/shells models. His first sketch was consistent with the diagrams he selected from Figure 13 (preferred 1 and 3, rejected 4 and 6), indicating that the status of this conception was at least Intelligible (I) and probably Plausible (IP). Dan's persistence with the orbit/shells conception throughout Semester 1 (see Figure 29) reinforces the conclusion that he found this model Plausible (IP).

At the end of the year, Dan again preferred diagrams 1 and 3 and rejected diagrams 4 and 6 from Figure 13. Based on this evidence, Dan did not materially change his conception of an atom during the year (compare Figures 29 and 30). Thus, his concrete orbit/shells model should again be afforded conceptual status of Plausible (IP) at the year's end. True, Dan did include an orbitals and an electron cloud model alongside the orbits and shells diagram in Figure 31, but this behaviour was typical of Dan, he was adept at adding new knowledge to old without seriously restructuring prior conceptions. The significant aspect of this was his retention of the orbit/shells
conceptions. It is asserted, therefore, that there was no strong restructuring as far as his prior conception was concerned; and this despite a year's instruction intentionally aimed at replacing the static concrete shells model with the dynamic spacious electron cloud model.

Dan's verbal approval of the ball model coupled with his rejection of diagram 6 (ball diagram, Figure 13) was paradoxical. His description of gas particles bouncing around like balls appears to have been Plausible (IP), but only in the gas pressure context. On his own admission, the ball model had zero status for explaining the structure of an atom. But therein lies the dilemma: in the atomic structure and bonding pretest, Dan returned to the ball model. His conviction in describing the shared and unshared attributes of the ball model identified its status at that time as Plausible (IP). This status, though, may be too high. If Dan really had reconciled the ball and the orbits model (as suggested in the data), then the status of both would need to have been Intelligible (I), otherwise, dissatisfaction should result. If, on the other hand, he employed the ball and the orbits conceptions in different contexts, then the status of each could be Plausible (IP) without generating dissatisfaction.

Dan ignored the electron cloud model at the beginning of the year, but by week 6 he called the fluorine atom's electron shell an electron cloud and supported his decision by saying that "electrons are whizzing around the nucleus very fast." His electron cloud conception was at least Intelligible (I) because, although incomplete, the attributes of electron movement and indistinct electron paths were there. Later, in the Semester 1 Examination, Dan said that the moving electrons formed an electron cloud. The lack of any additional descriptors required that the status of this conception remain Intelligible (I). The conception that "99.9% of the mass" of the atom resides in the nucleus also appears to be Intelligible (I). For this conception to rise to Plausible (IP), he would need to have used the masses of the subatomic particles to show that he possessed evidence that made the idea plausible.

Dan's pretest conception of an electron cloud that "the electrons surrounding the nucleus irregardless of layers ... moving so fast as to be like a 'cloud'" was compatible with the scientific concept. The fact that he differentiated electron clouds and shells justifies elevating the status of his conception of an electron cloud to Plausible (IP) for the beginning of Term 3. Dan's description of the spatial proportions of an atom was quite acceptable. Indeed, that evidence supports the assignment of Plausible (IP) status to his scientific conception of an atom at that time. Later in the interview, where he said that an atom "has an electron cloud going around where the electrons are ... mostly everywhere but there is quite a big distance between them, like there are a few layers of the electrons" confirms the status of the electron cloud conception as Plausible (IP). It is asserted that the electron cloud conception did
not reach Fruitful status (IPF) because Dan never used the notion of overlapping clouds to explain covalent bonding.

Dan's conception of covalent bonding and molecular shapes emerged during the organic chemistry free-form essay and in the interview. Point by point, he stated that, bonds were due to forces holding the atoms together, these forces were due to "the two atoms [being] held together by an electrostatic attraction between the shared electrons and the nuclei of the atoms", and methane's tetrahedral shape resulted from the four bonds being "evenly spaced out like if you put them two together they sort of bounce off so that's like the two electrons repelling each other at an equal distance from each other." Once cued, Dan also was able to use the balloons analogy to show that balloon air pressure was like electron-pair repulsion. He explained that, when one balloon was burst, the tetrahedral shape became planar. It is claimed that this scientific conception of electron bond-pairs repelling each other was Plausible (IP). This conception probably did not achieve Fruitful (IPF) status because although he used the conception to justify tetrahedral shapes, he did not use it to explain planar and linear structures.

The status of Dan's conceptions remain a paradox. Status evidence suggests that some aspects of his mental model of an atom were preserved over two semesters. While other aspects did change, he overtly rejected the balls model yet used it in a plausible manner to model gas behaviour. His electron cloud conception rose from Intelligible (I) to Plausible (IP) by the end of the year and his conception of covalent bonding and molecular shapes also achieved the scientific status of Plausible (IP). The question must be asked, Did Dan's conceptions really change? or did he just conceptually capture (assimilate) the course material in an effective but noncritical way?

**Modelling Ability**

When this case study is set alongside the record of Gina's and Alex's epistemological growth, it is evident that both Gina and Alex were more facile modellers than Dan. Although Dan's semester averages and grades were comparable to Gina's and Alex's, it must be admitted that his descriptive models were qualitatively inferior and less fruitful. Dan's descriptions of atoms and molecules should be characterised as technical rather than perceptive or critical. Few of his comments reflected the perception that models were tools that scientists consistently use to depict non observable and abstract phenomena.

Up to and including the atomic structure and bonding unit, Dan's difficulty in differentiating electron shells from electron clouds coupled with the stability of his paradoxical ball/orbits atomic model requires that he be classified as a Level 1/2 modeller (Grosslight et al., 1991). Level 1 modellers believe that there is a 1:1
correspondence between the model and reality, but Level 1 modellers choose one model and believe that "that is how it really is." Dan was much more accommodating than that because he maintained three, and then four, different atomic models. Conversely, his inflexibility regarding changing his mental model of an atom supports the belief that he thought that those models were, in some way, 'right.' But how can three different models be right? He seems to have rationalised that the different models were right in different contexts. For these reasons he was assigned to a Level 1/2, not a Level 1.

The organic chemistry topic with its emphasis on models, caused Dan to employ five models in the free-form essay. While he presented the advantages of each model (and a couple of weaknesses) and made a sound case for the use of multiple representations, the rest of his comments were factually oriented. Dan's reluctance to venture beyond the facts (he did not volunteer a single analogy) again suggests a preoccupation with achievement over understanding. In view of his use of five contrasting models and his use of the balloons analogy (when cued), a case could be made for promoting Dan to a Level 2 modeller. All the same, Dan's use in the interview of conflicting comments like "best" model, "it looks more realistic", and an atom "doesn't look that real", that scientists ideas are merely "a best idea", alongside his maintenance of the same atomic models over two semesters, raises doubts about any classification. The very problematic nature of Dan's modelling ability suggests that he be left at about the 1/2 Level.

Chemistry courses utilise both descriptive and process models. Examination of Dan's comments and answers in later topics such as kinetic theory and reaction rates reinforce this last observation. He was able to consistently score at around the 80% level without at any time critically (or even comparatively) discussing the models he used. He made quantitative deductions and qualitative predictions from models such as cooling curves, collision theory and reaction profile diagrams without offering a single comment indicating that he saw these devices as thinking tools or models.

It may be proposed at this point that some students find a technical curriculum a comfortable way to learn, especially where numerical achievement is their goal. Western Australia's Chemistry curriculum is highly technical with its emphasis upon factual content, a verification approach to practical work and a summative three-hour external examination. It is suggested that Dan's previous science curriculum was at least as technical as the Western Australian curriculum. Dan did not appear to be stimulated to become a more discerning modeller as the course progressed. This may be attributed to either the course form and content failing to challenge him, or simply to his desire for high marks. It may be concluded that Dan did not feel a need to extend himself with respect to the processes and models of chemistry.
**Intellectual Position**

Dan's intellectual position is probably easier to assign than his modelling level. His quest for the "right answer" while allowing the existence of multiple models places him in the Multiplist Position (Perry, 1970). According to Perry's definitions, Dan probably achieved Position 4 by the year's end (Relativism Subordinate). As stated in Chapter 2, students in this Position conceive of every opinion as equally valid and regard qualitative contextual reasonings as no more than special cases within multiplicity. (This could explain his concomitant use of the balls and orbits models.) Another scenario may also fit Dan: he may have advanced into Relativism (Position 5: Relativism Correlate, Competing, or Diffuse) but had Retreated into Multiplism because he was neither prepared to make the requisite effort to consolidate this position nor to advance within Relativism.

**Summary**

Dan was a very capable, intelligent and articulate student. It is conjectured that he was more committed to the rote learning of chemical information than he was to developing a scientific way of thinking. He may have believed that the accumulation and reiteration of information in a systematic way constituted scientific thinking. On the other hand, his motivation to score high marks may have led to a conscious decision to limit his intellectual pursuits to mark generating activities. On this basis, it is proposed that Dan's epistemological and ontological commitments differed from those held by the two previous successful students because even though he was conversant with better models, he maintained a planetary-style atomic model throughout. Intellectually, Dan seemed to prefer 'right' answers and the conceptual changes that did occur were limited to weak knowledge restructuring.
Chapter 5e

Case Study 4 - Ken the Competent Modeller

Biographical Sketch

Ken and his family were Vietnamese refugees and had been resident in Australia for about 10 years. Although English was Ken's second language, he was both fluent and articulate and was well adapted to the multicultural environment in which he lived and was educated. Ken was a sociable and intelligent student who was quite adventurous in matters intellectual. Most European students his age are very conscious of being 'right' and are reluctant to commit themselves to a knowledge position unless they are sure of themselves. Not so for Ken: he made the most mistakes in class because he would commit himself to a prediction or opinion more often than anyone else. Ken was less troubled by uncertainty than the other students; in fact, in the parallel physics course he progressed rapidly in an inquiry-based course that encouraged risk-taking because he was inventive and unconventional in the way he approached problems. Outside science, Ken was quite artistic and this helps explains his creative bent and ability to think laterally.

Ken was almost the antithesis of Dan. Whereas Dan was preoccupied with scoring top marks by memorising facts, Ken was more concerned with understanding. It may seem ironic, but Dan and Ken were good friends and preferred working together rather than individually. Overall, Ken was intelligent, curious and unconventional and while he did not achieve numerically high scores, Ken was possibly the most thoughtful and perceptive physics and chemistry student in the class.

Ken's Mental Model of an Atom

Commencement of Semester 1 Ken's preconception of a atom was sketched during the first week of instruction and is reproduced in Figure 34(a) and, like the other students, consisted of a large nucleus surrounded by a close electron cloud. Appended to the diagram were notes stating that the electrons in the electron cloud were moving and that the atom was only $10^{-5}$ mm in size. Following this, when asked to choose from Figure 13 the diagram(s) that best corresponded with his mental model of an atom, Ken selected diagram 2 (simple three-dimensional orbit model) and rejected numbers 4 and 8 (the orbitals and the stationary electrons models). It appears that, at this stage, Ken's mental model of an atom was dominated by a model comprising a substantial nucleus surrounded by a close region of moving electrons.
Figure 34: Ken’s Semester 1 diagrams of atoms.

The structure of matter test  After four weeks of instruction, Ken’s test responses showed that he believed that the atom’s nucleus was small compared to its total volume and his accompanying sketch of a fluorine atom, reproduced in Figure 34(b), was a typical two-dimensional planetary model. While the model-diagram would normally be classified as correct and is effectively what many teachers present to middle school students, it is a simple and limited model which needs qualification. It will become evident later on, that Ken was capable of identifying the shared and unshared attributes of models and could discuss and critique his own model-diagrams. The remainder of this test indicated that Ken could competently manipulate models like chemical formulae and chemical equations. It may be conjectured that he had memorised these latter items; however, his verbal in-class comments and his inquisitive behaviour in physics classes showed that Ken was anything but a rote learner. The opinion that Ken was intellectually honest and that he was a seeker of understanding came from an
independent observer who spent many hours working with Ken during physics lessons (Harrison, Treagust & Grayson, 1995).

*Models of atoms and molecules*  By the end of Term 1, Ken wrote that he understood an atom to be the simplest "single particle (eg: Ne)" that could exist on its own and that molecules were "combined particles of two or more atoms (eg: H₂O)." Several weeks into Term 2, a kinetic theory pretest was administered in which one of the questions asked for a description of particle arrangements in a kettle containing boiling water and steam. Ken drew spheres for water molecules (Figure 35). Throughout the course, Ken only ever used a spherical 'ball' model for particles when discussing kinetic theory concepts. It seems that students maintain subject and topic specific models; at least, this was the case with Ken when interpreting kinetic theory phenomena. During further written comments and in-class discussion, Ken made it clear that he visualised gaseous atoms and molecules as rapidly moving particles that collided with each other in an elastic manner.

(i) In the water? 

\[ \text{closer together,} \]

(ii) In the steam?

\[ \text{spread out in the air} \]

*Figure 35: Ken's depictions of particles in water and steam.*

Eight weeks later (Semester 1 Examination), when discussing sodium chloride, Ken implied that solid NaCl contains ionic molecules that separate into ions in aqueous solution. It is possible that Ken, like many students at this level, believed that NaCl, means that one sodium atom was bonded to one chlorine atom, thus making a molecule. He neither indicated that a formula model was merely a statement of proportion nor that bonding type was not a shared attribute of a formula. Also, as part of the Semester 1 Examination Ken wrote his first atoms essay. He was one of the
few students to answer this question without drawing a diagram, choosing instead to describe his conception in words. He described the atom's nucleus and its relationship to the electrons this way:

Ken An atom consists of 3 particles: protons, neutrons and electrons. The protons and the neutrons are positioned in the dense nucleus which has 99.9% of the whole atom's weight. Heavy as it may be, the nucleus is extremely dense, it has the diameter of \( \frac{1}{1000000} \) the diameter of the whole atom.

The electrons wizz around outside the nucleus at very, very high speed so that you couldn't see them if atoms were big enough to see. The position of the electrons is very far from the nucleus and the furthest out electrons can be gained or lost to make the atom have a charge. If it lost electrons it becomes positive and if it gains electrons it become negative. These are called ions.  

[Semester 1 Examination]

In this and other questions, Ken exhibited a clear understanding of the role of protons, neutrons and electrons in determining the element type, isotopes and ions respectively. He was proficient in using and interpreting notations like \( ^{16}_8 \text{O} \). His atomic proportions were scientifically accurate and his description of an electron cloud was appropriate although he did not name it as such.

The atomic structure and bonding unit pretest When asked "What do you think an atom looks like? If your idea of what an atom looks like could be compared to an everyday object, say what that object is and say how the atom is like that object", Ken responded with:

Ken I'd say that an atom looks like an egg. Because the egg yolk can represent the nucleus and the egg white/shell can represent different layers of electron clouds.  

[Atomic structure and bonding pretest]

This pretest continued by asking, "How is the atom unlike the object you have chosen?" Ken continued:

Ken The actual atom has a very small nucleus comparing to its electron cloud. But the egg's yolk is reasonably big in comparison with the eggwhite and shell. Also the electron cloud constantly moving while the egg white does not.  

[Atomic structure and bonding pretest]

Ken's ability to identify the salient aspects of his analogical models suggests that by this stage, he had considered or was beginning to see, his model as a representation of, rather than reality itself. This view is supported by his previous statement: "The egg yolk can represent the nucleus and the egg white/shell can represent different layers of electron[s]." The qualification stating that the egg's proportions were
inappropriate, indicated that the analogical model was discordant and was not intended to be taken literally. This is the first time that Ken had actually talked or written about atoms or molecules in this way. Apart from his qualifying comment that accompanied Figure 34(a), he had spoken or written about atoms and their constituent parts using the language of a realist. From Grosslight's perspective, at this stage, Ken shows a mix of Level 1 and Level 2 characteristics: his representational comments indicate maturity of thought (Level 2); however, his inclination to hold but one model was a Level 1 feature.

These remarks support the previous assertion that Ken held a satisfactory conception of an electron cloud even though he did not use the term. This is evidenced by comment: "a very small nucleus compar[ed] to its electron cloud ... the electron cloud constantly moving."

Ken explained that "all matters are made up of atoms and stay together by the attractive forces between the atoms." He then proceeded to describe his conception of electron shells:

Ken I think that "an electron shell" is composed of two or more electrons (depend on how far they are from the nucleus). These shells revolve around the nucleus, and an atom is very stable if all of its electron shells are completed with electrons (they're the noble gases). [Atomic structure and bonding pretest]

When asked to discuss his conception of electron clouds he added:

Ken I think it's the layers of electron shells of an atom. Because of its high speed around the nucleus, [the electrons] looked like a bunch of cloud. [Atomic structure and bonding pretest]

The concluding item asked him to think about a greatly enlarged atom whose nucleus was 1 cm in diameter. On this scale, where would the electrons start and finish? Ken estimated that the nearest electron would be about 600 m from the nucleus with the farthest, "at least 2 kms" from the nucleus. This was probably the most realistic estimate given in this class. Clearly, his statement that "the nucleus is extremely dense, it has the diameter of 1/10000 of the diameter of the whole atom" sits well with this prediction. It appears that Ken's mental model of an atom was dominated by four features: submicroscopic, moving, diffuse and spacious. His repeated use of some of these attributes points to the status of this conception being Plausible (IP).

Atomic structure and bonding test Ken successfully sorted each of 10 compounds into the categories of atoms, covalent molecules, covalent networks, ionic and metallic bonding. He correctly predicted three out of five electron configurations for atoms and ions and perfectly interpreted a set of questions dealing with models of the type \( _{16}^{32}O^2^- \). Furthermore, he correctly interpreted five out of seven
compound bondings given the positions of the constituent atoms on the periodic table.

By this juncture, Ken was able to use Lewis electron-dot model-diagrams to describe and explain chemical reactions and bonding; and using this type of model he succeeded in differentiating between ionic and molecular structures. In three quite different problems, Ken used Lewis electron-dot diagram-models to accurately and consistently describe ionic and covalent bonding.

Students also were asked to critique the statement: "When one molecule of copper II carbonate was heated, it produced one molecule of copper (II) oxide plus one molecule of carbon dioxide" and Ken declared that

Ken: The statement is correct because out of every molecule of CuCO₃ after heating we get one molecule of CuO and one molecule of CO₂.

[Atomic structure and bonding test]

This error of believing that CuCO₃ and CuO were molecules repeated Ken's mistaken interpretation that NaCl was a molecule and may be associated with a belief that chemical formulae illustrate actual objects rather than empirical or proportional models of substances. Ken may have attributed more to the union of the atoms in the formula that could be justified. Many students recognize diagrams and material representations of atoms and molecules as models but fail to recognize that chemical formulae are also models.

Modelling in the Organic Chemistry Unit

Organic chemistry pretest Carbon chemistry was the principal unit of study in Term 4. Ken's mental model of an atom was recapitulated in the pretest by asking, "Describe an atom of carbon ... use a diagram and some brief notes." Figure 36(a) shows his diagram and this was probably Ken's poorest representation and actually depicted magnesium! The error is explainable in terms of the relative atomic mass - he took the relative atomic mass to be the atomic number. After a further period of instruction in which carbon's atomic properties were reconsidered (Garnett, 1985, pp. 435-444), a week later Ken drew Figure 36(b) on a worksheet. By this time, the diagram-model had begun to reflect some of the issues that had been discussed throughout the year: diffuseness represented by the lack of a definite orbit and a larger distance between the nucleus and the electrons.

A second issue, molecular models, was canvassed at this time. When asked whether he preferred ball-and-stick or space-filling molecular models of methane, Ken stated a clear preference for the space-filling version and supported his choice with "it represents the covalent bond between the carbon and the hydrogen better because it..."
shows that the particles (the electrons) are shared." When asked later how the space-filling model shows electron sharing, he said that

Ken: The two atoms touch and that represents the electron clouds joining together ... the rod [ball-and-stick] doesn't show this, ... well I don't think it does ... the electrons cloud have to join up because the electrons are shared where the balls touch.

[In-class comment]

(a) Ken's diagram of a carbon atom drawn for the organic chemistry pretest.

(b) Ken's second carbon atom drawn one week later.

Figure 36: Ken's diagrams of atoms drawn during the organic chemistry topic.

The methane models were followed by ball-and-stick models of ethene, and in referring to the double (C=C) and single (C—H) bonds, he wrote that these bonds were "the bonding/attraction between the two particles, the atoms are held together by attraction for the shared electrons." On the worksheet, he was asked to give the
IUPAC names for Molymod models of 2-methyl-2-butene, 1,2-dichlorobutane and cis-1-chloro-2-methyl-propene followed by this question:

Look at the ball-and-stick models we have been constructing and using in class. Are these models accurate representations of the atoms and their bonds? Explain.

Ken Well, they are models so they are just similar. Differences: their colours and the distance of bond and the dimensions of the ball. Similarity; the ways the bonds are constructed.

[Organic worksheet]

Evidently, Ken had little difficulty interpreting the ball-and-stick models even though he believed these were the poorer alternative. Based on Ken's in-class work, it was anticipated that these comments would have been more perceptive and should have delved in greater detail into the shared and unshared attributes of these analogical models. From the commencement of the year and up to this point, Ken had maintained a single model in most circumstances; however, he now demonstrated that he was comfortable with, and could manipulate, more than one model while still expressing a definite preference for one model.

Free-form essay and interview Both of these activities yielded useful insights into Ken's end-of-year conceptions. The free-form essay probed molecular modelling while the interview examined Ken's ideas about atoms and molecules. Ideas about atoms were discussed at the beginning of the interview with the interviewer leading off with a question about organic chemistry.

Ken Like a molecule is a number of the same element together but a compound, is like a number of different elements combined together.

Int. What do you think the molecules look like?

Ken: They look like, the chains of, of little particles ... you know those atoms, ... yeah, it's like, an atom is like, spherical with, um, a nucleus in the middle. [Right] which has protons and neutrons, and an electron cloud around it, going like spherical-wise and whizzing around.

Int. So tell me about this part here [nucleus].

Ken Okay, Um, that where the main mass of the whole mass of the atom lies, which equals the number of protons plus the number of pro... neutrons ... and the um proton has a charge of one, plus one, and electrons, a charge of negative one.

Int. So this circle around here [Figure 13(3)] is that all filled in with electrons, or where are the electrons?

Ken It's, like a cloud, and the electrons travelling really very fast, and it looks like it's all over the place, and there's a number of them. [Interview]
The interviewer introduced the set of eight diagrams (Figure 13) and asked Ken to choose his preferred diagram(s). This time, Ken chose diagrams 2 and 3 (simple and complex three-dimensional orbits model) followed by number 5 (the electron cloud). He seemed to pause over diagram 4 (orbitals) but did not include it in his final preferences. When asked to state which diagram he thought was best, he replied:

Ken That one (3), because it sort of shows, like, the um path of the electrons, which are like, going, that way, that way, that way and that one (5) like shows the um, sort of like cloudy traces of the electron cloud. [Interview]

Finally, when asked which model(s) he disliked, he rejected diagrams 7 and 8 (enclosed atom and stationary electrons models). After considering the range of Ken's current responses, a reasonable summation is that Ken visualised an atom as a diffuse structure that was more abstract than concrete. His emphasis upon a dense central nucleus surrounded by electrons "travelling really very fast, and it looks like it's all over the place" and "an electron cloud around [the nucleus], going like spherical-wise ... and ... whizzing around" supports this interpretation.

Both the free-form essay and the interview probed Ken's mental model of molecules. In his endeavour to describe the structure and shape of organic molecules, Ken wrote:

Ken The four bonds of the carbon atoms ... are identical and are 109.5°. The bonds will always maintain these angles to each other (the same charges repel). And that's why they have the shape of a tetrahedral model. Let's think that the four bonds are four blown up balloons tied together in the centre. These balloons push one another and its shape finally becomes tetrahedral. [Free-form essay]

The spontaneous reference to the balloons analogy (Hunter et al., 1976) provided Ken with a mechanism for making sense of the mutual bond repulsions in methane. He made a similar comment in the interview conducted some days later. Ken used the balloons analogy to described an alkane this way:

Ken Because all the bonds are, um single bonds, so the shape must be three dimensional. ... Because like in the single bond, every atom is free to move, like all these [hydrogens], free to move, and so there three dimensional. ... It, is like, tetrahedral ... Cause like, I think, ... carbon has four bonds [Right?] and like the most, like they all have the same charge, and means that they repel each other. [Okay] And like that, as far as they can go, you know like if they go up a bit more, then they gonna be repelled by that one, [demonstrating] if this way then it's gonna be repelled by that one etc., so it's just like that.

Int. It's like what?

Ken It's just like .......... in equilibrium. [Interview]
In the essay, Ken summarised his ideas about molecular structure and discussed various ways of modelling molecules in the following terms.

Ken: There are many ways of describing these compounds, and they are

- Space-filling model: this model is best (I think) to describe methane (CH₄) [Figure 37(a)] the rigidity of the bond, how attracted they are to each other.
- Ball-and-stick model: this model is appropriate to describe methane (CH₄) [Figure 37(b)] the shape of bond in that molecule & and how the atoms can move freely within the molecule, in other words it describes the versatility of the bond.
- Electron dot model: methane [Figure 37(c)] this model is best to describe the position of electrons within that molecule and how they formed the bond.
- Structural formula: methane (CH₄) [Figure 37(d)] this model is best for easy recognition of the molecule which is very important when you are naming them. [Free-form essay]

(a) Space-filling model of methane.  
(b) Ball-and-stick model of methane.

(c) Electron-dot diagram of methane.  
(d) Structural diagram-model of methane and ethyne

*Figure 37: Series of analogical models for methane representing Ken's mental models.*

Ken continued by comparing single, double and triple bonds in the contexts of chlorinated derivatives of ethane and ethene, and ethyne. Throughout these explanations, he favoured Lewis structural diagrams. The three diagrams Ken used in his discussion appear in Figure 38. He explained the nature of these bond types by observing that:
These bonds also determine the shape of the molecule:

- Single bond molecules will be tetrahedral shaped (or three dimensional) because of the electrostatic repulsion to each other (like 4 balloons tied in the centre, — they all push the other balloons so their shape is tetrahedral: [Figure 38(a)].
- Double bond will be planar shaped (like 3 balloons tied in the centre and they all pushed each other but as there was more room, they became: [Figure 38(b)].
- Triple bond will be linear shaped because three of the bonds are tied together and the one bond gets to be as far away as possible: [Figure 38(c)].

(a) Tetrahedral molecule with all single bonds.

(b) Planar molecule with one double bond. (c) Linear molecule with one triple bond.

Figure 38: Analogical models of bonding in ethane, ethene and ethyne used by Ken to represent his mental models.

Another issue raised in the interview concerned ball-and-stick versus space-filling molecular models. One semester earlier, Ken declared his belief that space-filling models were the more real representation because they showed the electron cloud overlaps. He was shown ball-and-stick models, space-filling models and Lewis diagrams (structural and electron-dot) of 1,2-dichloroethane, trans-1,2-dichloroethene and ethyne. The independent interviewer gave Ken the names of the three compounds and asked him to comment on their shape and the appropriateness of the respective models.
Ken I think the ball-and-stick one, because it represent the bonds better. You can have like a double bond, shown like this, but without ... the space-filling doesn't show that ... the diagrams show just where the electrons are like the ball-and-stick ones.

Int. Okay, do either of these models accurately describe a molecule?

Ken I think it, they're just similar ... both ... all are useful at times.

Int. Did Mr Harrison use any other models to explain these shapes to you?

Ken Yeah, he used one of those polystyrene ball and stick, and he used ... (inaudible). [He used what?] You know he used two wooden poles and he put them on water, if that was like a single ball then it was easy to move all around in the water, but if it was like a double bond which means it's like um, what you call it, a raft or something, then it can't roll around freely, it's like the double bonds can't, like move around or rotate.

Int. So the double bond was like a raft, and the single bond was like a stick [Yeah,...] Right it could rotate, Um, did he use any other models that you can remember [The balloons] Tell me about the balloons.

Ken. Um, which, were in the shape of the um, the compound, when it was just a single, I mean when there was just single bonds, all hydrogens, the shape was three dimensional, but when he popped one of them, and there was only three left, and its sort of like planar, and when he popped the other one, it was sort of like, straight.

Int. Went sort of straight, So did that help you understand this?

Ken Yeah, It just helps with the idea of how the shape was formed. [Interview]

On several occasions during the interview, Ken compared and contrasted single, double and triple bonds with respect to their stability (by which he probably meant rotatability). He was the only student in the class to recall and utilise the raft analogy. Several students used the balloons analogy. The fact that he used several analogies in conjunction with the standard models indicated that he had come to terms with the existence of multiple models. Caution should be exercised in adducing too much from his comments because he was tentative and did default to one basic model (Lewis structural diagrams) for most of his explanations. It seems reasonable to conclude that he was making progress in restructuring his mental model but was not fully confident of his ability to choose the most appropriate model for a given situation.

In the latter half of the essay, Ken discussed hydrocarbon reactions and he again used the Lewis structural model in all his equations. Clearly, this was his preferred model for thinking about and describing the properties of organic compounds. This usage harmonises with his comments made with respect to Figure 37(d). By this point in the
chemistry course, Ken had apparently relinquished his conception that there was a single 'right' model in favour of a position in which he acknowledged that multiple models were useful because each of the multiple representations described a different content item. White (1994, p. 256) predicted that metaphors and analogies (and models) should play this sort of role in learning and explanations.

Semester 2 examination Ken chose to "Discuss the concept of atoms, bonding, molecules and ions." His essay was more technical than perceptive and comprised, in the main, a set of propositions about atoms that repeated much of what he stated earlier in the year. Several excerpts will suffice to show how he described atoms.

Ken All matters around us are made up of invisible and tiny particles called atoms. A single atom consist of a nucleus where the majority of its mass lie and electron clouds where its electrons are whirring within.

The electrons in an atom stay in different "shells." In the first shell: shell "K" there are 2 electrons, in the second shell, shell "L" it can have up to 8 electrons and in the third shell, shell "M" it can have up to 18 electrons.

An atom is mainly space, in fact the distance from the nucleus to the first electron shell is about 10^4 times the size of the nucleus.

A single atom of an element rarely exists on its own, except in the case of the inert gases. More common form of element are molecules where 2 or more atoms join together by covalent or metallic bond ... [Semester 2 Examination]

Ken proceeded to discuss metallic, covalent and ionic bonding, molecules, lattices and isotopes without making any reference to models. This essay stands as counter-evidence suggesting that the modelling progress described to this point was tentative and in need of reinforcement. In Ken's defence, it should be remembered that this essay was the last question of a 3-hour final examination and his response may be as much an artefact of the technical nature of the assessment as it was an index of his mental models. Other studies have encountered similar situations in which standard tests and assessment methods do not measure the factors that have been emphasised during instruction (e.g., Raghavan & Glaser, 1995). It is asserted that new curricula and new learning methods require concomitant changes in the assessment process (Wolf, Bixby, Glenn & Gardner, 1991). It seems that this is especially necessary where conceptual change strategies and modelling skills are emphasised in science teaching.
Discussion

Status of Ken's Conceptions

At the beginning of Year 11, Ken's mental model of an atom was dominated by a model comprising a substantial nucleus surrounded by close electrons moving in an electron cloud. The accompanying diagram of the electron cloud was sufficiently diffuse to suggest that this conception was Intelligible (I). Ken's electron cloud model was not Plausible (IP) because he chose diagram 2 in Figure 13 which showed electron orbits and he failed to approve diagram 5 (electron cloud model). His fluorine atom drawn about three weeks later was a classic electron shell model.

Ken's notion that an atom was very small, "10^-5 mm" in size, is compatible with the scientific concept, thus, this conception was at least Intelligible (I). No higher status can be ascribed because he provided no further details. Ken's belief that both electrons and atoms were constantly moving, and his use of particle motion to explain a range of kinetic theory phenomena, suggests that he was comfortable with the scientific model of dynamic atoms and molecules; this conception probably qualifies as Plausible (IP). Within the kinetic theory context, the 'ball' particle conception appeared to be Plausible (IP) to Ken because he used it to describe the states of matter and to explain gas pressure.

Semester 1 concluded with Ken describing an electron cloud in terms that lent weight to the assertion that he found the scientific conception of an electron cloud Plausible (IP). His atomic proportions and spaciousness were reasonably scientific and were also classified as Plausible (IP) because of the frequency and consistency with which he used this conception. These assertions are supported by the excerpt:

Ken  Heavy as it may be, the nucleus is extremely dense, it has the diameter of \(\frac{1}{100000}\) of the diameter of the whole atom. The electrons wizz around outside the nucleus at very, very high speed so that you couldn't see them if atoms were big enough to see. The position of the electrons is very far from the nucleus.

 [Semester 1 Examination]

By the year's end, Ken's atom was more spacious with a tight central nucleus surrounded by electrons in relatively indistinct (or partly diffuse) orbits. He volunteered this point on several occasions. The proportions of his latter diagrams showed much more space between the nucleus and the electrons and Ken's diagrams were the most spacious in the class by this time. The scientific aspects of this conception were thus adjudged Plausible (IP). Electron cloud explanations offered during the interview confirmed this assertion, when he said, "It's like a cloud, and the electrons travelling really very fast and it looks like it's all over the place ... sort of like
cloudy traces of the electron cloud" (italics added). What is more, he exchanged diagram 2, the orbits model (at the start of the year) for diagram 5, the electron cloud model (at the end of the year). On one occasion, Ken's conception showed signs of being Fruiful (IPF) and that was when he described a covalent bond as "the electron clouds ... join up because the electrons are shared where the balls touch." He would need to use this conception consistently and more often to support the ascription of Fruiful status on a permanent basis.

Ken's diagrams were probably as good as can be expected from Year 11 students; after all they were being asked to draw a diagram that is really not drawable. Student alternative conceptions are to some degree a product of the activity: asking students to sketch their mental model implies that it can be done. Strike and Posner (1992) and Vosniadou (1994) described how instructional activities like these can generate alternative conceptions.

The question "What had happened to Ken's conceptions?", is worthy of consideration. At the beginning of the year, Ken maintained a single model of the atom. Not only had he broadened his view to include at least three models, his mental model of an atom appeared to have moved from a planetary conception towards a diffuse electron cloud model (though not completely). An important observation was that he preserved diagram 2 (the 3-dimensional orbits model) throughout and added diagram 5 (electron cloud model) to his conception. His qualifying comments all relate to diffuseness and motion. He also described covalent bonding as electron cloud overlap. It appears that Ken's conceptual restructuring was predominantly assimilation or conceptual capture (Hewson, 1981, 1982; Posner et al., 1982). There may have been some conceptual exchange, however, no unequivocal supporting evidence emerged.

There was no evidence that he had experienced conceptual conflict or dissatisfaction during this change. The change consisted of adding a belief (like "the arrival of two elephants" at the zoo, Hewson, 1981, p. 386). The addition of beliefs consisting of a "new strong rule that plays a frequent role in problem solving and explanation" or a "new part-relation" is conceptual change (Thagard, 1992a, p. 35). The majority of Ken's conceptual changes were piecemeal accretive additions (Duschl & Gitomer, 1991; Laudan, 1984; Villani, 1992) thus characterising his restructuring as incremental (evolutionary) rather than revolutionary.

Ken's changes were more than a growth in expertise because he used this new information to look at problem situations in a new and more facile way; however, it seems premature to call his change "strong" or "radical" restructuring (Carey, 1985, 1986; Vosniadou & Brewer 1988; Vosniadou, 1994). There is simply insufficient
evidence to consider whether or not he has ontologically changed his model of atoms and molecules (Chi et al., 1994).

Modelling Ability

Ken commenced the year asserting that one model out of eight described an atom. His own drawing sufficiently resembled diagram 2, Figure 13, to support the claim that he maintained a single atomic model. During Semester 1, he moved to a position where he maintained three models - electron clouds, electron shells and spheres. Each of these models showed signs of being content specific. As described above, his model of an atom lost its semi-discrete structure and assumed a more diffuse and dynamic form. These data support an assertion that, at the beginning of the year, Ken was a Level 1 modeller and that he advanced to a Level 1/2 by the close of Semester 1. The basis for this assertion is that he added concurrent models and he moved his focus from structural to functional attributes.

Early in Semester 2, Ken provided further evidence that he could identify the shared and unshared attributes of metaphors and analogical models. With the advent of organic chemistry, Ken's modelling powers blossomed. Having made and discussed a variety of covalent molecular models over a month of instruction, he critiqued ball-and-stick and space-filling models saying that "well, they are models so they are just similar." He also began to consistently speak of models as "representations." He facilely discussed multiple models using space-filling, ball-and-stick, electron-dot diagrams, structural diagrams, the balloons analogy and raft analogy. The transcripts show that Alex and Ken were comparable modellers. Ken rapidly advanced to become a sound Level 2 modeller with hints of Level 3 capabilities.

There was, however, a flaw in Ken's modelling skills. Ken experienced difficulty in thinking of formulae as models. Even though students possess sufficient chemical knowledge to correctly manipulate models, they do not always apply this knowledge in a critical manner when dealing with proportional models. If a student fails to recognise that a single item (e.g., a formula) can represent two or more objects or situations, it is difficult for that student to become dissatisfied with his/her limited interpretation. Dissatisfaction depends on conceptual conflict. A student must recognise that a scientific interpretation actually exists before that conception can conflict with his or her prior conception. And only when the scientific conception achieves a higher status than the student's prior conception can conceptual exchange result (Hewson, 1981, 1982; Posner et al., 1982). Also, when thinking about modelling, conceptual change should also be considered from the ontological perspective. If the student thinks that a model is reality, if they think that atoms and molecules are material entities in the way that Ken thought that the formula NaCl
implied that it was an independent molecule, then they are unlikely to restructure their thinking to conceive of formulae as models (i.e., atomic relations or proportional statements). With respect to chemical formulae as models then, it seems that Ken did not fully appreciate the difference between atoms, ions and molecules.

**Intellectual Position**

When these data and interpretations are considered from an intellectual development perspective (Perry, 1970), it appears evident that Ken made significant progress during the year. However, this progress is not so easy to quantify or classify. Ken never spoke like a Dualist, that is, that there is just one right answer to each problem; Ken's curiosity, inquisitiveness and willingness to 'have a go', even if it meant making an error, suggests that he was atypical. Another study, involving Ken's physics learning (Harrison et al., 1995; Harrison & Grayson, 1995) revealed that he was an 'original' problem solver. Ken was rarely constrained by the norms of right and wrong. It has already been pointed out that Ken's numerical assessment was not outstanding, yet he was a constant source of stimulating ideas and questions in class.

How to describe Ken's intellectual development is problematic. It has been suggested by colleagues, and the author's anecdotal experiences adds some support, that Ken's Asian background may have introduced non-western thinking processes. This issue will not be pursued here but is worthy of separate research and analysis. Suffice to say that by the end of Year 11, Ken showed distinct elements of Relativism. He was comfortable with multiple models, he did not try to classify alternative models as right or wrong, and he was able to critically evaluate individual models by identifying their shared and unshared attributes. Yet he failed to recognise one important group of models - chemical formulae.

**Summary**

The several perspectives on conceptual status, modelling ability and intellectual development individually and collectively support the claim that Ken's conceptions changed over two semesters. Apart from the rapid change in his modelling ability late in Semester 2, none of the changes were dramatic, that is, they were evolutionary rather than revolutionary. One change did not fit this pattern. The advances in modelling ability that occurred during the organic chemistry unit appear to have been more dramatic and sudden. Nevertheless, without more detailed data, no claim for a more revolutionary change can be sustained.
Chapter 5f

Case Study 5 - Mary the Multiplist

Biographical Sketch

Mary, one of three girls in the Year 11 Chemistry class, spent most of the year working closely with Gina. Mary was similarly reserved in class and both girls rarely volunteered comments during class discussions. Mary was constrained by her reticent nature, her limited knowledge and the assertive behaviour of boys like Dan and Tim. Mary also had difficulty understanding and explaining the more conceptually taxing items in the syllabus. Nevertheless, Mary was the type of student who could succeed by rote learning the factual items like formulae, equations and chemical properties. Mary's problem solving abilities were limited: she experienced difficulty with calculations involving more than one or two steps and could not successfully analyse and resolve detailed problems. Her approach to problem solving was typical of a novice as it consisted of substituting values into equations in the hope that the answer would appear (Carey, 1986; Chi, Glaser & Rees, 1982).

Mary was keen to succeed and was diligent both in classwork and homework. Her level of achievement oscillated between a middle D and a low C grade. Gina and Mary's reserved nature inhibited Mary's learning because neither girl was forthcoming in discussing chemistry problems with each other or other class members during group work like laboratory activities and problem solving sessions. It seems that the classroom culture, steeped as it was in male dominance, compromised Mary's learning more than it did Gina's.

Mary's Mental Model of an Atom

Commencement of Semester 1 Mary produced her first sketch of an atom in the first week of Term 1; the diagram is copied in Figure 39(a) and resembled a space-filling diatomic molecule like O₂ or H₂ rather than a single atom. In the accompanying comment she stated that "I don't think an atom can be seen by the naked eye or a strong microscope." Her reaction to Figure 13 ("Which diagrams do you like? and which do you dislike?") was to choose in order, diagrams 2 and 3 (simple and complex three-dimensional orbits models) and reject diagrams 5 and 8 (electron cloud and stationary electron models). Mary's diagram and her choices from Figure 13 indicated that she visualised an atom as a three-dimensional planetary-like structure. It also suggests that she pictured atoms as discrete concrete objects (as opposed to diffuse cloud-like structures).

The structure of matter test Mary's responses indicated that she had a sound understanding of the mole concept but she was able to write appropriate chemical
equations for straightforward chemical reactions. When asked to draw a diagram of a fluorine atom of atomic number 9 and mass number 19, she first of all sketched a diatomic model (F₂) and followed this with the 'standard' atom consisting of a large central nucleus surrounded by close electrons. Both diagrams are reproduced in Figure 39(b).

(a) Mary's first diagram of atoms.

(b) Mary's diagram of a fluorine atom.

Figure 39: Mary's early diagrams of atoms (Redrawn for clarity).

Models of atoms and molecules  Several weeks into Term 2, a kinetic theory pretest was administered in which Mary described her conception of the arrangement of water molecules in water and steam at 100°C (i.e., water boiling in a kettle). Like several other students, she drew the water molecules as separate spheres [see Figure 40(a)]. Later in this pretest, she described the air particles in a flask [Figure 40(b)] this way:

Mary  The air is able to move about freely without having to leave the flask. When the air is heated, it expands and needs somewhere to go. The only place to go is into the balloon. ....  When air is heated, it expands and the particles begin to bump into each other.  [Kinetic theory pretest]

Apparently, Mary did not visualise particles as being in a state of constant motion; or was it just her poor expression? She did recognise the particles' freedom to move but described the particles as starting to bump into each other as a result of heating, rather than seeing the increase in collision rate as a function of temperature.
For the end of semester examination, Mary chose to write about the gases carbon dioxide and oxygen rather than answer the atoms essay. No information about atoms per se, or models, could be gleaned from this essay. Nor did Mary attempt to answer several questions on this paper which could have yielded information about atoms, molecules and models. The inability of weaker students like Mary to even attempt questions, or recognise what the questions were asking, reduced the amount of available data and limited the interpretations.

(i) In the water?

(ii) In the steam?

(a) Water molecules in water and steam at 100°C.

(b) Air particles in a heated flask.

Figure 40: Mary's diagrams of liquid and gas molecules (kinetic theory pretest).

The atomic structure and bonding pretest This pretest was administered early in Term 3 and question 1 opened with: "What do you think an atom looks like? If your idea of what an atom looks like could be compared to an everyday object ... say how the atom is like that object." Mary's response is shown in Figure 41 and was accompanied by the following comment:

Mary An atom is similar to a fan. In the middle it has protons and neutrons and buzzing
around it is electrons. [Atomic structure and bonding pretest]
Figure 41: Mary's diagram of an atom drawn for the atomic structure and bonding pretest.

During the structure of matter topic in Term 1, the fan analogy was used to model an electron cloud and to present the concept that 'electrons are everywhere all the time.' Mary described the structure of the analogical model but did not state how the fan analog was like an atom. Question 1(b) then asked, "How is the atom unlike the object you have chosen?" This time, Mary stated that

Mary When the fan is turned off[+] the blades are attached where as electrons are not attached to protons and neutrons. [Atomic structure and bonding pretest]

Based on these written comments, it must be concluded that Mary's analogical model was limited to structural mappings. She was able to identify the shared structural attributes but was unable to identify the shared functional attributes; this observation seems characteristic of conceptually weaker students. The point of the analogy was that when the blades are rotating, the fuzzy disc indicated that the blades are functionally everywhere in the disc; that is, the electrons surrounding the nucleus are everywhere all the time. The analogy was demonstrated using the classroom's ceiling fan. When the fan was switched on, small paper balls were thrown into the 'disc' and most were hit by a blade; when the fan was turned off, it was easy to throw a paper ball through the disc without it being hit by the blades. The fact that she used material attributes to model electron behaviour (fan-blades connected to the fan's motor) suggests that Mary visualised electrons as physical items rather than a region in which processes (like bonding) take place.

To question 2 asking "Are all substances made up of atoms. Explain?", Mary made no response. She had written "No" but had partly rubbed out this answer. Was she unsure? Her conception remains an open question.
The next question "Have you heard of an 'electron shell'" received a cursory "Yes." In explaining what this comment meant to her, she simply wrote, "The outline of an electron." Question 4 asked the same question about an 'electron cloud' to which she replied

Mary Yes. This is what occurs in an atom, it is what you see buzzing around the protons and neutrons. [Atomic structure and bonding pretest]

The use of physical terms "you see the [electrons] buzzing around" presents an image that was much more like the planetary model than a diffuse electron cloud. Mary's electron cloud was more concrete than the abstract scientific conception.

Finally, question 5 asked her to estimate how far from the nucleus the electron cloud started and finished if an atom was magnified so that the nucleus was 1 cm in diameter.

Quest. How far away would the nearest electron be?

Mary About 1 cm away from the atom.

Quest. How far away would the farthest electron be?

Mary On the opposite side of the container in which the atom is. [Atomic structure and bonding pretest]

The comment "on the opposite side of the container" may be a reference to the idea that gas particles fill their container or she may have thought that the particles must be as far from each other as possible. Whatever the case Mary appears to have constructed a 'synthetic model' (Vosniadou, 1994). Synthetic models are generated when students uncritically combine scientific concept attributes with alternative conception attributes, or they unite attributes from two or more scientific concepts. Situations like this can only be resolved when the student recognises that the attributes (or conceptions) are incommensurable (Hewson & Hewson, 1984) and the ensuing dissatisfaction stimulates them to reject the conception that has the lower status. Hewson (1981, 1982) cogently argued that unless the rival conceptions were at least Plausible (IP), dissatisfaction could not arise. The data describing Mary's conceptions suggests that it was unlikely that the status of any of her conceptions had exceeded Intelligibility (I). It is in this type of situation, argues Vosniadou, that uncritical melding of conceptions most often takes place.

Atomic structure and bonding test By this stage, Mary was able to interpret notations like $^{16}\text{O}$ and was also able to correlate atomic numbers and an element's position on the periodic table with its bonding properties. She appeared to be familiar with Lewis electron-dot diagrams but was not able to use them consistently in practice. The covalent electron sharing diagrams and the ionic electron transfer diagrams that she
sketched in solving problems were correctly drawn but were applied to the wrong elements. For instance, magnesium sulfide was drawn covalently and water was shown as ionic. While she knew how to correctly choose the bonding type when presented with elements on the periodic table, it seems that she did not use the periodic table when treating real elements. This was typical of Mary's approach to problems: she applied a method and hoped. This is a reported characteristic of inexperienced problem solvers (Chi et al., 1982).

Mary also failed to recognise the error in the statement which spoke of "one molecule of copper (II) carbonate [and] one molecule of copper (II) oxide". When asked, "Is the statement correct or not?", she wrote an incorrect equation for the reaction and replied, "No because the equation is not balanced." Based on the fact that she had not mentioned or discussed models thus far, it is likely that she simply accepted the statements "molecules of" as fact and did not consider them as representations, much less delve into the appropriateness of the label "molecule."

Her inability to recognise that formulae were limited models that said nothing about the substance's bonding was reinforced in the next question which asked her to "describe the bonding in all the substances involved when a piece of magnesium ribbon burns in air." The question warned students to "think carefully!" Mary stated that "magnesium oxide is bonded ionically" and proceeded to draw a Lewis electron-dot diagram of a covalent molecule of MgO. Viewed from Grosslight et al.'s (1991) perspective, these statements suggest an unquestioning acceptance that models represent the way things really are. She may have concluded that the formula MgO meant that one atom of magnesium was joined to one atom of oxygen. This would account for her bonding one magnesium ion to one oxide ion. Thus far, Mary is classified as a Level 1 modeller.

*Modelling in the Organic Chemistry Unit*

*Organic chemistry pretest* The first three questions probed the students' conception of "organic", "hydrocarbon" and asked them to classify 15 compounds as either organic or inorganic. Question 4 asked: "Describe an atom of carbon." Mary's diagram is shown in Figure 42(a) and her explanatory notes were limited to saying that "the electrons are all moving." This diagram was a significant improvement over her diagrams drawn at the commencement of the year and in the first test. The present diagram shows the electrons moving in shells with hints of an electron cloud; however, without supporting information, it is difficult to ascertain the status of Mary's electron cloud conception.

When asked to choose between the space-filling and ball-and-stick molecular models, Mary preferred the space-filling model and explained that "it shows real bonding
whereas the ball & stick doesn't look realistic." The use of clauses like "real bonding" support the classification of Mary as a Level 1 modeller. It is worth noting that she recognised that the ball-and-stick model was a representation, that is, not real. Her comments about ethene's and ethyne's bonds were restricted to identifying C—H, C=C and C≡C as single, double and triple bonds respectively.

(a) Organic pretest diagram of a carbon atom.

(b) Organic chemistry worksheet diagram of a carbon atom.
(c) The atom sketched in the free-form essay.

Figure 42: Mary's diagrams of carbon atoms drawn during the organic chemistry unit.

*Organic chemistry worksheet* The organic chemistry worksheet was completed following instruction on carbon bonding, alkanes, alkenes and alkynes. Mary was asked to describe the bonding found in alkanes, alkenes and alkynes and to illustrate each type using appropriate diagrams. Mary's response was limited to drawing the three diagrams shown in Figure 43. She again drew a carbon atom and this is reproduced in Figure 42(b).
When asked if there were any similarities between molecules of ethene and propene that made them different from butane, she wrote: "The[y] have double bonds which means they are unable to rotate." The question "How could you explain or describe this similarity?", was left unanswered.

![Diagram of three types of bonding]

Figure 43: Mary's representations of the three types of bonding found in alkanes, alkenes and alkynes.

The last page of the worksheet posed a series of questions relating to physical molecular models.

**Quest** Look again at the ball-and-stick models that we have been constructing and using. Are these models accurate representations of the atoms and their bonds?

**Mary** The atoms are not joined together with stick-like projections they are bonded directly to one another. [Organic chemistry worksheet]

This statement correlates positively with Mary's opinion that space-filling models were 'real bonding.' She did not, however, describe how the balls in the models represented atoms.

The next two questions asked Mary to comment on the extent to which the hydrogen, carbon and chlorine atomic models in a ball-and-stick model of cis-1,2-dichloropropene were like and unlike real atoms. The final two questions asked how the carbon-carbon bonds and the carbon-hydrogen bonds were like or unlike real bonds. Mary was unable to comment on either of these items apart from stating that the carbon-carbon bonds and the carbon-hydrogen bonds were "tetrahedral, planar or linear." This response indicated that Mary's conception was weak and/or tentative. Whether or not she had an understanding of these bonds, is indeterminate.

**Free-form essay** For the essay entitled "Structure and bonding of a hydrocarbon", Mary wrote two full pages which contained the following relevant extracts:
Mary  This structure [methane] is known as a tetrahedral meaning that all carbons are surrounded by four other atoms. The angle of these bonds are 109°. The single bond is able to rotate and is the most stable of all the bonds. [Figure 44(a)] ....

A single bond has what is known as a s bond which means that the electron bond is between the two carbons.

The second bond is known as a double bond which means that the two carbons are joined by two bonds. [Figure 44(b)]

This structure is known as a planar which describes the way the two atoms and four hydrogens are arranged. The angles of the bonds are 120°. The double bond is unable to rotate but is the strongest bond of them all ... it has a s bond between the two carbons and a p bond on either side of the s bond.

The third bond is known as the triple bond meaning that there are three bonds joining the carbons [Figure 44(c)] The third structure is known as linear for it makes a straight line. The angles of these bonds are 120°. The triple bonds make the molecule immovable, this bond is very weak. [Free-form essay]

This essay contained a mixture of correct and incorrect statements. Mary was a diligent student and the information presented in this answer is dominated by facts which she had probably rote learned. The knowledge is superficial and does not examine the processes underlying bonding and molecular shapes. The essay was also devoid of critical comments comparing and contrasting the various analogical models that Mary had encountered during the preceding weeks. Mary's effort must not be trivialised because it was her best effort; nevertheless, it is important to recognise that the essay was simply a descriptive recall of the basic facts that had she had collected to this point.

The comment "a s bond ... means that the electron bond is between the two carbons" is worthy of note. Even though Mary summarised carbon-carbon bonds as C—C, this statement shows that she understood the — to mean bonding electrons.

The interview  Following introductory comments, the interviewer asked Mary to sketch and describe an atom. This sketch is found in Figure 43(c). and is almost identical to the diagram she drew a couple of days earlier. She also was shown Figure 13 and asked to choose the diagrams she liked and disliked.

Mary  First it's got a nucleus [Right?] and carbon has six protons and neutrons and ... an electron shell which contains two electrons and a different shell that contains four electrons ... that's carbon

Int.  Look at Figure 13. Which diagrams best suits your idea of what an atom looks like?
Mary: Um, ... I'd say that one [OK, number 5 - any others you can circle? as many as you like] um, ... that one [diagram 2] ... and that one [diagram 8]. [Interview]

(a) A single carbon-carbon bond. (b) A double carbon-carbon bond.

(c) A triple carbon-carbon bond.

Figure 44: Mary's diagrams of single, double and triple carbon-carbon bonds (redrawn for clarity).

The interviewer then asked Mary to rank these three diagrams from most preferred to least preferred and the final ranking became: diagram 2 (three-dimensional orbits model), diagram 5 (electron cloud) and diagram 8 (stationary electrons). This was an interesting development because up to this point, Mary had not volunteered more than two models (previously she drew an electron shell model and a ball model). It is interesting that she prioritised the electron cloud model but then relegated it to second preference. This was the first indication, over two semesters, that Mary favoured a series of different models and also the first time she explicitly chose or drew an electron cloud model. It appears that she was beginning to recognise that the different models represented aspects of reality, not reality itself.

The interviewer then showed Mary a ball-and-stick molecular model of 1,2-dichloroethane and asked her to describe and explain its shape.

Mary: I'd say that was planar .... planar shape, yea.

Int.: Um, why did it have that shape?

Mary: I'd say it's a tetrahedron. ... It's a tetrahedral shape.

Int.: And why do you think it's a tetrahedral shape?
Mary  Carbon has four bonds on each side of it and tetra meaning four ...

Int.  Tetra means four and it's got four bonds. Why did it go into that shape and not another shape do you think?

Mary  Um ... ... I'm not sure.  

[Interview]

This response pattern mirrors Mary's comments in the free-form essay: While she could recall the facts, she could not explain why the molecule had this structure, nor could she recognise that this representation was a context-bound best-fit model.

The discussion moved to the ball-and-stick model of trans-1,2-dichloroethene for which Mary was asked, "How is this molecule different from the previous one?"

Mary  First of all it's a planar shape and there's double bonding and its unable to rotate around and it's stronger than the other one. ....

Because it's double bonded and it needs to have four bonds but it's got two bonds there and two bonds there ... carbon has four bonds and so they end up like that.

Int.  Why is this molecule sticking out here in this other direction?

Mary  Because they have to be they're arranged um, ... evenly around the carbon atom.

Int.  Try to tell me in normal words, like everyday language, what you're thinking.

Mary  They're actually, they've been pushed around as far as possible from each other because they're so that, that, ...

Int.  OK, here's a third molecule this is ethyne or acetylene ... how would you describe this molecule's shape?

Mary  It's linear ... it's just a straight and it's triple bonded at 180 degrees.

Int.  And why did this molecule have this shape?

Mary  Because it's got triple bonding and there is only one more um are for it so it goes straight out.

Int.  So why does this white atom here stick out of the end, tell me again?

Mary  Because they're all, the electrons are pushing against each other so it has to be out evenly apart ... so.  

[Interview]

This is an interesting exchange because it depicts Mary's struggle to explain what she had learned. She knew that her description was right, but the best reason she could offer was, "because they have to be." It was only after much probing that Mary introduced the idea of electron repulsion. Although Mary had seen the balloons analogy, which demonstrated bond repulsion, she did not access this analogy for her explanation.
This discussion highlights the value of one-on-one discussions with low achieving students. With help, they can work through an idea and arrive at improved understanding, but they need an understanding guide. This is where peer tutoring is so useful, and this could be where Gina, and especially Mary, missed out.

The focus of the interview then moved to a comparison of ball-and-stick and space-filling models. The interviewer showed Mary both types and asked, "Which model type is more appropriate, the space-filling ones or the ball-and-stick ones?" The discussion proceeded thus:

Mary  The space-filling ones. [Why?] Because they, in reality you don't see all the bonding electrons but just see the actual stick molecules, they are practically joined together.

Int. So you can't see these sticks? What do these sticks represent?

Mary  Um, bonds ... the bonds.

Int. Do either of these models types accurately describe the molecule?

Mary  No, not really ... [Why not?] They don't really know what shape an actual molecule is or how it is shaped, what the proper carbon to hydrogens really is.

Int. What about how it looks? Do you think these accurately describe how it looks or represents how it looks?

Mary  Um ... I'm not sure.  

[Interview]

In this exchange, Mary initially spoke of "reality" but then qualified her comment by adding, "they don't really know what shape an actual molecule is ..." In view of her acquired ability to accept multiple models, and these statements, a real change in her modelling level was becoming apparent. It is claimed that Mary was now a Level 1/2 ("I'm not sure", "they don't really know"). The tenor of the discussion sounds like a firm, "they" don't know, accompanied by a tentative, "I'm" not sure. Modelling level must be determined by what the student thinks, not what others think.

In view of the fact that Mary had made no mention of the balloons analogy, she was cued with this analogical model and asked if she recalled its use.

Mary  [Mr Harrison] used the electron-dot diagrams and the actual structures.

Int. So electron-dot diagrams, any other models that you can remember?

Mary  No not any other models.

Int. What about using the balloons?

Mary  Oh yea, we used balloons.
Int. Can you tell me about that?

Mary Um, he just joined them up and where they joined, that was the carbon atom and the balloons, they were the shape of the repulsion showing how they were all pushing away from ... and why it was always in the same shape.

Int. What did he do next?

Mary He popped one to show the different, um, bonding ...

Int. And what happened when he popped one?

Mary It made another molecule, another compound.

Int. Did that help you understand about shapes at all?

Mary Yes.

Int. How did it help you?

Mary Well it showed us how many bonds carbon has to have um, showed us the shapes and ... um ...

Int. What shapes could you see?

Mary Um, we saw when there were two balloons that it was a linear one and two pushing apart in a line, um tetrahedral when there were four balloons all going off in different directions but they were still together um, planar when there.

[Interview]

Once cued to the analogy, Mary was able to describe the balloons’ behaviour and relate some of their features to tetrahedral, planar and linear molecules. The need to extract the shared attributes from her indicated that the analogy’s status, for Mary, was probably limited to Intelligible (I).

The interviewer then drew Mary’s attention to the Lewis electron-dot and structural diagrams. The discussion went like this:

Int. Electron-dot diagrams. Are the electrons situated between the atoms here? Do you think, or not?

Mary Just moving around.

Int. What about this one here, the hydrogen ...

Mary Yes.

Int. So they're sitting there between the carbon and the hydrogen.

Mary ... Yes ... They're constantly moving.  

[Interview]

The degree of cuing in this instance reinforces the previous notion that the status of these representations were no higher than Intelligible (I). Mary was reluctant to
volunteer comments even though she agreed with the interviewer’s propositions. It
appears that she did not have enough confidence in her understanding to make
predictions about these models.

Semester 2 examination  For the essay question, Mary decided to write about organic
chemistry. The question read: "Discuss the nature of organic compounds and their
role in our lives." The five suggested headings included types of organic compounds,
bonding, homologous series, reactions and the petroleum industry. There was a
strong resemblance between this essay and the free-form essay written about two
weeks earlier indicating that Mary had memorised compound names, formulae,
properties and simple reactions. Her description of alkanes, alkenes and alkynes as
tetrahedral, planar and linear was almost a word for word repeat of the free-form
essay. Similarly, there were no specific references to models (again, as in the free-
form essay) until she made the following comment:

Mary  In a double bonded molecule where the names have the suffix "ene", the double
bonded molecule forms the shape of a planar (for it looks like a plane with two
sets of wings). Because the two carbons are double bonded [Figure 45(a)], there is
only room for two hydrogens on each carbon. [Semester 2 Examination]

\[
\begin{align*}
&\text{H} \\
&\mathrm{C} \quad \mathrm{C} \quad \text{ethene} \\
&\mathrm{H} \\
\end{align*}
\]

(a) Plane with two sets of wings.

\[
\begin{align*}
\mathrm{H} &\quad \mathrm{C} \quad \mathrm{C} \quad \mathrm{H} \\
&\text{ethyne}
\end{align*}
\]

(b) Linear shape - straight line.

Figure 45: Mary’s "plane" analogical model for ethene and linear model of ethyne.

Mary had written next to the diagram that the angles were 120° but she drew the
structural diagram like a "plane" to which she likened the molecule. In the next
paragraph, she used another simple analogy to describe an alkyne:
Mary had not chosen to use an analogy or model for almost two semesters and during the interview she had to be cued in order to even recall the major in-class analogy. And yet, here she is using two simple self-generated analogies to explain the planar and linear structure of double and triple bonds. This represents a significant advance in Mary's thinking. Not only did she choose three models for an atom during the interview, she was at last able to use analogical models to describe her mental model of the structure of organic compounds.

**Discussion**

*Status of Mary's Conceptions*

At the beginning of the year, Mary's conception of an atom was very basic; her sketch was ball-like and from Figure 13 she chose the three-dimensional orbits diagrams and rejected the electron cloud model. She stated that she thought atoms were too small to be seen, however, this opinion was not stated with conviction. Thus, Mary's rudimentary model was at best Intelligible (I) and from her standpoint, the scientific conception must be rated as having no status.

Four weeks of instruction led Mary to sketch a rough orbits diagram alongside her ball atom model. At the same time, she acknowledged that an atom was mostly space. Eight weeks later Mary reverted to the balls model (kinetic theory pretest) and tentatively proposed that gas particles were moving. Throughout Semester 1, the electron cloud concept was absent from all her statements and at her one formal encounter with this model, she rejected it outright. Thus, at the close of Semester 1, the scientific conception still had zero status for Mary and her ball conception was at best Plausible (IP).

Mary graduated to a planetary 'shells' model early in Term 3; meaning that her conceptual development lagged about one semester behind the higher achieving students. She was able to use the fan analogy to model electrons in a structural sense but was unable so say much more about electron shells and clouds other than to admit that she had heard of them. She stated that an electron cloud was related to the rapid motion of the electrons. It is probable that Mary's electron cloud conception had at last achieved Intelligibility (I).

The case study shows that up to and including this time, Mary was a Level 1 modeller. The proposition that Mary probably believed that her models of atoms and molecules were reality, implies that her conception of atoms (balls, orbits, shells) held a higher status (IP) than the scientific conception. Hewson (1981, 1982) established that the scientific conception cannot generate dissatisfaction for the intuitive conception until
until the scientific conception is at least Plausible (IP). The absence of this condition explains why Mary's conceptions could not be exchanged. The best that she could achieve in these circumstances was to assimilate or conceptually capture the scientific ideas resulting in co-existence of the scientific and the intuitive conceptions.

Following the atomic structure and bonding unit, changes to Mary's mental model of atoms were discerned during the organic chemistry unit. For the organic chemistry pretest, she drew a diagram showing the electrons moving in shells with hints of an electron cloud. In this pretest, she talked about "real bonding" and "realistic" models but went on to acknowledge that ball-and-stick models are only representations. These comments suggest that she may have been struggling to make sense of disparate ideas. Subsequent statements indicate that she was in a transition state.

In the free-form essay, Mary's descriptions were dominated by factual recall type answers. All the same, snippets of information like "the electron bond is between the two carbons" and her promotion of the electron cloud diagram (Figure 13) to second favourite showed that her mental model was changing. Similarly, her explanation that molecular shapes are like they are "because they have to be" was modified, with encouragement, to include statements like, the atoms have "been pushed around as far as possible." And even this idea was further refined as "the electrons are pushing against each other so it has to be out evenly apart." It is asserted then, that Mary's conception of electron behaviour as being cloud-like and responsible for bond structure and molecular shape was at least Intelligible (I) and possibly Plausible (IP). This characterises her conceptual development as piecemeal and accretive (Duschl & Gitomer, 1991). The most likely explanation of Mary's conceptual restructuring was conceptual capture or assimilation.

Modelling Ability

The above changes in Mary's conceptual structure were accompanied by an improvement in her modelling ability. By the close of the year she was tolerant of multiple models (three concurrent atomic models) and she was able, albeit in a limited sense, to compare and contrast molecular models. She never appeared to be fully at ease with competing models, thus the earlier conclusion that she had advanced to a Level 1/2 modelling status is sustainable (Grosslight et al., 1991). The hints of Level 2 in certain contexts was not maintained.

Intellectual Position

From Perry's (1970) perspective, Mary commenced the year a clear-cut Dualist. Low achieving students rote learn facts because they believe that this is what is expected of them, they accept the right answers, learn them and reiterate them in tests and examinations. The plurality of models and explanations in chemistry obviously
worried Mary. By the end of the year, she willingly talked about alternative models but there was repeated evidence that she believed that one answer was right. This is typical of Multiplism. To paraphrase the Multiplist's dilemma: "I know that I've been shown a lot of answers, but my job is to discover which one is right." The case study indicated that this would be a fair assessment of Mary by the year's end.

Summary

Even though Mary's intellectual gains were small in comparison with the more successful students, her conceptual growth was commensurate with her academic ability. Her conceptions did change and she achieved measurable gains in modelling ability. Whether Mary's conceptions are assessed from the viewpoints of Carey (1986, 1991), Hewson (1981, 1982), Hewson and Hewson (1984, 1992), Posner et al. (1982), Strike and Posner (1992) or Thagard (1992a), her conceptions of atoms and molecules were restructured.

Issues of opportunity For students such as Mary, learning can be constrained by both social and intellectual factors. Low achieving students often function at the class periphery, and this was often true for Mary. However, social interaction with other students significantly improves learning (Solomon, 1987), particularly when low achieving students are peer tutored by capable students, or even where the low achieving student simply listens in on discussions and problem solving interactions between higher achieving students. In this class, both Mary's and Gina's learning may have been affected by reduced opportunities. Both girls had equal access to the physical resources because the school had an abundance of equipment. But it was in the social milieu of the class where both girls suffered reduced interaction in the social/intellectual learning discourses that took place throughout the year.

In this sense, a significant educational event occurred during the interview. Mary said that molecules were shaped the way they are "because they have to be." If the interviewer had just accepted that reply, Mary would not have been stimulated to try to explain what she suspected was true, that is, that molecular shapes are a result of pairs of bonding electrons repelling each other. The fact that the interviewer took the time to work through the problem with her encouraged her to offer an explanation that was scientifically appropriate. This event had a motivational effect on Mary (Pintrich et al, 1993). Probably, this was one of the few times in Mary's science education that she had felt sufficiently encouraged to "go the extra mile" and for her, it resulted in significant learning.

A strong message for classroom teaching and learning is that teachers can sometimes achieve more for some students by attending to the social interactive fabric of the class than they can by direct teaching. The potential conceptual benefits for students like
Mary are considerable because without a motivational 'push or pull' they will not feel encouraged to attack a problem. And if they do not attempt the problem, there will not be an opportunity for conceptual change.
Chapter 5g

Case Study 6 - Tim the Dualist

Biographical Sketch

Tim was the second Vietnamese student in the class and, as he had spent most of his school-life in Australia, was a fluent speaker of English. Even though he daily lived in two cultures, Tim was well adapted and was a friendly and assertive young man. His principal interests were sporting and social activities with school clearly in third place. Tim was a low achieving student; nevertheless, he was keen to succeed and was active in most class discussions. Unfortunately, he tended to blurt out answers and make comments without thinking through a problem. Early on in the chemistry and physics course, he appeared to be quite able, but after some weeks, his strategy became obvious. He would wait until one of the successful students answered a question and would quickly repeat that answer. When pressed to answer an original question, or to explain the answer he had repeated, it became clear that he was lacking in factual knowledge and understanding. Tim performed poorly in tests, examinations and activities where he had to work on his own. His final grade for the year was a low D.

Tim’s predilection for sport, physical and social activities was understandable: He was good at those things but found academic activities challenging. He performed adequately in group learning activities when working with committed students but tended to waste time and veer off task when working with Jon. Initially, the successful students made genuine efforts to include Tim because he was an affable character, but after a while they tended to avoid him whenever he distracted them or the class. If he had been more co-operative and less inclined to dominate activities, he may have received more help from the successful students.

Tim’s Mental Model of an Atom

Commencement of Semester 1 The first time that Tim described an atom occurred during week one of Term 1; the diagram he drew is reproduced in Figure 46(a). The diagram is a typical solar system model and he described his diagram this way:

Tim

An atom - has an equal amount of neutrons and protons as a nucleus. And are surrounded by electron shells. An atom is invisible but you can identify it under microscopes, eg air particles. [Semester 1 pretest]

When asked to identify the diagrams in Figure 13 that were acceptable, he preferred, in order, diagrams 1, 2 and 8 (two-dimensional planetary, simple three-dimensional orbit and stationary electrons models). He also indicated that diagram 6 (the ball model) was the worst diagram followed by numbers 5 and 4 (electron cloud and orbitals).
An atom - has an equal number of neutrons and protons in a nucleus and are surrounded by electron shells. An atom is invisible but you can identify it under microscopes - eg air particles.

(a) Tim's preconception of an atom.

(b) Diagram of a fluorine atom.

(c) Diagram of an atom drawn for the Semester 1 Examination.

Figure 46: Tim's Semester 1 atomic diagrams.

The structure of matter test  Three weeks later in the topic test, Tim drew a diagram of a fluorine atom [Figure 46(b)]. Apart from labelling the electrons, there were no comments describing particle charges or electron movement. In the only multiple choice question that he answered correctly (one out of ten), he indicated that the statement, "The atomic nucleus makes up most of the volume of an atom" was false. From this answer it can be taken that he recognised that the nuclear volume was small. The incorrect answers given to the other questions showed that he was not competent with the mole concept, formulae or chemical equations.

Models of atoms and molecules  Term 1 concluded with a major test in which Tim scored only 18%. In most parts of this test he failed to write and interpret chemical formulae and equations, and could not distinguish between an atom and a molecule. Early in Term 2, Tim completed a kinetic theory worksheet on which he was asked to describe the arrangement of the water molecules in boiling water and steam in a kettle, and later, in ice and water in a beaker. His responses are shown in Figures 47(a) and
48(b). It appears that Tim held the conception that during boiling, water molecules break up into their constituent elements (Osborne & Freyberg, 1985, p.11). His idea of the spacing between ice and water particles (at the same temperature) is intuitive and resembled Nussbaum and Novick's (1982) findings.

(a) Water molecules in water and steam at 100° C.  
(b) Water molecules in water and ice at 0° C

*Figure 47: Tim's diagrams of water particles drawn during the kinetic theory pretest.*

One of the questions in the kinetic theory topic test required Tim to describe and explain what happens when a car tyre's pressure increases on a hot day. He wrote:

Tim  ... when the temperature in the car tyre increases the velocity of the particles will increase. So when the temperature in the tyre increases, the particles expand therefore the pressure will be increased.  

[Kinetic theory test]

Evidently, Tim understood that gas particles were constantly moving; however, he held the common alternative conception that the particles themselves expand when the substance expands (or increases in pressure) (see Andersson, 1990).

For the end of Semester 1 Examination, Tim wrote an essay describing his conception of an atom.

Tim  A typical atom would consist of something like, a proton and a neutron nucleus (center) which is surrounded by electrons. The first electron shell is made up of one electron which travel at a constant speed (which is very fast). A typical atom would look something like the diagram [Figure 46(c)].  

[Semester 1 Examination]

The diagram shown in Figure 46(c) resembled the two previous diagrams suggesting that his mental model of an atom had not changed during Semester 1. He continued:

Tim  The nucleus is surrounded by an electron shell. The first shell consists of 2 electrons then it starts going up by two (4, 8, 18 etc). ....

The atoms travels around inside matter in very high speeds. Atoms are the light most weightless things in the world / or in matter.  

[Semester 1 Examination]
The single positive outcome of all Tim's comments were his consistent assertions that all atoms were moving. At the same time, he was incapable of using and interpreting notation like $^{16}_8\text{O}$ and could not differentiate between atoms, molecules and ions, nor could he write or interpret formulae and equations. The few items that he answered correctly appeared to be rote facts that he had learned in previous years or during Semester 1.

**Atomic structure and bonding pretest** Tim responded to the question "What do you think an atom looks like ... and say how the atom is like that object?" with:

Tim  
An atom would be best, I think described as small molecule. Using an analogy for an atom I would use a small pea compared with a huge cricket pitch. Another analogy would be using marbles or pool table/snooker balls joined together by straws as arms etc.
An atom consists of a nucleus made up of neutrons and protons, then it is surrounded by electron shells.
Something like this

![Atomic structure and bonding pretest]

The question then asked Tim to identify the ways an atom was unlike his analog. Tim described the unshared attributes thus:

Tim  
Well an atom is 1 millionth of a time smaller than the objects I have chosen. The atoms also move around, this tells us its weightless.

[Atomic structure and bonding pretest]

These answers and descriptions contain two distinctive features: his answers were lengthy but inaccurate. Most of Tim's written work contained one or more alternative conceptions, for example, analogies that were incomplete or unqualified and statements like "atoms are weightless" (stated on two separate occasions). The intuitive notion that particles are so small that they have no weight has been reported by Driver et al. (1994). However, not every comment was flawed as is evident from his answer to the second question: "Are all substances made up of atoms?"

Tim  
Yes, all substances contain / made up of atoms. Solids, liquids and gases are all made up of atoms, they are all atomic structured. Atoms in solids have fixed positions - this means that the atoms do not collide. Liquid atoms are not fixed they move around but very slowly. Atoms in a gas fly around / collide with each other and bounce of[f] each other.

[Atomic structure and bonding pretest]
This comparative description of the three states of matter contained some of the facts and processes expected at this level.

The next two questions asked Tim whether he was familiar with the terms 'electron shell' and electron cloud, and if so, to describe his understanding of these terms. His response to each item was:

Tim: Yes ... 'an electron shell' surrounds the nucleus of an atom. The electron wiz around very fast, they are negatively charged.

Yes ... [an electron cloud] means that there are a lot of electron shells wizing around or lots of electron shells. [Atomic structure and bonding pretest]

This explanation raises some doubt about Tim's conception of an 'electron shell.' Chapter 4 showed that many students visualised the entity, 'electron shell', as an enclosing spherical shell like a clam or egg shell. Tim's comment - "surrounds the nucleus" - indicates that he visualised an 'electron shell' as a structure or discrete boundary. His mental model of an 'electron cloud' as consisting of a number of moving electron shells supports the notion that he imagined an 'electron shell' to be a material object rather than a level, region or status. Ontologically, his 'electron shell' was an object, not a level or effect.

Finally, Tim estimated the extent of the 'electron cloud' around a greatly enlarged nucleus (i.e., if the nucleus was as large as a 1 cm sphere).

Quest. How far away would the nearest electron be?

Tim 100 cm (approx).

Quest. How far away would the furthest electron be?

Tim 1 000 000 cm away. [Atomic structure and bonding pretest]

Although the near estimate was far too close, his further extent, 1000 m, was appropriate.

Indeed, every model that Tim mentioned contained appropriate and inappropriate attributes. Tim's attention span was limited and his comprehension of concepts was the poorest in the class (along with one other low achieving student). The question is, were Tim's deficient and idiosyncratic descriptions and explanations due to a lack of application or lack of understanding (or a combination of each)? Records of Tim's homework performance show that he rarely completed set work and anecdotal recollections of his in-class behaviour recall that he often distracted the class with jokes and attention-seeking behaviours. Tim's poor performance can, to some degree, be attributed to inattention and laziness.
Atomic structure and bonding test  This test result (52%) was Tim's best score for the year. He remained unable to consistently use and interpret statements like $^{14}_7\text{N}$ and continued to confuse atoms, molecules and ions. He demonstrated competence in the use of Lewis electron-dot diagrams and was able to correctly use these models in four different problem settings. Furthermore, he was able to describe electron transfer and electron sharing in ionic and covalent bonding situations respectively. He was partly successful in identifying the error in the statement: "When one molecule of copper (II) carbonate was heated, it produced one molecule of copper (II) oxide plus one molecule of carbon dioxide."

Tim  It's ionic bonding so how can it be called a molecule?

[Atomic structure and bonding test]

Modelling in the Organic Chemistry Unit

Organic chemistry pretest  The year's final topic, organic chemistry, was commenced with a pretest for which Tim sketched the carbon atom shown in Figure 48(a). As remarked earlier, Tim's models showed few variations throughout the year and it should be remembered that the type of diagram he drew on each occasion was avoided by the teacher during Year 11, nor was it found in any textbook used during the course. The robustness and resilience of this model, which dated from Year 10 or earlier, was outstanding.

When Tim was presented with diagrams of a space-filling model of methane and a ball-and-stick model of methane, he answered the question, "Which of these models do you think is the better representation of a molecule" by circling the space-filling model and explaining:

Tim  Because the molecules join, they don't have space between them, except for electron shells.

[Organic chemistry pretest]

The last item presented Tim with structural diagrams of an alkene and an alkyne in which a C=H, a C=C and a C≡C bond were circled. The challenge was to "briefly describe what you think the circled parts of these diagrams represent." Tim's reply was limited to stating that they were "sharing electrons" and that C=C represented a triple bond.

About 10 days later in a worksheet activity, Tim drew another carbon atom [Figure 48(b)]. He then drew Lewis structural diagrams of ethane, ethene and ethyne and added simple comments which were limited to naming the bond types and describing the molecules' shapes as tetrahedral, planar and linear. Half of the worksheet questions probed his ability to identify shared and unshared attributes of ball-and-stick
and space-filling molecular models. Tim was unable to critically evaluate these models. His best response was:

**Quest.** Are these models accurate representations of the atoms and their bonds? Explain.

**Tim** They are similar but not accurate. Because atoms are much smaller.

---

**Figure 48:** Tim’s diagrams of carbon atoms drawn during the organic chemistry unit

Even though he was given ample opportunity and clues, he failed to make any constructive remarks about the ways in which ball-and-stick models were like and unlike actual molecules.

**Free-form essay** Tim’s essay began with a description of an atom of carbon and this diagram is shown in Figure 48(c). His commentary read as follows:

**Tim** Carbon as we know it consists of 6 neutrons and 6 protons (very charged), and the outside electron shell of 6 electrons. The electron shell of a carbon atom
consists of 2 electrons in its 1s orbital and 2 electrons in its 2s orbital and another
2 electrons in its 2p orbital as [Figure 48(c)] illustrates. [Free-form essay]

Tim decided to describe the shapes of organic molecules and observed that hydrocarbons exist in "tetrahedral, planar, and linear shape." In continuing, he stated that "tetrahedral shape are 3 dimensional shape whereas planar is 2 dimensional and linear is a flute shaped." The use of the "flute" metaphor was unique to this statement (no other student used this metaphor) and Tim offered no explanation as to why he used this image. He did expand on molecular representations in the following way:

Tim  I think that using ball-and-stick models are the best way to show and describe molecular bonding. This is because the sticks that are used in the model tells us how much bonding there are between the atoms. For example triple bond between carbon atoms etc ... The sticks also represents the space between the bonding atoms; the space between the electrons. I also think that the sticks represent the shared electrons in the bonding (The rotation of the atoms) [Free-form essay]

The statement that the sticks represented the number of bonds between atoms was a shared attribute of this analogical model. When he said that the sticks represented both the space between the atoms and the shared electrons, Tim left the reader with doubts as to what he really thought the sticks represented. Even though Tim declared that the sticks were representations, the fact that he attributed to the model more than it was capable of conveying, suggests that he was either confused or imagined that there was some direct correspondence between the model and reality. Tim stated that the ball-and-stick model was "the best way to show and describe molecular bonding." By failing to entertain any other model, it is reasonable to suggest that Tim was a Level 1 modeller (Grosslight et al., 1991) and that he thought that ball-and-stick models were 'correct'.

Tim then drew diagrams of ethane, ethene and ethyne which were accompanied by simple descriptions of the molecules' structure and bonding. The diagrams are reproduced as Figure 49. None of his explanations extended further than stating which bond types were present (single, double, triple) and defining the molecules' shapes - tetrahedral, planar and linear, respectively. He concluded that

Tim  ... every time the bond between the carbon gets stronger and stronger, we get less hydrogen on each end. ... Therefore the shape gets more and more simple. And the rotation between the carbons gets more fixed. [Free-form essay]

Tim appeared to believe that the number of bonds was as an index of bond strength in much the same way that the number of supports in a mechanical structure determined its strength. It is conjectured that he equated the bond line (—) with a mechanical strut. This is classic Level 1 modelling (Grosslight et al., 1991).
Figure 49: Tim’s diagrams of ethane, ethene and ethyne.

Interview The free-form essay was succeeded by an extended interview about atoms and molecules. The interviewer solicited Tim’s mental model of an atom. Tim’s sketch is reproduced in Figure 48(d). The interview continued:

Int. What do you think an atom looks like? Can you draw me a sketch?

Tim I think an atom looks like this, they have a very tiny nucleus containing a proton nucleus of a certain number depending on the element and um, outside it has an electron shell consisting of ah, how much the amount of electrons in the element and those electrons just move around real fast and ... just here.

Int. We’ve got a lot of pictures here [Figure 13] of what people think an atom might look like, .. which of those is your best preference?

Tim An atom ... I think number 2, and number 5, they’re the best.

Int. Can you give me some reasons why number 2 is so much more agreeable to you

Tim Just say for hydrogen it has one electron and one proton each it has a nucleus and um, say that one electron just travels around outside in the shell, that would represent this one and ... circumference and it’s travelling in all directions so I think that would describe one of the electrons I mean the atoms ... and um, for this one [diagram 2], this one would tell me that um, there might be two or three electrons outside in this shell and there’s a couple of atoms in the outside of this shell, so that was, it travels in space there’s space between those ... and for this
one [diagram 5], it would be like 2, but they're travelling around everywhere.

[Interview]

This was an interesting development. Tim noted that "those electrons just move around real fast" when he chose diagram 5 (the electron cloud model). While he never volunteered the conception 'electron cloud', this model played some part in this explanation. Nevertheless, he preserved diagram 2 (simple three-dimensional orbits model), this being one of his preferred models from the beginning of the year. The fact that he interchanged atoms and electrons indicated that his conceptions and terminology were tentative or it could just be a simple mistake.

When the interviewer showed Tim a ball-and-stick model of 1,2-dichloroethane, he was unable to name it or make any sense of the model other than identifying the white balls as hydrogens and the black balls as carbon. Following a series of direct hints, Tim named the compound as

Tim  1,2 dichloroethane (sofily) two carbons ...

Int. What shape would it have?

Tim  Ah, tetrahedral.

Int. Right ... can you suggest why it might have this shape?

Tim  Well it's a 3-D um, because it's a 3-D figure so therefore it would ... ... be three dimensional.

Int. Right ... when I was in your class last week Mr Harrison had some balloons hanging up [Yea] did they help you with an understanding of the shape of molecules?

Tim  Um, ... well not ... I haven't done that much I think ... well it did, it's like an analogy to the thing to what the atom's bonding is but ... I didn't quite catch up with it.  

[Interview]

This excerpt highlights Tim's lack of knowledge and low level of reasoning skills. The analogy meant little to him, in fact he admits that he didn't understand the lesson or the analogy. Similarly, despite having constructed and studied a series of molecular models over 4-5 lessons, his understanding was limited to the recognition that alkanes were 3-dimensional.

The interviewer next showed him an unsaturated hydrocarbon where, with respect to the C=C bond, Tim asserted that:

Tim  Ah, yea that can rotate.

Int. Yes, OK, so how?
Tim  Well the carbons can rotate like that part there can rotate and ...

Int.  Between the two carbon atoms? [Yea] What do you call that molecule?

Tim  That's ... an ethene [Yes] and it's plano-shaped ... double bond between the two carbons and four single bonds between the chloride and ... [Interview]

Apart from identifying it as an ethene, he was unable to name the compound. The discussion progressed to a discussion about cis and trans isomers

Int.  I'm not familiar with what you're telling me ... here's another molecule, what do we call that one? Can you tell me about it?

Tim  Oh, there's a triple bond between the carbons ... between the carbons and two single bonds between the carbon and the hydrogen. ... I think this one's called an ethyne.

Int.  That's exactly what it is. And what shape does this have?

Tim  This is a linear shape.

Int.  Can you explain why it's linear?

Tim  Because um, the hydrogen is like in a flat um form it's like a linear joined, it's linear bonding between the carbon and the hydrogen. [Interview]

Again, Tim offered no suggestion as to why the molecule was linear. The ensuing conversation consisted of little more than Tim rephrasing the interviewer's statements. The student profile at the head of this case study indicated that this was Tim's classroom strategy. Next, the discussion focussed on space-filling versus ball-and-stick models:

Int.  There are different types of molecules like this that are called space-filling ... which of these two types of atoms and molecules do you think are the easiest to understand?

Tim  Ah, these [ball-and-stick] ... this shows whether they are triple bond or double bond where these don't show how much bonding there are between the atoms so the stick-and-ball model is the best.

Int.  When they call this space-filling, can you imagine why they call them space-filling?

Tim  Um because they there is no space in between them. ... It is either, I don't know like ... they don't actually show the space between each atom ... [Interview]

Tim successfully justified his selection of ball-and-stick models by reasoning that they "show how much bonding there are between the atoms." His inability to explain the
meaning of space-filling stimulated the interviewer to tutor Tim about this concept and then lead into the balloons analogy.

Int. If you talk about those balloons, which do you think the balloons are most like - the ball-and-stick or ...

Tim I think they're a bit like the space-filling ones because they show the space between the bodies. [Interview]

Tim saw a link between the balloons and the region occupied by the bonding electrons. The interviewer then introduced Lewis structural and electron-dot diagram-models.

Int. There are diagrams of those three molecules and can you tell me how you read the three sketches? Those diagrams. What are the lines all about? The circles all about?

Tim I think um, that they're, the one in front of the whole thing tells us that the bonding between the two carbons. [Interview]

The "one in front" pointed to the "1" of the 1,2-dichloroethane. The name's ending designates the bonding, not the number out front. In this instance, Tim showed that he was unable to map the name's components onto the molecule. In organic chemistry, the systematic name is itself a model because it defines a precise set of shared attributes between the name and the object. The discussion focussed in on the lines representing the bonds.

Int. What about these lines? The lines between the atoms?

Tim Oh, the lines ... these say the arrow [spayed bond] is like an arrow, say an arrow is coming from the carbon, this is like a 3-D image so the dotted line shows that the hydrogen carbon, the hydrogen atom is at the back and this line here is telling us that the hydrogen is at the front and that line tells us that the chloride atom is on top. [Interview]

Tim's interpretation of the Lewis structural diagrams, though incomplete, contained enough detail to be satisfactory. He distinguished bonds in front of the plane from those behind and his conceiving that the molecule was 3-dimensional infers that he also saw bonds in the plane. His performance on this diagrammatic model exceeded his interpretation of all other models except Lewis electron-dot models (which he successfully drew and explained during the bonding topic). All the same, his understanding of the line-bonds was limited:

Int. What does the line represent in terms of anything to do with this atom?

Tim Bonding? ... The bonding between the atoms and the ... yea ...

Int. What does it represent, the bonding?
Tim    Whether it's ... covalent or, I dunno.

Int.    Let's say covalent. What is it, what is a covalent bond, what makes it?

Tim    A covalent bond ... it's made up of carbon and hydrogen and chlorine ....

Int.    .... now what I am asking you, you see these lines here, or a cross and a dot there, what do they represent? The cross and the dot?

Tim    They're sharing the electrons? Say the dot's here, say the carbon it has an x dot and the hydrogen has an circle dot and therefore the hydrogen must combine with the atoms to have two electrons so that's the bonding ... a sharing bond.

[Interview]

This statement, along with previous comments, indicated that Tim was hampered by a substantial lack of basic chemical knowledge. He was able to distinguish between single, double and triple bonds but was unsure of their type and he regularly confused atoms and electrons; for example in this statement he said that the covalent bond was composed of carbon, hydrogen and chlorine atoms! Tim was able to decipher Lewis electron-dot diagrams because he recognised that the dots, circles and crosses represented shared electrons, but he still explained that "the hydrogen must combine with the atoms" when he should have discussed the electrons.

It can be concluded that Tim only really thought about molecules in terms of ball-and-stick models. Granted, he adequately interpreted Lewis structural diagrams, but these were pictorial versions of ball-and-stick models. As Grosslight et al. (1991) showed, students who cling to one model and whose descriptions equate that model with reality are Level 1 modellers because they fail to realise that models do no more than represent reality. Model-wise, Tim appeared to be a naive realist whose conceptions underwent little change over the two semesters. For Tim, two conceptual issues were involved: First, he was insufficiently motivated to assimilate sufficient knowledge to elevate his epistemological awareness to a level where he could become dissatisfied with his alternative conceptions; and second, his intellectual capabilities as evidenced in this class (and/or chemistry content knowledge) prevented him perceiving that many of the atomic and molecular concepts were processes, not physical objects.

Semester 2 examination Tim expounded the topic "Discuss the concept of atoms, bonding, molecules and ions." In this essay, Tim provided a final view of his conception of atoms and molecules. He began by describing atoms:

Tim    Atoms as we know exists everywhere. The whole universe is made up of atoms. Atoms have a size relatively small and is naked to the eye. Atoms contain a nucleus which contains a certain amount of neutrons and protons depending on the element. An atom has an electron shell containing electrons which are negatively
charged (protons are positively charged) and these electrons move around the nucleus very, very fast. Actually almost as fast as light; and once again, the number of electrons in an atom depends upon the element.

Atoms float around in the sky and could not be seen, or they could be in solids, but also could not be seen. [Semester 2 Examination]

Tim proceeded to discuss atomic and mass numbers and notations like $^{16}\text{O}$ but made numerous errors. The only items he described correctly were the atomic number (which locates the element on the periodic table), the relative atomic mass unit (carbon-12 = 12 atomic mass units) and Avogadro’s number ($N = 6.02 \times 10^{23}$). Tim’s description of bonding was limited to

Tim ... the process of bonding between elements is called chemistry bonds which means that they either attract to each other by opposite charges or they are sharing electrons. [Semester 2 Examination]

The collection of diagrams in Figure 49 show that Tim’s conception of an atom underwent little change over two semesters of instruction. The status of his conception was unaffected by the variety of metaphors and analogical models that were presented and discussed during this period. Why was there no impetus for change? Because Tim did not experience any dissatisfaction as far as his mental model was concerned. He did not even appear to assimilate convincing analogical evidence favouring alternative models. At certain times, he appeared to understand evidence contrary to his views but there was no evidence that the additional information became plausible for him. As Hewson (1981, 1982) argued, unless the new conception achieves at least a plausible status (IP), dissatisfaction cannot arise. And when there is no dissatisfaction, why should a student relinquish his/her conception in favour of a concept that is not compelling?

The failure of the scientific conception to achieve intelligibility or plausibility was probably related to Tim’s limited attention span, lack of basic scientific knowledge, and his inability to appreciate scientific concepts. This conjecture is supported by the interview transcript in which Tim stated his ideas tentatively and many of his comments were little more than reiterations of the interviewer’s words. The interview showed that even though he remembered the balloons analogy, he neither recalled the analogy’s structure nor its meaning. All was not negative, however, because Tim did achieve competence with Lewis structural and electron-dot diagram models, and he did exchange his conception (stated at the beginning of the year) that atoms were visible under a microscope for the view that they were invisible. He also appeared to have assimilated the model that both atoms and electrons were in constant motion.

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Discussion

Status of Tim's Conceptions

Tim's preconception of an atom at the beginning of Year 11 consisted of a symmetrical static shell/orbits model with stationary electrons close to the nucleus. Tim retained this model, almost unchanged, throughout Year 11. In view of the stability of this model, this conception should be awarded Plausible (IP) status. Evidently Tim thought this was how an atom should be described, probably because he believed that this was what an atom looked like. For a brief time during the kinetic theory topic, he depicted atoms and molecules as balls; however, this model was understandable as a simplification of his circular/spherical shell model.

Tim made minor adjustments to his mental model, the more significant being the inclusion of the descriptor, that electrons "wiz around very fast" and "electron[s] which travel at a constant speed (which is very fast)." The data show that he confused atoms and electrons in his descriptions of atoms. Tim made no discernible progress towards the scientific conception of an electron cloud other than saying that an electron cloud consisted of moving electrons and moving electron shells. Throughout the year, the scientific conception was deemed to have no status for Tim. Thus, as measured in terms of conceptual status, Tim did not restructure his knowledge over the two semesters; at best he assimilated the information that atoms and electrons were moving. He remained a novice who simply added bits of information to his basic conception without restructuring (Carey, 1985, 1986).

In a similar vein, Tim restricted himself to ball-and-stick and Lewis structural molecular models. Based on the similarity of these models, it can be asserted that he visualised ball-and-stick style models as definitive representations of organic molecules. During the atomic structure and bonding topic he successfully manipulated Lewis electron-dot diagram-models but only returned to these models during the organic chemistry topic when cued. It is probable that Tim believed that ball-and-stick representations were close to molecular reality; thus, this conception is given the status of Plausible (IP). His possession of this conception can best be attributed to conceptual capture (Hewson, 1981, 1982) or assimilation (Posner et al., 1982). Tim's predilection for definitive molecular and atomic models supports the interpretation that he believed that there was a close relationship between his single models and reality. The observation that the atomic representations in ball-and-stick models (namely, balls, spheres) was generally incompatible with his atomic model does not seem to have worried Tim. And as Hewson points out, where there is no dissatisfaction, there will be no conceptual exchange.
Modelling Ability

The above evidence points to an interpretation that Tim started and ended the year as a Level 1 modeller (Grosslight et al., 1991). The predominant support for this assertion came from his preference for a single atomic or molecular model. There was a time, at the start of the year, when he preferred three models from Figure 13 and rejected four. His subsequent behaviour, however, ran contrary to this indication. It is just possible that he felt he had to say something about every diagram in Figure 13. Tim's biography, and the interview, revealed that his lack of chemistry content knowledge ensured that he simply grasped every piece of information and treated it as valid. In this sense then, his move to a single model was probably an advance in his understanding.

Intellectual Position

The above data and comments lead to an interpretation that Tim was firmly rooted in Dualism (Perry, 1970). His response to multiple molecular models was to use a single model in each explanation and he only used two models; either the ball-and-stick or Lewis structural model. The same was true for atoms; he maintained the orbits/shell model throughout. From Perry's perspective, Tim believed that there was a right answer and he had found it. Why should he try to use other models when he was already right?

Summary

Each of the ways in which Tim's learning was analysed revealed that he made little progress during Year 11 other than to add isolated pieces of information to his conceptual framework. Whether the perspective is conceptual status, modelling ability or intellectual development, at best, Tim's prior conceptions underwent minimal restructuring. When Tim did add information, the uncritical way in which it was added to his existing knowledge meant that his conceptual changes never exceeded conceptual capture or assimilation. Assessing the learning of low achieving students is difficult given the paucity and irregular nature of most of Tim's comments and written work, and for this reason, the foregoing assertions about Tim's learning are more tentative than for the more able students.
Chapter 5h

Conceptual Changes in the Case Studies

The preceding six case studies describe the experiences of six individual students and should not be seen as representative of the whole class. Each case study describes one student's Year 11 chemistry learning experiences. The one generalisation that can be made is that all the students are different. The similarities and differences that characterise each student are summarised in Table 5. Columns 1-3 in Table 5 describe each student's intuitive and learned conceptions, the relationship between the student's ideas and the desired scientific conception, and the number of models used. Each entry in columns 1-3 fits one of three times: the beginning of the year, the end of Semester 1 or the end of Semester 2. Next, columns 4 and 5 record each student's modelling level and intellectual development position at the beginning, and again at the end, of the year. Finally, columns 6-9 contain summative conceptual change interpretations, that is, each evaluation applies to the whole of the year or the end of the year. For instance, motivational influence and evolutionary conceptual change were year-long effects whereas conceptual change perspective and the types of conceptual change describe the students' end-of-year positions or a conceptual change event during the year. The Table 5 entries should not be interpreted apart from the discussions at the end of each case study; they should be considered in light of the evidence and arguments presented in the respective discussions.

All that remains for this chapter is to revisit the Research Questions and to inquire how well the study has answered the questions posed in Chapter 1. These answers will suggest further lines of research and those issues will be pursued in Chapter 6. The next section will review Research Questions 2 and 3.

The Conceptual Change Research Questions

It is now appropriate to examine the degree of fit between the case study conclusions and the relevant research questions from Chapter 1. This discussion will proffer answers to Research Questions 2 and 3 and their component parts.

Research Question 2

Research Question 2 asked, "Do systematically presented metaphors and analogical models, and multiple models, contribute to conceptual change in learning about atoms, molecules and chemical bonds?" Three of the systematically presented analogical models made useful contributions to the students' understanding of atoms, molecules and bonds. First, the "student's address analogy" (which replaced the MCG analogy for atomic spaciousness) appears to have succeeded in causing most of the students to exchange their compact atom with close electrons for an atom where the diameter of
the nucleus: electrons is 1:100 000. This change was not reflected in any student's end of year essay, interview or diagrams of an atom, but then, these proportions are not drawable. The balloons model of bond-electron interaction did prove fruitful for Alex, Gina and Ken and plausible for Dan (he had to be cued to the analogy) for explaining molecular shapes. A tenable proposition is that the explanatory power of the balloons demonstration engendered at least conceptual capture and probably (for Alex and Ken) conceptual exchange. The extensive use and discussion of ball-and-stick, space-filling and Lewis electron-dot models also provided Alex, Gina, Ken and Dan with alternative and complementary models for describing molecular structure. This last example, and the degree with which the more successful students used multiple representations in their free-form essay and interview, supports the claim that multiple modelling was a viable conceptual advance for these students.

The first subsidiary question asked, "Is the learning of a new metaphor or analogical model conceptual change?" In light of the preceding comments it is claimed that better analogical models do contribute to conceptual change and that changes in model use may be conceptual exchange or strong restructuring.

The next two questions in RQ2, "When students revise or exchange their metaphors and analogical models, is this conceptual change learning?", and "Is the toleration/employment of multiple models conceptual change?" can be answered together. Again, based on the general answer to RQ2, it is proposed that revision of metaphors and analogical models is conceptual change. Access to more meaningful or visualisable analogical models may result in an inferior model being replaced by a superior model such as the 'student's address analogy' or the balloons model. Also, recognition that all models break down somewhere and that several complementary models possess greater explanatory power than any single model means that the student has changed his/her view of models. Acceptance that all models are limited (i.e., they are not real) and that concomitant use of multiple models is more scientific, means that the student has made progress from a matter to a process view of science. Such an ontological shift is, in Chi et al.'s (1994) and Thagard's (1992a) terms, tree swapping (switching) and constitutes strong conceptual change.

The last part-question in RQ2 asks, "Should changes to a student's modelling ability be classified as conceptual change learning?" Based on the answer to the previous question, the reply is yes. The three modelling levels described by Grosslight et al. (1991) show that advances in modelling ability must be accompanied (even preceded?) by changes in the way the student views science and reality. This involves some degree of ontological change, and for reasons already advanced here and in Chapters 2 and 3 qualifies such changes as conceptual change learning.
**Research Question 3**

Research Question (RQ) 3 asked: "Do the various theoretical perspectives on conceptual change learning complement each other?" This question is best answered by addressing the components questions which are considered in the following paragraphs.

The first component question asked: "Is conceptual change learning always a rational-cognitive process?" Much of the learning described in Chapter 5 was rational-cognitive; however, in the case study discussions, evidence and argument was used to show that motivation was a significant factor for several students. Learning can take various tacks: a student's goal may be a high grade (like Dan), knowledge for interests sake (partly the case with Ken) or a variable mix of the two. Whether the goal is marks or understanding, the student's reasons for seeking his/her goal introduces an affective element that cannot be totally subsumed by logic or rationalism. In any social environment, and classrooms are social, motivation plays a significant, if unpredictable, role. Enough evidence has been tendered in this study to show that conceptual change is not solely a rational-cognitive process.

The second part-question asked: "Are conceptual status changes valid indicators of conceptual change learning?" Posner et al.'s (1982) synthesis of the CCM emphasised the centrality of the three cognitive conditions of intelligibility, plausibility and fruitfulness. These conditions are hierarchical measures of a conception's appeal to the learner and they also are the conditions that have to be met for conceptual change to occur. Hewson (1982) proposed that these conditions could be used as indicators of a learner's conceptual progress and status use was described by Hewson and Thorley (1989). The question is, were status changes effective indicators of conceptual change in this study? From a rational-cognitive position, informed estimates of each student's conceptual status at various times during the year agreed with the other qualitative assessments which claimed that conceptual restructuring did occur. These claims are supported by arguments in each discussion and are summarised in columns 1 and 2 in Table 5. However, the data were not sufficiently detailed to pinpoint individual student's conceptual status changes at each point in the teaching/learning sequence. But in a general sense, predicting the status of conceptions of atoms, molecules and bonds did contribute to the overall picture of conceptual change, or the lack thereof. Student knowledge changes were predominantly changes in content and detail, that is, epistemological; however, it is claimed that epistemological changes interactively included changes to ontological beliefs. Chapter 1 explained that this thesis takes the position that when the evidence indicates that a student has changed the way he/she views reality, then this change is deemed to be ontological. Ontological changes in
which scientific objects are reinterpreted as processes (Chi et al., 1994; Vosniadou, 1994) is well supported by changes in modelling level and intellectual position.

The third component of RQ3 inquired, "What role does dissatisfaction play in classroom conceptual change learning?" Given the year-long nature of the study, the daily interaction between the teacher/researcher and the students, and the comprehensive data-base, it is surprising that most of the conceptual changes were evolutionary. It was also surprising that not one instance of conceptual competition emerged in the form of dissatisfaction. The chemistry content seemed to provide ample scope for conceptual conflict that could have been manifest as dissatisfaction. Comparisons between Alex's, Gina's and Ken's beginning and closing conceptions shows that their knowledge restructuring involved more than just the assimilation of new information. In these three cases, the status of the scientific conception rose and the status of their preconceptions fell but there was no evident dissatisfaction.

The students' preconceptions certainly did not vanish; they were gradually transformed by the rising credibility and viability of the dynamic, diffuse, spacious model of an atom. Alex was probably the one student for whom conceptual exchange may have occurred, but even in his adoption of a sophisticated and critical view of multiple models, no dissatisfaction was evident. In fact, the acquisition of multiple modelling skills may have masked or prevented dissatisfaction because multiple modelling permits the student to hold and use alternative conceptions. Likewise, the maturation of Alex, Gina and Ken into Relativists may have circumvented dissatisfaction as predicted back in Chapter 2 (pp. 30-31). Whether the lack of dissatisfaction was due to multiple modelling or Relativism, the proposition that the old model could wholly or partly survive in the student's mental model is worthy of consideration. Indeed, Mortimer's (1995) idea of a conceptual profile works the same way; the old model is there but is not used because the context is inappropriate. This line of reasoning proposes that dissatisfaction was not observed because it did not occur.

The absence of dissatisfaction does raise other questions. Was dissatisfaction actually absent or did dissatisfaction occur but the probes/data collection methods were insensitive to it or wrongly directed? Posner et al. (1982) describe dissatisfaction as the initiating event for conceptual change in the original CCM. If a student became dissatisfied with his/her prior conception because it failed to answer problems or was inelegant, and a replacement conception possessing superior intelligibility, plausibility and fruitfulness was available, then accommodation (conceptual exchange) may occur. On the other hand, Hewson (1981, 1982) consistently placed dissatisfaction after intelligibility, plausibility and fruitfulness implying that dissatisfaction was a consequence of conceptual competition rather than the cause. The position of dissatisfaction may depend on whether the student actively seeks a replacement
conception (like in the Posner et al. model) or the teacher confronts the student with a better conception (a more passive approach). Maybe the position depends on student and/or content characteristics (White, 1994b)? Further research into the nature and role of dissatisfaction is warranted.

The fourth item asked, "Were the observed conceptual changes revolutionary or evolutionary?" With one exception, the observed conceptual changes were mainly piecemeal accretive evolutionary changes. The exception was Alex: His rapid transformation into a critical multiple modeller during fourth term may have been revolutionary. On the other hand, Gina's conceptual development was gradual with no perceptible major shifts in her thinking. These conclusions however, may be artefacts of the study methodology. Ethical considerations (Wong, 1995) requiring that the class be as normal as possible precluded the frequent probes and interviews necessary to more fully answer this and the previous question.

The fifth component question asked, "Are other learning measures like modelling ability and intellectual development indicators of conceptual change?" As the study progressed, it transpired that predicting individual student's modelling capabilities provided strong support for the claim that several students strongly restructured their mental model of atoms, molecules and bonds. In particular, Alex, Gina and Ken became more sophisticated and critical users of analogical models in terms of the descriptors used by Grosslight et al. (1991). Each of these students used models to communicate their understanding of atoms, molecules and bonds (a level 2 characteristic) but they also used multiple models (especially Alex) to compare and contrast properties and uses of organic compounds. Sufficient evidence was identified in the free-form essay and the interviews to claim that these three students derived heuristic value from their repertoire of models (a level 3 characteristic). Based on this evidence a claim is made that each of these three students made strong changes to ontological components of their mental model of atoms, molecules and bonds.

Furthermore, it has already been argued in the discussions concluding each case study, that intellectual development parallels modelling ability in the sense that both processes require the student to restructure the way he/she understands the world and their own knowledge. It is therefore claimed that modelling ability and intellectual level changes (concerning a concept or area of study) are evidence of conceptual change, and that this evidence can support claims for both epistemological and ontological changes.

The sixth part-question inquired, "Is there any evidence to support Thagard's notion of holistic explanatory coherence?" The theory of explanatory coherence requires sets of positive and negative propositions and hypotheses. This sort of information could not be gleaned from the student portfolios. Nevertheless, the notion that conceptual
change derives support from a holistic understanding of the subject matter is appealing. While a strong argument cannot be made either way, it does seem possible that holism may have been involved in Gina's evolutionary conceptual change. A broad and consistent knowledge base like the one Gina gradually accumulated should have the potential to convince a student of the need to restructure his/her conceptions. The same may be true for Alex's rapid maturation during Term 4. The level of coherence evident in his free-form essay and interview transcript seems to suggest that he found the totality of the multiple models argument compelling.

The final component question in effect rephrased RQ3 by asking: "Is a multi-dimensional approach a better way to interpret conceptual change learning?" Analysing the case study data from multiple perspectives such as epistemology, ontology and motivation has constructed a fuller picture than could have been achieved using any single approach. This statement may be both a tautology and a given, but the literature has reported many studies that used only one interpretive perspective. Multiple perspectives can do two things; they can enhance case studies like Alex's, Gina's and Ken's and they can complicate the issue with students like Dan. When just his rational-cognitive achievements were analysed, Dan appeared to progress conceptually; however, his limited progress intellectually and as a modeller led to a rethink and, when motivational factors were factored in, doubts was cast on the extent of his conceptual restructuring. Despite achievement of a high grade (equal to Alex and Gina), Dan's deep knowledge restructuring was limited.

This study shows that the accretive evolutionary explanation of conceptual change learning is credible and viable in secondary chemistry classrooms. Holistic explanatory coherence also may provide another way to analyse and describe conceptual change learning for certain students and concepts. This study's results strongly support the use of multi-dimensional frameworks for interpreting conceptual change learning.

**Conclusion**

Chapter 5 outlines the conceptual development of six Year 11 chemistry students as they learned about atoms, molecules and bonds. The chapter commenced with a description of the year-long research program. Next, six case studies detailed each student's learning and went on to discuss each student's conceptual development, modelling ability and intellectual development. Finally, the case study findings were summarised in Table 5 and discussed in light of the original research questions. This study concluded that Year 11 students begin their study of chemistry with naive conceptions of atoms and molecules that are dominated by the solar system/orbits atomic model. The scientific view that atoms are dynamic, diffuse, spacious entities is
absent from most students' mental models. The teaching program set out to remediate the students' preconceptions by systematically presenting better analogical models and by encouraging the students to use multiple models. Three of the six students substantially changed their conceptions in favour of the scientific conception, one student achieved a high grade but only evidenced weak conceptual change and the remaining two students achieved a small conceptual change and almost no change respectively. The multi-dimensional interpretive framework used in this study to diagnose conceptual change learning was found to be effective. The implications and recommendations that emerge from this study will be presented in Chapter 6.
<table>
<thead>
<tr>
<th>STUDENT</th>
<th>Time</th>
<th>EVENTS OF LEARNING CONCEPTUAL CHANGES</th>
<th>SCIENTIFIC CONCEPTION OF ATOM AND RELEVANT CONCEPTUAL STATES</th>
<th>NUMBER OF MODELS USED</th>
<th>MOVING LEVEL</th>
<th>INTELLECTUAL PERSPECTIVE</th>
<th>CONCEPTUAL CHANGE STRENGTH</th>
<th>CONCEPTUAL CHANGE OVER TIME</th>
<th>MOTIVATIONAL INFLUENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEX</td>
<td>Start of Year 11</td>
<td>Electron cloud model, close electrons diffuse, diffuse electrons distant - Intelligible I, Atom submicroscopic - Plausible IP</td>
<td>No status (i.e., not Intelligible)</td>
<td>One atomic model</td>
<td>Pred Level</td>
<td>DUALIST, plausibly</td>
<td>Epistemological change, Ontological change (revised view of models in lecture)</td>
<td>Strong restructuring of knowledge about atoms and molecules, probably conceptual exchange</td>
<td>Most changes occurred, changes in modelling ability were fairly dramatic (over a period of 4 weeks)</td>
</tr>
<tr>
<td></td>
<td>End of Semester 1</td>
<td>Electron cloud model, close electrons diffuse, diffuse electrons distant - Intelligible I, Atom submicroscopic - Plausible IP</td>
<td>Not assessed</td>
<td>Three atomic models</td>
<td>Level 6</td>
<td>RELATIVIST</td>
<td>Epistemological change, Ontological change area in change in type and number of models used</td>
<td>Assimilation and accommodation, weak and strong restructuring, conceptual capture and probably some conceptual exchange</td>
<td>Evidence supports the evolutionary accretion of knowledge</td>
</tr>
<tr>
<td></td>
<td>End of Semester 2</td>
<td>Compact atom with electrons in discrete shells, sparsely atoms</td>
<td>Electron cloud close to scientific view - Plausible IP</td>
<td>Three atomic models</td>
<td>Level 6</td>
<td>RELATIVIST</td>
<td>Epistemological change, Ontological change area in change in type and number of models used</td>
<td>Assimilation and accommodation, weak and strong restructuring, conceptual capture and probably some conceptual exchange</td>
<td>Evidence supports the evolutionary accretion of knowledge</td>
</tr>
<tr>
<td>GINA</td>
<td>Start of Year 11</td>
<td>Static microscopically particle with large nucleus, close electrons moving in shells, Intelligible I</td>
<td>No status</td>
<td>One atomic model</td>
<td>Pred Level</td>
<td>MULTIPLE</td>
<td>Epistemological change, Ontological change (revised view of models in lecture)</td>
<td>Strong restructuring of knowledge about atoms and molecules, probably conceptual exchange</td>
<td>Most changes occurred, changes in modelling ability were fairly dramatic (over a period of 4 weeks)</td>
</tr>
<tr>
<td></td>
<td>End of Semester 1</td>
<td>Dynamic electron cloud - Intelligible I</td>
<td>Not assessed</td>
<td>Three atomic models</td>
<td>Level 6</td>
<td>RELATIVIST</td>
<td>Epistemological change, Ontological change area in change in type and number of models used</td>
<td>Assimilation and accommodation, weak and strong restructuring, conceptual capture and probably some conceptual exchange</td>
<td>Evidence supports the evolutionary accretion of knowledge</td>
</tr>
<tr>
<td></td>
<td>End of Semester 2</td>
<td>Dynamic electron cloud - Intelligible I</td>
<td>Electron orbiting, spinning mostly space, tiny nucleus - Plausible IP, sending fruitful IP</td>
<td>Critically multiple analogical models of molecules</td>
<td>Level 6</td>
<td>RELATIVIST</td>
<td>Epistemological change, Ontological change area in change in type and number of models used</td>
<td>Assimilation and accommodation, weak and strong restructuring, conceptual capture and probably some conceptual exchange</td>
<td>Evidence supports the evolutionary accretion of knowledge</td>
</tr>
<tr>
<td>DAN</td>
<td>Start of Year 11</td>
<td>Atom has orbit and electrons in shells - Plausible IP</td>
<td>No status</td>
<td>Two atomic models, 1 &amp; 3 in Figure 13</td>
<td>Level 6</td>
<td>DUALIST</td>
<td>Epistemological change, and minor ontological change (models retained)</td>
<td>Assimilation, weakening restructuring or conceptual capture</td>
<td>Most knowledge addition was probably accretive</td>
</tr>
<tr>
<td></td>
<td>End of Semester 1</td>
<td>Electron cloud - Intelligible I</td>
<td>Not determined</td>
<td>Indeterminate</td>
<td>Level 6</td>
<td>MULTIPLE</td>
<td>Epistemological change, Ontological change area in change in type and number of models used</td>
<td>Assimilation, weakening restructuring or conceptual capture</td>
<td>Most knowledge addition was probably accretive</td>
</tr>
<tr>
<td></td>
<td>End of Semester 2</td>
<td>Electron cloud and electrons moving in shells - Intelligible I</td>
<td>Two atomic models, 1 &amp; 3 in Figure 13</td>
<td>Five atomic models, 3 in Figure 13</td>
<td>Level 6</td>
<td>MULTIPLE</td>
<td>Epistemological change, Ontological change area in change in type and number of models used</td>
<td>Assimilation, weakening restructuring or conceptual capture</td>
<td>Most knowledge addition was probably accretive</td>
</tr>
<tr>
<td>KEN</td>
<td>Start of Year 11</td>
<td>Tiny atom, large nucleus, close electrons moving in a cloud - Intelligible I, Atoms and molecules dynamic - Plausible IP</td>
<td>No status</td>
<td>One atomic model (planetary)</td>
<td>Pred Level</td>
<td>MULTIPLE</td>
<td>Epistemological change, Ontological change area in change in type and number of models used</td>
<td>Assimilation, weakening restructuring or conceptual capture</td>
<td>Some evolutionary conceptual change</td>
</tr>
<tr>
<td></td>
<td>End of Semester 1</td>
<td>Tiny dense nucleus, electrons wiz at very high speed - Intelligible I</td>
<td>Spacious, dense nucleus, electrons in indistinct (partly diffuse) orbit, like a cloud, all over the place - Plausible IP, approaching fruitful IP</td>
<td>Indeterminate</td>
<td>Level 6</td>
<td>RELATIVIST</td>
<td>Epistemological change, Ontological change area in change in type and number of models used</td>
<td>Assimilation, weakening restructuring or conceptual capture</td>
<td>Some evolutionary conceptual change</td>
</tr>
<tr>
<td></td>
<td>End of Semester 2</td>
<td>Tiny dense nucleus, electrons wiz at very high speed - Plausible IP</td>
<td>Three atomic models, four molecular models</td>
<td>Level 6</td>
<td>MULTIPLE</td>
<td>Epistemological change, and minor ontological change (models retained)</td>
<td>Assimilation, weakening restructuring or conceptual capture</td>
<td>Some evolutionary conceptual change</td>
<td>Strong motivation to understand, marks a secondary consideration, active in class</td>
</tr>
<tr>
<td>MARY</td>
<td>Start of Year 11</td>
<td>Atom a ball of balls - Intelligible I</td>
<td>No status</td>
<td>One atomic model</td>
<td>Level</td>
<td>DUALIST</td>
<td>Weak epistemological change, minor ontological change, weak restructuring of some concepts.</td>
<td>Assimilation of some information, weak restructuring of some concepts.</td>
<td>Where knowledge did grow, process was evolutionary</td>
</tr>
<tr>
<td></td>
<td>End of Semester 1</td>
<td>Adds mostly space, balls moving - Intelligible I</td>
<td>Not assessed</td>
<td>Indeterminate</td>
<td>Level</td>
<td>MULTIPLE</td>
<td>Weak epistemological change, minor ontological change (analogue models in interview)</td>
<td>Assimilation of some information, weak restructuring of some concepts.</td>
<td>Where knowledge did grow, process was evolutionary</td>
</tr>
<tr>
<td></td>
<td>End of Semester 2</td>
<td>Electron moving in shells, hint of a cloud, close diagram 5 in Figure 13 - Intelligible I or maybe Plausible IP</td>
<td>Three atomic models, two molecular models, used uncharacteristic</td>
<td>Level</td>
<td>MULTIPLE</td>
<td>Weak epistemological change, minor ontological change (analogue models in interview)</td>
<td>Assimilation of some information, weak restructuring of some concepts.</td>
<td>Where knowledge did grow, process was evolutionary</td>
<td>Strong motivation to succeed, lacking in ability, passive in class</td>
</tr>
<tr>
<td>TIM</td>
<td>Start of Year 11</td>
<td>Static shell orbits model, close nucleus - Intelligible I</td>
<td>No status</td>
<td>One atomic model</td>
<td>Level</td>
<td>DUALIST</td>
<td>Minor epistemological change, no ontological change</td>
<td>Assimilation of some information, no restructuring observed</td>
<td>No significant changes</td>
</tr>
<tr>
<td></td>
<td>End of Semester 1</td>
<td>Static shell orbits model, close nucleus - Intelligible I</td>
<td>Not assessed</td>
<td>Indeterminate</td>
<td>Level</td>
<td>DUALIST</td>
<td>Minor epistemological change, no ontological change</td>
<td>Assimilation of some information, no restructuring observed</td>
<td>No significant changes</td>
</tr>
<tr>
<td></td>
<td>End of Semester 2</td>
<td>Static shell orbits model, close nucleus - Intelligible I</td>
<td>Mentions but did not use electron cloud - No status or Intelligible I</td>
<td>One atomic model, almost always one molecular model</td>
<td>Level</td>
<td>DUALIST</td>
<td>Minor epistemological change, no ontological change</td>
<td>Assimilation of some information, no restructuring observed</td>
<td>No significant changes</td>
</tr>
</tbody>
</table>
CHAPTER 6
MULTIPLE MODELS AND MULTIPLE PERSPECTIVES ON
CONCEPTUAL CHANGE IN CHEMISTRY

Introduction

This final chapter purposes to draw together the theoretical and research threads that wind their way through the preceding five chapters. The methods, theory and research described in those chapters was based on the knowledge that people do construct ideas about how parts of their world works and that intuitive science often competes with scientists' science (Driver et al., 1994). During schooling, the competition between children's science and scientists' science often inhibits meaningful learning and many classroom strategies have been devised that attempt to redress this imbalance (Osborne & Freyberg, 1985). Thus, conceptual change teaching and learning is an important educational strategy in this quest for scientific understanding (Hewson, 1981, 1982, 1996; Posner et al., 1982).

Science learning is also impeded by the non-observable nature of many items of science content knowledge. Students cannot actually see entities like life, forces, electricity, plate tectonics or atoms and molecules. Consequently, a broad range of analogical models have been constructed to help students bridge the conceptual gap between everyday activities and abstract scientific phenomena (Duit, 1991a). The positive and negative aspects of analogical learning were principal concerns of this study. From a modelling and a conceptual change stance, the three Research Questions could be consolidated into one question: "Are better models of scientific phenomena available to teachers and students and are there better ways to use existing models in science learning?" It was believed that answers to this question and the Research Questions would emerge from a study of how students use metaphors, analogies and models when learning about atoms, molecules and bonds.

The argument that conceptual change learning is a multi-dimensional process (Treagust, 1996) also was pursued in this research. The multiple dimensions or perspectives on conceptual change that were considered during this study were epistemology, ontology, motivation, piecemeal evolution of knowledge, holistic explanatory coherence and age-dependent development.

The extent to which this thesis has answered the questions concerning the multi-dimensional nature of conceptual change learning and the role of metaphors, analogies and models in supporting learners as they restructure their scientific conceptions will be discussed in the Summary of Research Findings. The chapter then examines the
study's Contribution to Theory Building and will conclude by considering some Recommendations for Educational Practice.

Summary of Research Findings

The relevant literature and data that provided answers to the three research questions and their component parts have been presented in Chapters 2, 4 and 5. These answers were comprehensive and several issues were the subject of detailed debate. Consequently, only the stem of the Research Questions will be revisited here and the answers provided also will summarise the study's research findings.

Research Questions Revisited

Research Question 1: With which models of atoms and molecules are Western Australian pre-Year 11 chemistry students familiar; and what is the relative status of these models for these students?

The interview-based study of 48 Year 8-10 science students' mental models of atoms and molecules found that many of these students preferred models that are both discrete and concrete. Most of these students had difficulty separating models and reality, and given that 50% of the students thought that scientists had seen atoms, it is likely that these students ascribe some degree of reality to scientific models and diagrams. Language that is common to chemistry and biology (e.g., nucleus and shells) also was a source of confusion for some students because they concluded that atoms and their nuclei divide and that atoms grow. Electron shells were visualised as enclosing shells that protected atoms while electron clouds were structures in which electrons were embedded. These, and other alternative conceptions may be the product of discussions where the students' and the teacher's words have different meanings or where chemistry/biology contexts overlap.

Most of the Year 8-10 students preferred a solar system or a simple orbits atom in which the electrons were very close to a large nucleus. Students also expressed a strong preference for space-filling molecules as opposed to ball-and-stick models. There were significant differences between the Year 8-10 students' conceptions of atoms and molecules and the scientific conception expected in Year 11. The study's outcomes highlight the need for strong/radical restructuring of student conceptions of atoms and molecules during Year 11. The baseline study also indicated the need for instruction in scientific modelling and the need for students to think about atoms and molecules in process as well as matter terms.

Research Question 2: Do systematically presented metaphors and analogical models, and multiple models, contribute to conceptual change in learning about atoms, molecules and chemical bonds?
The successful students' final conceptions of atoms, molecules and bonding supports the claim that the systematic presentation of metaphors, analogies and models both enhanced the students' learning about atoms, molecules and bonding and reduced the incidence of alternative conceptions. This finding also is supported by an earlier study by the author (Harrison, 1993). The educational advance evidenced in this study was the demonstration that multiple modelling not only enhanced the students' understanding of atoms, molecules and bonds, it also strengthened their scientific process thinking. Multiple modelling was more than a new skill, it brought with it a more comprehensive way for thinking about the world, reality and science.

This study therefore proposes that the systematic presentation of familiar multiple models enhances students' understanding of non-observable abstract phenomena like atoms, molecules and bonding. The study also shows that improvements in student modelling ability enhanced student scientific thinking skills and facilitated conceptual change learning, especially ontological conceptual change. This finding reinforces Fensham and Kass' (1988) assertion that "the use of multiple models ... [have] very positive learning effects" in chemistry instruction (p. 8).

Research Question 3: Do the various theoretical perspectives on conceptual change learning complement each other?

The six perspective on conceptual change learning that were canvassed in this thesis were: epistemology, ontology, motivation, piecemeal evolution of knowledge, holistic explanatory coherence and age-dependent development. The discussions at the end of each case study have argued that the best sense of each student's learning can only be made by employing multiple interpretive perspectives. Treagust (1996) suggested that all cases of conceptual change learning should be interpreted from at least the perspectives of epistemology, ontology and motivation. The case studies described in Chapter 5 point to the credibility and viability of this suggestion. In fact, the case study findings were enhanced by the multi-dimensional interpretive framework and Dan's case in particular suggests that inappropriate conclusions may have resulted if the multi-dimensional framework had not been used.

The case study findings also showed that the piecemeal accretion of knowledge was credible and viable in several cases, especially Gina's. Furthermore, holistic explanatory coherence may be applicable to longitudinal cases because extensive databases facilitate assessment of the holistic appeal to a student of unified concepts like atoms, molecules and bonds. Finally, if intellectual progress through Perry's (1970) positions is allowed as developmental conceptual change, then the cases described in this study support the inclusion of development as an interpretive method. Intellectual development seems to be a function of opportunity and of multiple quality experiences;
therefore, intellectual development should be equally applicable to the adult and adolescent years. In this sense then, no place was found for age-dependent conceptual development (Carey, 1985) in the study of Year-11 chemistry learning.

It is therefore claimed that the evidence and arguments presented through this thesis do support the acceptance of the proposition that "the various theoretical perspectives on conceptual change learning complement each other."

**Contribution to Theory Building**

*Multi-Dimensional Perspective on Conceptual Change Learning*

The synthesis of a multi-dimensional interpretive model for conceptual change learning has been a major concern of the Conceptual Change Research Group at Curtin University of Technology. The independent roles of epistemology, ontology, motivation, piecemeal evolution of knowledge, holistic explanatory coherence and age-dependent development are widely described in the social science literature. However, Research Question 3 must be re-asked: "Do the various theoretical perspectives on conceptual change learning complement each other?" Treagust (1996) describes the Conceptual Change Research Group's progress so far and this group's collective thinking is represented in Figure 50(a).

The triangle model [Figure 50(a)] reminds researchers that there are at least three different ways for looking at conceptual change learning. Epistemology, ontology and motivation provide three alternative 'lenses' through which conceptual change learning events can be interpreted (Harrison, 1996). Even though the study reported in Chapter 5 showed that the alternative perspectives sometimes yield conflicting results, the overall effect is complementary. The multiple perspective on conceptual change are complementary because the distortions from one 'lens' can be compensated for by the image from another lens. Methodologically, a three-fold analysis of a learning event brings theory triangulation to the study of conceptual change learning.

A triangular model may, however, seem too prescriptive and for this reason the interacting perspectives also can be represented as overlapping fields of varying size [Figure 50(b)]. The idea of variable sized fields might be used to represent the relative contribution of each perspective to the final description of a conceptual change learning event. Showing the perspectives as overlapping fields reminds researchers and readers that epistemological, ontological and motivational influences do not act independently during conceptual change learning. Most conceptual change studies can be criticised for implying that conceptual change perspectives stand alone as being solely epistemological. Pintrich, et al. (1993) sensitised the author to this problem when they showed that classroom cognition and motivation cannot be separated.
Motivational forces affect how and why students join in learning activities and how teachers enhance students' engagement?

(a) Epistemology, ontology and motivational as three interactive perspectives.

Conceptual change influences can also be thought of as areas or fields which overlap or intersect. The size of each field and the degree of overlap would probably depend on the student, the concept and the context.

Figure 50: Two methods for representing the three-fold multi-dimensional framework for interpreting conceptual change
(b) Alternative representations of the interaction between epistemology, ontology and motivation.

*Figure 50 continued:* Two methods for representing the three-fold multi-dimensional framework for interpreting conceptual change.

*Extending the Conceptual Change Interpretive Framework*

This thesis has extended the Conceptual Change Research Group's three perspective model by adding the piecemeal evolution of knowledge, holistic explanatory coherence and intellectual development to the three-fold interpretive framework. This six-fold interpretive framework was reported as *Extending the conceptual change model* (Harrison & Treagust, 1996). While six perspectives cannot be represented in a simple model (like Figure 50), this in no way impedes their use; it simply means that each learning event needs to be considered from as many perspectives as appropriate.

The significant contribution of this research, and of the Conceptual Change Research Group, to theory building is the formulation and implementation of coherent multi-dimensional interpretive frameworks. The case study findings reported in Chapter 5 show that the multi-dimensional approach enhanced the interpretation of student learning about atoms, molecules and bonding. It remains to be seen how utilitarian the methods depicted in Figure 50 will be in wider conceptual change settings. These descriptions should, at the least, heighten researchers' and teachers' awareness of the
multi-dimensional nature of knowledge restructuring during conceptual change learning.

Multiple Modelling, Intellectual Development and Science Learning

This thesis makes a second contribution to theory development by showing that changes in modelling ability and intellectual position are forms of conceptual change. A reasonable conjecture seems to be that modelling ability and intellectual position changes involve strong or radical knowledge restructuring. When students advance in modelling ability and/or intellectual position, they change the way they view the world and how they understand knowledge. The case study discussions argued that modelling and intellectual changes involve ontological change. To become a multiple modeller, a student has to relinquish ideas which suggest that models are reality. Recognition that the best a person can do is to represent reality is common in science but uncommon in classrooms. Thus, when a student legitimates and uses multiple models, this represents a major ontological/epistemological shift because not only is the student's knowledge (epistemology) changed by adding extra models, the way he/she views reality (ontology) also changes. Previous studies (e.g., Grosslight et al., 1991) showed that modelling level changes involved significant changes in thinking about knowledge but did not link these changes to strong conceptual change or accommodation of a new conception. This study introduced the nexus between modelling changes and strong conceptual change but more research is needed.

The same case can be made for intellectual development (Perry, 1970). Just as changes in modelling ability reflect changed thinking about reality, progress along the Dualism-Multiplism-Relativism-Commitment in Relativism continuum also reflect deep-seated changes in the way the student thinks about his/her knowledge and the world outside. Much positive and critical work has been conducted in relation to the Perry model, but there is sufficient support for the model to permit its use in the conceptual change field. Finster (1989, 1991) has argued that the Perry model can inform pedagogical improvements and this study suggests that Finster's recommendation (teaching students at one Perry position above their current position) does enhance some students' intellectual status. This study's finding supports the notion that there is also a nexus between intellectual position changes and strong conceptual change.

Research Papers and Conference Presentations

A third contribution made by this study to science education knowledge consists of journal papers and conference presentations. So far, this study has produced three journal papers (one published, one in press and one submitted), and one local, two
national and eight international conference papers and presentations. Details of these papers and presentations are supplied in Appendix 1.

Recommendations for Educational Practice

Future Research Directions

The survey of students' conceptions of atoms and molecules reported in Chapter 4 and the longitudinal case studies described in Chapter 5 have been designed to make useful contributions to the science education knowledge base. Chapter 4's additions to the alternative conceptions field are straightforward; however, the multi-dimensional study of conceptual change learning has left many loose ends. While some progress has been made, further research is warranted and some of the areas that require further elucidation are described under the next three headings.

Dissatisfaction and conceptual change The role of dissatisfaction in conceptual change learning is perplexing. Conceptual change theory (Hewson, 1981, 1982; Hewson & Hewson, 1984; Posner et al., 1982; Strike & Posner, 1992) insists that dissatisfaction plays a central role in accommodation and conceptual exchange. This study offered two explanations for the absence of dissatisfaction: that dissatisfaction-mediated conceptual change is limited to naïve learners (Dualists and possibly Multiplists), and that the probes used in this study were not sufficiently sensitive. Both propositions should be investigated in a variety of age, skill and content settings because the viability of dissatisfaction-based conceptual change learning is important. It is important because the framework of discrepant event and cognitive conflict learning strategies depends on dissatisfaction (Guzetti & Glass, 1992). If dissatisfaction is less common than supposed, then other techniques for challenging students' alternative conceptions are needed.

Monitoring conceptual status The conceptual status construct is a valuable tool for assessing students' conceptual understanding. However, the notion that researchers can assess status from student comments and behaviour has been questioned (Hewson, private conversation). Hennessey (1993) taught her students the status terms of the CCM and encouraged her students to make comments about the intelligibility, plausibility and fruitfulness of their in-class conceptions. Is having children define their conceptual status more or less dependable than an external researcher? Gunstone (1994) has argued that only the student can decide what he/she does/does not believe and this accords with constructivist theory and practice; but Norman (1983) argues that any person's description of his/her mental models is unreliable. Clearly more research and debate on this issue is warranted.

The multi-dimensional interpretive framework Further applications of the multi-dimensional interpretive framework are required to establish it as a credible and viable
research method. The results to date (Tyson, 1996; Venville, 1996) have been encouraging but these findings need to be supported across a wider range of contexts and content areas. It is likely that further research will consolidate and/or modify the theoretical position and it is hoped that other researchers will recognise the suitability of the multi-dimensional approach to classroom conceptual change research and incorporate it into their research.

**Implications for Classroom Practice**

The background research described in Chapters 2 and 3 and the outcomes reported in Chapters 4 and 5 suggest a number of improvements to classroom practice. These include:

*Evaluating students’ preconceptions* Chapters 4 and 5 showed that alternative conceptions about atoms and molecules are widespread amongst science students and that these preconceptions interfere with science learning. While the interview probe used in Chapter 4 is unsuitable for normal classrooms, the findings provide a sound basis for constructing pencil-and-paper pretests and classroom probes like interviews-about-events and interviews-about-instances (Carr, 1996). Concept maps (Novak, 1996) are another way to monitor the presence of alternative conceptions at the start of and throughout a topic. Unless teachers are cognisant of the variety of alternative conceptions that exist in their classes, they will neither be stimulated nor be able to remediate their students’ unscientific conceptions.

*Revisiting prior conceptions* Conceptual change learning strategies like those described in this thesis do not guarantee long-term conceptual change. Posner et al. (1982) warned that conceptual change may not occur and, if it does, it may not be permanent. Hashweh (1986) recommended that teachers revisit their students’ alternative conceptions to highlight for their students the conceptual changes that had occurred. Not only does this reinforce the changes, it can identify cases where the changes did not happen. Nussbaum and Novick (1982) found that eliciting, discussing and revisiting students’ conceptions produced meaningful learning. Teachers should remind students of how and why they changed their ideas.

*Scientific modelling* The review of literature in Chapter 3 and the studies in Chapters 4 and 5 showed that high school students often view models as ‘right’ or as mirrors of reality and that only a minority of students see models as representational thinking tools. Scientific modelling should become part of the science curriculum and scientific modelling should be regularly revisited using a spiral curriculum approach. Many teachers and textbooks use multiple models implicitly but do not explain to students the reasons for or value of multiple models. Teachers will probably need in-service education workshop opportunities to learn scientific and multiple modelling skills.
Scientific and multiple modelling instruction also should be an essential component of pre-service teacher education. Likewise, opportunities for learning analogical teaching skills [the TWA model (Harrison & Treagust, 1993) and the FAR guide (Treagust et al., 1994)] should be available to all in-service and pre-service teachers.

Curriculum design The previous issue should be augmented by the development of curriculum materials that explicitly foster scientific and multiple modelling skills. An ideal content area for the development of model-based curriculum materials is the atoms, molecules and bonding unit in junior secondary science and in senior chemistry. To date the writer is not aware of anyone taking up this challenge.

Semantic differences One source of the alternative atoms conceptions in Year 8-10 science was the misapplication of language terms common to biology and chemistry. Garnett, Garnett and Treagust (1992) have described specific semantic problems in chemistry and Sutton (1992, 1993) has written extensively on this subject. Teachers should therefore take care that they and their students ascribe the same meaning to the words used in class. Language differences pose the same threat to understanding as unfamiliar analogies; the students simply do not understand the teacher's intent or they wrongly interpret the teacher's intent. This situation can be resolved by socially negotiating the meaning of scientific terms, instances and events with the class (Solomon, 1987). The most problematic words in chemistry are those common words that have context-dependent scientific meanings (e.g., nucleus, shell, cloud).

Assessment changes A major hindrance to conceptual change teaching and learning is the assessment system. Students learn what is valued and many teachers only teach what is assessed. If the assessment system values rote learning, why should teachers or students value meaningful learning? This issue has strong motivational overtones (Pintrich et al. 1993). If students are not motivated to, they will not feel any need to restructure their conceptions. Gunstone (1994) asserts that rote learning courses "usually prevent conceptual change. The positive alternative is of course clear - change the assessment" (p. 135). Assessment raises the question of what is valued in secondary education, and if meaningful learning is valued, then assessment needs to be renegotiated at classroom, school and system level.

Metacognitive opportunities The free-form essay and the interview at the end of Year 11 stimulated several students to re-examine their thinking and ideas. Metacognitive activities are opportunities where the students examine, explain and justify their beliefs. Metacognition appeared to enhance both Alex's and Gina's conceptions. Time is a most valuable but limited resource in the classroom and students need time to pursue metacognitive activities. Metacognition can occur during writing, talking, role playing, investigations and relevant problem solving. But metacognition can only
occur where the students possess the essential information and skills and are given time on tasks that stimulate them to rethink their understanding. This study has indicated that the processes and goals of conceptual change learning and metacognition are clearly complementary. The message for schooling is clear: more time should be allocated to less content and some of the extra time should be devoted to enhancing metacognition (Baird & White, 1996, p. 195).

**A need for caution with new technologies** A recent scientific innovation has been the scanning tunnelling electron microscope. This instrument can scan the atomic surface of a solid and generate an image of the surface atoms. Images from these instruments show individual atoms as solid, close-packed spheres. The portion of the atom delineated in these micrographs is actually a contour of electric potential for the outermost layers of the electron orbitals. Even though the electron orbitals are nearly all empty space, the computer-generated models look like solid hills and valleys in both cross-sectional and oblique views. Many of these models have now been published and constitute another potential source of alternative student conceptions. This will likely occur because uninformed students will probably interpret these models as meaning that atoms are discrete, hard balls and not mostly space.

A similar scenario is reported by de Vos (1990) where he writes that

> In a well-known textbook on physical chemistry (Atkins, 1986) the first chapter begins as follows: "We know that atoms and molecules exist because we can see them, figures 0.1 and 0.2." The first of these figures shows a more or less symmetrical pattern of black dots of different sizes, ... an image of a platinum needle obtained by field-ionisation spectroscopy. The second [was] obtained by X-ray diffraction ... in a molecule of anthracene" (p. 163).

The scanning tunnelling electron microscope could become another example of modelling gone wrong. The depicted models do not actually exist. The models are generated by a computer from the contours of electrical potential. This example further highlights the need for our science courses to include explicit instruction on modelling and the use of analogies (Gilbert, 1993). If students develop an understanding of the role, status and limitations of scientific models, it is likely that they will be less inclined to see the variety of models used in textbooks and classrooms as 'reality.' Grosslight, et al. (1991) showed that the literature and their own studies indicated that the 'model is reality' outcome is a very real possibility with naive students (e.g., Years 8-10).

**Limitations Present in this Study**

Like all studies, this investigation suffered at the hand of internal and external limitations. Internal limitations were those that were due to structural weaknesses in the study method and might have been foreseen, and external limitations were those
unforeseen factors over which the researcher had little control. The detectable limitations in the study were:

*Failure to identify dissatisfaction* As discussed previously, the absence of dissatisfaction in the learning episodes may be attributable to inappropriate probes or a misplaced expectation as to where dissatisfaction should occur. The study aim was to monitor the conceptual development of each student in the class. A study that could detect dissatisfaction, if it did occur, necessitates studying fewer students in greater depth. This limitation was partly internal; however, the realisation that dissatisfaction was not occurring came too late to change the study method without jeopardising the quality of the data already collected. The question of whether dissatisfaction occurs in all instances of accommodation or conceptual exchange can only be answered by more intensive data.

*Precise explication of conceptual status* Individual student's conceptual status was not explicated in sufficient detail to monitor the status of all the specific concepts in the atomic, molecular and bonding units. Again, this was partly an internal limitation that may have been avoided if all the problems had been foreseen. However, some of these limitations were external because school timetable constraints, unexpected interruptions, sickness and the need to satisfy an external syllabus limited the time available for probing understanding. Involvement of an external observer in a project of this type should overcome this limitation.

*Ethical dilemmas* In the ethics section of Chapter 1, the conflicts experienced by a teacher/researcher were discussed at length. On several occasions, the author found himself in situations like the dilemma described by Wong (1995). During class questioning, a student's answer suggested that there was research value in pursuing a lengthy discussion with that student. When Wong re questioned the student, however, she became frustrated and the class became inattentive and the teaching/learning discourse broke down. In similar situations in this study, the needs of individual students and the whole class took precedence over data collecting activities. This resulted in lost data but it maintained the flow of student learning. While research conducted by teachers is always plagued by this constraint, the disadvantage is partly compensated by the teacher's familiarity and close knowledge of his students. The author taught both Year 11 chemistry and Year 11 physics and four of his five physics students were represented in the six case studies (only Gina and Mary did not study physics). This prolonged engagement with most of the students helped compensate for the lost data collecting opportunities. Again, assistance from an external observer may have allowed data to be collected while the teacher continued teaching the class but that may have disrupted the social fabric of the class. In the study's defence, it
should be said that this was a normal class, normal teaching was the order of the day, and the study's findings are reported with these constraints in mind.

*Holistic explanatory coherence* This construct was not pursued with the rigour anticipated at the beginning. The reasons for the study's inability to systematically comment on this process in the case studies are the same as for dissatisfaction and conceptual status. The data corpus was extensive but needed to be even richer to make informed comments on this type of conceptual change learning. Future studies that concentrate more effort on a smaller group of students may provide fruitful answers as to whether or not holistic explanatory coherence is a sound measure of conceptual change learning.

*The Thesis is a Personal Construct*

The last limitation is one that permeates every qualitative analysis of human behaviour. The data were collected, organised, analysed and described by a person. It would be wrong to suggest that the data and the interpretations are any more than the teacher/researcher's view of what happened in his classroom. True, the method, data collection and interpretation were grounded in established social science theory, but the very constructivist nature of those theories insist that the interpretations and findings are personal and individual. This construct is as applicable to the teacher/researcher as it is to the individual students in the class. Being the classroom teacher, the author was a significant and influential factor in the learning environment. The author operated from a position of power and was affected by his personal presuppositions and his opinions of the school, the course and the students. Each of these factors impacted to some degree on his observations, interpretations and his telling of the case studies. The author has tried to distance himself from his personal biases and metaphysical commitments but it is important to realise that these factors are always there and that they both strengthen and weaken the study. These factors strengthen the study because they endow the record with human feelings and tell the story of an actual learning environment. These factors also weaken the study because no two researchers would analyse and tell the case stories in exactly the same way.

**Conclusion**

Chemical knowledge is dominated by a rich set of metaphors, analogies and models that are mental constructs of non-observable particles and processes. Chemistry teachers therefore try to explain chemical properties and the behaviour of atoms and molecules in every-day terms and as courses progress, the metaphors, analogies and models increase in sophistication. Along the way, many students accumulate unscientific alternative conceptions that need to be challenged and this involves conceptual change learning. The initial phase of this study investigated junior
secondary science students' conceptions of atoms and molecules and found both common and individual alternative conceptions. With these alternative conceptions, and others described in the literature in mind, a year-long study of student learning about atoms, molecules and bonding was conducted in a Year 11 chemistry class.

The conceptual change literature was reviewed and six theoretical perspectives were identified from which conceptual change learning could be observed, interpreted and described. A multi-dimensional interpretive framework comprising epistemology, ontology, motivation, piecemeal evolution of knowledge, holistic explanatory coherence and age-dependent development was then synthesised. Two other learning measures, modelling ability and intellectual development were subsumed within the epistemological and ontological perspectives. The year-long qualitative study of Year 11 chemistry students' progress investigated student learning when multiple analogical models of atoms, molecules and bonding were used in the classroom.

The findings reported in the six longitudinal case studies indicate that three of the six students substantially changed their conceptions towards of the scientific conception that atoms are dynamic, diffuse, spacious entities. The same three students found that multiple models were a more scientific way to describe particle behaviour and two of these students emerged as facile multiple modellers. A fourth able student made less progress towards the scientific conception of an atom and as a multiple modeller than his grade indicates. The two remaining students achieved a small evolutionary conceptual change and no change respectively. For the students whose conceptions did change, most of the changes were piecemeal evolutionary changes. However, the changes were both epistemological and ontological, and motivational influences played a variable role in each student's learning.

It is proposed that the multiple perspectives used in this study to diagnose conceptual change learning were found to be effective, that is, the various theoretical perspectives on conceptual change are complementary. The Conceptual Change Research Group's work and this study's author have synthesised a multi-dimensional interpretive framework for studying conceptual change and it is recommended that future research into conceptual change learning consider the value of using a multi-dimensional interpretive framework.
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Appendix 1

Journal and Conference Papers Arising from Studies in the Year 11 Classes
Journal and conference papers arising from this study


Appendix 2

Permission Letter sent to the Parents of the Year 11 Students
John Septimus Roe Anglican Community School
Mirrabooka WA

February 15 1994

Dear Parent

I am writing to provide you with information about a new approach I am using to teach the Year 11 Physics and Chemistry. I have recently obtained from a visiting colleague, a set of materials developed and trialled over the past 10 years in the US and South Africa. I believe that these materials are very appropriate for the current Physics in Context course. I am also interested in how students learn new concepts and with Mrs O'Neill's permission, I am observing student learning. The research will involve an examination of how students in upper school make sense of scientific concepts in Physics and Chemistry. To carry out this research, I will be the teacher, and a visiting colleague from South Africa, Dr Diane Grayson, and Associate Professor David Treagust from Curtin University will occasionally be in the classroom. Dr Grayson is a codeveloper of the Physics materials we are using.

The classroom work will entail videotaping the class activities from time to time. The findings from our work will be fed back to the students on a regular basis, so we envisage that the research will directly help these students with their understanding of science.

I trust that this work and research meets with your approval and I appreciate the school's support. I will be pleased to discuss any of this with you at your convenience should you so desire. You can phone me at school or at home (344 1880).

Thank you.

Yours sincerely

Allan Harrison
Appendix 3

Interview Protocol used with the Year 8-10 Science Students
Interview about atoms and molecules

1. I have here a block of metal and a piece of foil. Can you tell me what they are made of?
   Most recognise that the foil is aluminium
   Reasonable number call the iron cube iron, steel or lead
   Let's say it is aluminium, that it's very thin. If we could examine the alfoil in great detail by magnifying it
   so that we could see what it's made up of, what do you think you'd see?
   If atoms not mentioned in this response,
   Well, if we kept dividing that piece of aluminium foil in half and then again in half over and over and
   over, what we end up with?
   Nearly all students introduce atoms in this response. If not, 'atoms' are cued.

2. You mentioned an atom, what do you understand by the term atom?
   Can you tell me any more about atoms?
   Do you have a picture in your mind of what an atom might look like?
   I'd like you to try and draw me a simple picture of what you think an atom might look like? what you think
   it looks like?
   What do these circles represent?
   What does this centre bit represent?
   Why have you drawn these little dots out here?
   If the student mentions electron clouds, proceed directly to question

3. Now you've drawn your atom as a circle, I'd like you to look at this ball here [polystyrene ball, 5 cm dia],
   Does this ball in any way represent for you what an atom looks like?
   [Add the pompom, same size] Here's another ball for you to think about - do you think your atom would
   be hard or soft?

4. Let's have a look over on the other side of the sheet. Here are a number of diagrams of some of the ways
   that atoms have been described. Look at these six diagrams and put a circle around the one you think best
   describes what an atom would look like.

   You've chose number __. Put a circle around it. Why do you like number __?
   Is there any diagram there that is the next best for you?

   You like number __ as well. Why do you also like number __?
   If the student seems to like others, continue and establish an order of preference as far as the student wants
   to go

   What do you think these lines out here ['orbit' like paths of electrons] represent on this atom in number __?
   Is there diagram you really don't like? - put a circle around it.

   Why don't you like number __?

5. Often atoms join together to make molecules [picking up 2 molecular models] We represent molecules
   using models like these here [space filling + ball and stick for H₂O]. Have you ever seen models like these?
That's model A [space filling] and that's model B [ball and stick]- you can have them for a moment. Which on of those two models is the better model for you - A or B?

Why do you like _ better than _?

6. Have you heard of electrons?

What do you know about electrons, what can you tell me?

Where would you expect to find electrons?

What do the electrons do?

Do they just sit there?

7. Have you ever heard of the term an electron cloud?
   If yes, then
   When I mention the word cloud, what do you think of?
   Is an electron cloud like a cloud in the sky?
   What is a cloud made of?

8. Have you ever heard mention of an electron shell?
   If yes, then
   When I say the word shell, what do you think of?
   What sort of shell do you mean?
   How can an atom have shells?
   Do electron shells do what you think a shell does?

9. Is there anything else about atoms which you have in your mind but we haven't mentioned here?

What size do you think an atom is?

Is it possible to see an atom?

Even with a very powerful microscope?

Scientists seem to know a lot about atoms, do you think they've ever seen an atom?

Is everything made out of atoms?

10. If we assume that this polystyrene ball here is the nucleus of an atom and the electrons surround the nucleus, if this ball is about 5 cm in diameter, how close on this scale do you think the electrons come to the nucleus?. Point to this position.

Do they actually come in and touch the nucleus?

Any idea how far the electrons might spread out away from the nucleus on this scale?

How far on this scale is the furthest that electrons move away from the nucleus?

Thanks very much for your help. It's been very useful.
Appendix 4

Year 11 Chemistry Semester 1 and 2 Programmes

Note: For copyright reasons Appendix 4 (pp 309-10 of this thesis) has not been reproduced.

(Co-ordinator, ADT Project (Retrospective), Curtin University of Technology, 8.1.03)
Appendix 5

Year 11 Chemistry Syllabus (Secondary Education Authority, 1994, pp.11-21)

Note: For copyright reasons Appendix 5 (pp 312-16 of this thesis) has not been reproduced.

(Co-ordinator, ADT Project (Retrospective), Curtin University of Technology, 8.1.03)
Appendix 6

Structure of Matter Test: Items Relating to Atomic Structure

Note: For copyright reasons Appendix 6 (p318 of this thesis) has not been reproduced.

(Co-ordinator, ADT Project (Retrospective), Curtin University of Technology, 8.1.03)
Appendix 7

Transcript of Lessons of March 29-30, 1994
Transcript of lessons on March 29-30

March 29

Teach. We've been talking in chemistry about the structure of the atom... certainly using the method of showing how many protons, neutrons and electrons that are present in an atom and talking about what isotopes are, alright. We very briefly covered that section of work. Alright, what I wanted to do today, - you've all got that diagram down from the chemistry yesterday - discussion about the chem experiment?

Class. Yes we are.

Teach. Now when we come to have a look at nuclear energy, we are dealing with atoms and of course, very fundamental particles which make up matter such as the three basic particles that we know of - which are?

Ken. Atoms?

Teach. What is an atom made of?

Alex. Neutrons... protons.

Dan. Electrons

Teach. So atoms are made of protons... neutrons... electrons. Alright then... what was that Tim?

Tim. They've got electron shells.

Teach. You say an electron shell, why do you use that term?

Tim. To explain how the electrons surround the nucleus.

Teach. Why do you use the word shell then?

Ken. In relation to the first one, I mean two electrons are in the first one, and then there's eight and eighteen... and...

Teach. OK Ken, but why do you use the word shell?

Jon. Because it's shell-like.

Teach. Cause it's out, outside... it's covering the nucleus.

Jon. It's covering the nucleus is it?

Tim. Yea... [that's what you think?] yea...

Teach. I'm interested in what you think at the moment, I'm not in any way being critical of what your ideas might be, I'm simply interested in what they are. Where did you meet up with this term an 'electron shell'?

Jon. Last year, Mr Sollis... during chemistry

Teach. Was it just mentioned to you?

Jon/Tim. He was trying to explain.

Alex. Explaining how they get like that, saying they're in shells, drawing them and like that.

Teach. I'm interested in why the word 'shell'? and not the word layer?

Jon. That's the way we did it.

Teach. Basically it's just the nucleus and the electron holding shell.

Jon. Like an egg with a shell.

Teach. Like an egg with a shell?

Jon. Yea... the yolk is the nucleus.

Teach. And the calcium bit is the, is the um, the electron shell [Jon says this almost simultaneously]...

Ken. What were you saying Ken?

Teach. It doesn't go, like just in circles, it goes around [what goes around?] the electron... the electron shells in circles nearly so it goes around.

Jon. It goes really fast.

Teach. In circles nearly.

Ken. So it goes in layers, probably go in circles. [Hmm]

Teach. Has anyone ever mentioned when talking about shells a comparison to say and onion.

Jon. No.

Teach. Wait, wait, wait... um no.

Jon. But did you have this reference to the idea of an egg?

Teach. Yea.

Jon. No that was just what I had thought.

Ken. We just made it up.

Teach. So Mr Sollis didn't say an egg.

Jon. No naa.

Teach. But that's what you though of, Jon?

Jon. Yea.

Teach. And who made the link between the idea of the yolk and the nucleus?

Jon. Me.

Teach. You say you did, did you Jon?
Tim: We both did.
Jon: Both of us thought that’s what he meant, at least that’s what I thought he was trying to say.
Teach.: That’s interesting because we use a metaphor like that, you’d know about this from English where you talk about metaphors, we use a metaphor, and sometimes when we use a metaphor like saying electron shell; you link the idea of a shell for an electron, sometimes the ideas that you come up with can be quite different. That’s why I’m talking about this so we can actually get the picture of what we’re trying to visualise. So you think of the calcium shell on the outside of the egg, Jon, as being where the electrons are?
Jon: Yea.
Teach.: How do you account then for how you have the idea of 2 or 3 or 4 shells?
Ken: There’s the white to fit.
Tim: Electron cloud?
Teach.: What’s that Ken?
Ken: There’s the white that’s also like an electron shell.
Teach.: So now you’re using the white of the egg as a fill in layer?
Jon: I didn’t see that, I just looked on the nucleus, the yolk and then the shell as the electrons, so the electrons are on the outside, that’s all.
Teach.: So the electrons are out there, you didn’t refine the ...
Jon: I was generalising really.
Teach.: Just generalised [yea] OK, Dan, in Singapore, did you use any of these sorts of ideas? have you heard the term an electron shell?
Dan: Yea
Teach.: What do you think of when we say electron shell?
Dan: Just something ... just something moving around it.
Teach.: But the idea of shell doesn’t normally give the idea of something moving does it?
Dan: No.
Jon: It’s more like he told us you have to take my word for it [class laughing].
Teach.: OK, well, what I thought I’d do now is very briefly in looking over some of the evolution of the ideas of the nature of the atom, trace through how scientists have refined and changed their visualisation of what an atom is like. Now probably if I use this box of models, ... they’re snooker balls
Tim: Ah wicked ...
Teach.: Quite often one of the first models that is used for atoms was to use what’s called today, the billiard ball model. Billiard balls are hard and a lot of people in old times, if you went to the grammar schools in England, most of the students came from privileged backgrounds and one of the things they were familiar with was billiards or snooker - gentlemen played billiards ... [discussion of billiards vs snooker] The very first of the models which was used for atoms probably goes right back to the ancient Greeks - one of the Greek philosophers, we’ve heard of people like Plato, Aristotle, Socrates, etc. there was ... [Plato discussion] there was one of them, a lesser known Greek called a scientist of those days, named Democritus. Democritus was the first recorded instance of suggesting that all matter is made up of individual particles. You can take a piece of a substance and you can divide it up, but you couldn’t divide it infinitely there comes a point where you can’t divide it any more because it was made of what he viewed were basic fundamental objects - atoms. The word electron is also a Greek word meaning brightness. Probably that idea stood for about 2000 years that all objects were made up of indivisible ball like particles. Then came John Dalton, late 1700s to early 1800. Dalton was the first person who ... realised from natural observations that there was a large range of individually different types of atoms, such as oxygen, hydrogen, nitrogen, and so forth. He only had a dozen or 15 different elements because that was about all they could account for by their scientific observations of the time. Now Dalton proposed that each atom is a fundamental particle that they come in types, all oxygen atoms will be the same, all nitrogen atoms will be the same, all hydrogen atoms will be the same. A lot of people wouldn’t accept his ideas. The experimental evidence that was collected by a number of chemists like Davy, Priestly - who actually discovered oxygen - he was the first person to prepare oxygen but because of certain ideas he had, he would never accept that he had made oxygen [discussion about method HgO]. It was Frenchman Antoine Lavoisier who actually recognised that he had separated and isolated the most reactive element in the atmosphere. Priestley would not accept that he had prepared the reactive portion of the air because he held some very ancient theories that he could not let go of. Lavoisier recognised what Priestley had made and the history of science says that sort of, it was Priestley who found oxygen but it was Lavoisier who discovered oxygen - recognised what he had. it was about then that John Dalton proposed that atoms are the smallest indivisible particles of matter and that each one has its own separate
characteristics. All oxygen atoms are the same, all hydrogen atoms are the same and so on. Whenever they react, they always react in the same proportions and it's out of this work that you get the law of definite proportions or the law of constant composition. He was the first person to put chemistry on a proper footing. By the late 1800s - about 1880, a very famous physicist, J. J. Thompson discovered the electron.

Humorous comment about Thomson and Thompson
He proposed following on from Dalton's idea that atoms were spheres, he came up with what is called the 'plum pudding' model of the atom. OK, this probably doesn't mean much to you because we don't eat plum pudding here.

Jon There is a plum pudding.
Tim What's a plum pudding?
Teach. Thanks Tim, that's a good reasonable question. In England then, it was a very common sweet just as ice cream is so common for us as a sweet
Humorous comment (inaudible)
Jon It's like Australians have got their pavlova.
Teach. Yes. It was the common sweet of central England because in a cold area it had high energy value and was easy and cheap to make. It was a fatty cake which was made from animal fat cooked up with flour and sugar to make a heavy dough in which pieces of cut up plum were mixed. It was cooked in a bag so that it came out round with all these pieces of plum spread evenly through it. So you get a model (draw on Whiteboard) of J. J. Thompson's plum pudding model is that you had a round spherical object with pieces of plum embedded all through it like this. Now J. J. Thompson discovered the electron so he wanted to show was an idea of the pieces of plum scattered throughout the pudding were like the electrons scattered throughout a spherical atom. At this stage atoms were still viewed as being solid, spheres. Democritus had the idea as a rock breaks down into sand, the sand grains were solid little objects which made up a large solid object.

Jon So they thought that an atom was made up of electrons?
Teach. Yes, they thought that the electron was one of the major components of the atom because one of the most obvious things we can detect about atoms is their electrons. Take a plastic rod rub it on a woollen cloth or cat's fur and it becomes charged. Obviously, in their eyes, electricity was something that was being rubbed off one substance onto another substance and therefore electrons were all over atoms or the main thing that made up atoms.

Jon How come when we rub out feet like this ... and lift out feet off the floor, we can give shocks to ourselves and other people. It starts off at your feet and then goes to your hand.
Tim Your hair can go all up.
Teach. When you've got two different substances rubbing on each other, one has greater affinity or a greater attractive power for electrons that the other. Different substances have different attracting powers therefore they move.

Jon How can I shock him up here?
Teach. You're a good conductor that's why the charge moved from your feet to your hand - you contain lots of salt solution.

Jon There was electricity in the atom ...
Ken Where is the nucleus in this model? Where did it fit, in the middle?
Teach. They did not have a nucleus in this model, they didn't know about such a thing as a separate object.

Ken So did they think that the elections were in the nucleus?
Teach. Yes, they thought of the atom as a sphere of substance that had electrons embedded in it evenly all the way through and that's why the plum pudding model fitted that idea - it was even all the way through, it was round and even consistency throughout. The plum particles represented the electrons. They weren't saying any more than that.
That was about 1880s, at the turn of the century, 1890-1900 a New Zealander, Ernest Rutherford went to work at Cambridge with Thompson - Thompson was the pre-eminent physicist in his time, no one questioned J. J. Thompson except his new student who later became Lord Rutherford and won a Nobel prize for his work in physics in refining the understanding of what the atom was like by discovering the nucleus.

Tim You know how you have the metal balls in the rings and rings outside it and they move
Teach. What do you mean Tim?
Tim You know how you have those metal rings.
Ken Go and draw it
Tim I can't really do ...[what are you referring to] it's like Saturn, like,
Teach. You're talking about the solar system?

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Tim: Yea, it's go like rings, and it's got, like inside it has smaller rings, and there's a metal bit and a metal ball in the centre of the thing.

Teach.: You mean the models of the solar system?

Tim: A model in relation to the atom?

Jon: The rings around Saturn are like an atom?

Tim: Yea, and when you um, when they rotate.

Jon: The rings on Saturn are like

Tim: They're like the electrons when they're moving, they're moving fast and

Teach.: Around what?

Tim: The nucleus...

Teach.: So you're using a mental image of saying that ... the ... Saturn like we have up here on the chart of the solar system ... isn't Saturn in itself with the picture of the rings a bit like a repeat of the solar system?

Jon: Yea

Teach.: We have this idea of the solar system, with the Sun in the middle - what planets are they as we go out.

Many: Mercury ... Venus ... Earth ... Mars ... Jupiter ... Saturn ... Uranus ... Pluto Nup. ...

[Teach.]: ... old king of the ocean ... [Neptune] and then [Pluto].

Teach.: Right now look up at that model there or that picture of the solar system, this is just what Rutherford came up with. Rutherford said, what we know about the solar system is a good image that can represent what we think the atom is like. You see what's the big change from going from Thompson's plum pudding model to a planetary solar system model?

Jon: The electrons are separate from the rest of the atom

Teach.: Yes, the electrons are separate and they're in

Dan: Orbits

Jon: Their own plane of orbit.

Teach.: What else is there in the centre of that isn't in Thompson's model?

Jon: The Sun.

Teach.: The Sun which we're comparing to ...

Alex/Ken: A nucleus.

Jon: What about those movements around in ...

Teach.: This starts to make it more difficult doesn't it - if you're going to apply that - if you say, the atom is like the solar system, we mentally would say, what's the Sun match up with?

Many: The nucleus.

Teach.: What do the planets match up to?

All: the electrons.

Teach.: Well what do the moon's match up to?

Dan: But there is, there is only one line

Tim: Only one plane

Dan: But there's only one planet in each orbit instead of like as the atom has 2, 8, 18 ....

Teach.: Dan, good point, there is only one planet in each orbit, where we expect

Dan: Two ...

Alex: Two

Teach.: Two electrons per orbit, alright ...there are differences then aren't there ..

Many: Yes

Tim: What about the asteroids?

Teach.: There's the asteroid belt which ... would we be able to compare that to any part of the atom?

Ken: What about the cloud ...

Dan: The cloud?

Jon: What about a black hole

Teach.: Not within the solar system.

Alex: Don't the electrons surround the atom, or just go round like this (gesturing with hands as a sphere shape).

Teach.: So Alex, you're saying all the planets are basically in one plane aren't they, but are the electrons, do we believe they're in one plane?

??: They're around this way, all around the atom ... all over the place.

Teach.: What is the picture we use? It's called an electron ...

Alex: Cloud

Teach.: The idea of a cloud is all ...

Jon: Around, like a cloud, a haze
Can you see that there is an important change from Thompson to Rutherford. Rutherford brought in the concept that ... Thompson contributed the idea of individual electrons surrounding or making up the atom. Rutherford said, Ah there is also a dense central nucleus, the evidence for that was ...

Did Thompson agree with Rutherford?

Thompson was the director of Cavendish lab at the time and Rutherford worked under him, Rutherford himself became director of the Cavendish lab after Thompson retired. Basically Rutherford couldn't walk in and say here's a new idea you're wrong - it's not the way to win friends and influence people is it, he would have had to have evidence. Can you think of how the evidence went? Can you remember what I told you about Rutherford's experiment?

The pea on the cricket pitch?

The string ...

The gold string?

A piece of gold foil. He had some radium in a lead block with a narrow hole so a beam of alpha particles which are the nuclei of helium atoms - two protons plus two neutrons - were being projected in a constant stream. A beam of alpha particles - these alpha particles hit the gold foil. We all know that gold is a very heavy, very dense metal even though it was roiled out into a thin layer. We know today that it was at least 10, 20, 30 atoms thick and yet 999 approx. out of a 1000 alpha particles went straight through.

Just went straight through it?

Yes went straight through, hit nothing. In one side and out the other.

It's like transparent [yes] transparent to the alpha particles?

Clearly the gold foil isn't transparent to light and clearly it was a dense metal.

So it had holes in it ... you could feel that it was solid right, but the things still went through it.

Would it hold water? [Sure] water could go through this (gesturing a hole in a piece of paper)

How come the water atoms wouldn't go through?

Because what you've got with an alpha particle is a helium atom with all its electrons ripped off it.

It's just the nucleus?

Yes. Just the nucleus. remember the analogy about the MCG?

Partly ...

The hydrogen atom, the electron is going around the outside of the arena and the nucleus is as big as an pea on the middle of the cricket pitch. Now in the alpha particle all the electrons are stripped and all you're left with is the pea. So we're now throwing that pea - if you put a pea in a very high powered gun in the MCG would it be reasonable to shoot straight across through it without hitting any one on the field?

That's what Rutherford was doing, showing that this tiny nucleus with no electrons around it taking up almost no space and it went straight through the gold and this experiment was done with Thompson so Thompson couldn't disagree with what was happening. Everybody knew that they had found something very basic - that most matter is nearly all ...

Empty space.

So they had to revise Thompson's model. So Rutherford came up with the solar system model because it best fitted the facts as they saw them. There is one problem. Do you have in your mind a clear picture of what the solar system looks like?

Mmm

Tim, would you describe without looking at that picture, what the solar system looks like.

Well you have the Sun in the centre ... and you have um, ... couple of rings of orbit, and you have one line of um, planets, but that doesn't work ...there are seven in one plane ... ...it's hard to, ... it's hard to see ...

Let's say we're in a space ship and we're above the plane of the solar system here (indicating on the diagram well above) like this flat sheet ... we're in a space ship sitting above about the distance of the earth from the Sun above the plane, would we be able to look down and see the solar system?

No ... no!

No [others saying no too] ...

Why?

Because it's too big and there's too much space.

There are planets around here as well (indicating other side of the Sun) ... the planets aren't just there, scattered around, not gathered around together ...

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Dan: No but [about 3 people talking] ... from the Sun to Mars would be hard to see because it's so far, but let's say if you were really good at seeing you might see some of it ...

Ken: It's like, it's like you're in the middle of the ball and you can't see outside, because it's just one ring ...

Teach: Back to Dan's point, is the solar system small enough for you to see it all at once?

Some: No, nap ...

Teach: How great are these distances?

Alex: Very, very large

Dan: Only a certain amount can be seen at once ...

Jon: Ask ourselves, I can't even see to the coast from here, you know when you, the Earth is probably a hundred times the size of that and on top of that you've got the orbit of the planets and the distance between the planets from one orbit to the next...the distance between the planets makes it impossible to actually see those sorts of distances.

Dan: No but this is, you can't see the coast because the earth's round, in this case.

Jon: But I'm talking about the distance ...

Alex: I suppose you probably could if ...

Jon: Look a lot of the time you can't even see Rottnest

Tim: Yea, but how come we can't see across ...

Teach: Well what I'm trying to ask you is do you think you can see - and I think we're all pretty much in agreement - the solar system is so big

Teach: Jupiter is over double the distance so we're talking about a planet halfway out in the solar system that is as far out from us as we are from the Sun. Would we be able from our spaceship to be able to see all this solar system at once?

Jon/Alex: It's too big to see and the planets are too small ...

Tim: You know that model where you have the um, as string of metal wires going down and you have the balls at the end of it, and everytime you knock the end ball it makes the others move.

Teach: Newton's cradle? ...

Tim: Yea, well this model, they have that ball in the centre and they have like orbit rings out:

Yea, and once you spin one ring, the others spin.

Dan: A gyroscope

Tim: Yea, that's it, that's it ...[gyroscope, so you think that's a good representation of an atom to you]? yea.

Teach: That's an interesting one that I hadn't heard before

Jon: What's that?

Tim: A thing with rings around a metal ball with metal balls on each ring and they go round each other ...

Teach: A ring within a ring, perpetual motion toy

Dan: The rings move round inside each other ... and it stays the same way ...

Tim: Yea.

Dan: But say if you were looking at the solar system or something, if you were far enough up, high enough, you would be able to see all the

Teach: If you were far enough away.

Dan: Yes you should be able to see it.

Teach: Is the idea of the great vast distances between the planets the same as the great distance between the nucleus and say the electron as in the analogy of the MCG?

Most: Mmm

Dan: How far away from each shell are they, how far is each shell away from each other?

Teach: They vary

Dan: Oh, ...

Teach: They do vary, I couldn't tell you accurately. Now OK, so the next one was Rutherford's planetary model which based upon his gold foil alpha particle experiment. So, ... now ... unfortunately, ... Rutherford's planetary model didn't last more than about 7-8 years before he was challenged by further experimental evidence which came from another Nobel prize winner called Nils Bohr

Jon: Never heard of him.

Teach: He was a Dane ... in about 1910 he was doing a lot of calculations and thinking about what Rutherford had done and of course Rutherford's model was very important because it stimulated further ideas. Remember we talked about the line emission spectra in chemistry the particular wavelengths that come out of specific atoms,

Dan: Yea

Teach: When they are heated or excited by a flame or electric discharge like the fluorescent tubes you always get the characteristic lines for that element like the strong yellow in sodium
vapour lamps, he came up with the model which was variant of the planetary model which removed all the ideas of concentric circles in one plane and said they must be all over the place and they must be in all planes. Bohr came up with what is still in most physics textbooks which is the Bohr model of the atom because he was the first person who could actually explain why different coloured lights were emitted by atoms - by different elements when they were excited. There were flaws found with his model and it was a Swiss by the name of Erwin Schrödinger and a Frenchman named Louis de Broglie.

All: Laughter

Teach. Who [Sollis comes in and starts joking]
Teach. These two physicists produced the most exact but highly mathematical description of the atom by talking about matter as waves and showing that the electrons are best thought of as regions of probability. This is the quantum mechanics idea and works for most atoms.

30 March

Teach. I'd like to round off from yesterday, remember we were talking about models of atom, I said that the very first model or idea that all substances were made up, of tiny indivisible particles came from the Greek philosopher Democritus that view basically held that they were like grains of sand making up a lump of sandstone or something like that and that went on far about 200 years. The rise of the scientific age ... the first actual model of the atom was proposed by Dalton who set forth the idea that atoms were little round spheres, a bit like the ... Dan

Billiard balls.

Teach. This model certainly explained a few things such as when they collide they bounce of one another very easily with what we call perfectly elastic collision - these aren't [snooker balls being handled] but they are the nearest common things we can use. Then came along J.J. Thompson with his plum pudding model of the atom, that was fairly quickly - that was needed because he was the discoverer of the electron and because they now knew that there were individual little particles within atoms, electrons, he had to have a model that distributed these electrons evenly throughout the atom, hence the plum pudding model. Then came Lord Rutherford with his planetary model sort of the atom is like a solar system. What do you think the things that fit here?

Jon The nucleus is like the Sun ...

Teach. Planets are like the ...

Tim The electrons.

Teach. The orbits ... are

Tim Like the electron shell

Teach. Thanks Tim. What sorts of things did we say didn't fit though?

Tim The electrons are in one shell ...

Dan In one orbit

Teach. OK Tim, how many planets are in one orbit?

Tim Only one planet in it.

Teach. So we have one planet in an orbit but normally we work on two electrons per orbit as a rule, and of course we have shells with a lot of electrons at the same level. In one sense, the nearest thing we talked about yesterday, didn't think of it at the time, but the asteroids are a shared idea, because at one particular level you have a whole lot but then they're not consistent. What go around a lot of the planets?

Alex Moons.

Teach. That won't fit will it

Ken No.

Teach. Why Ken?

Ken Because like there's nothing around the electrons.

Teach. Yes, nothing orbits the electrons. So it was a limited idea, Nils Bohr went on and used a type of planetary model but in a more

Jon Electrons still could have a 'moon' but we just haven't discovered it yet. Like, it's each idea of the atom, maybe there is something more to the atom that nobody knows about. Like there could be more inside the electron ...

Ken What thing inside the electron?

Teach. Do we know?

Tim There is an electron shell.

Teach. Do we know that there's nothing inside the electron or do we just know that nobody's so far has found anything?

Jon No-one's found anything but that doesn't mean nothing's there ...
Teach. Sure. If we go back to Democritus.
Jon  Yes ...
Teach. Atoms were solid little things, Dalton saw them as round solid balls, the evidence which
Rutherford came up with said they're all space, or mostly space.
Ken  Rutherford?
Teach. Yes, what you say may well be true, we can't really say, we like to say things are proved
and we know everything, that's only till someone comes up with better information. Bohr
went on an he dealt with a single electron atom - what would that be?
Ken  Yes ... helium
Tim:  Hydrogen
Teach. OK hydrogen, and he did that because he realised he could mathematically explain the
emission lines and the colours and the wavelengths of the various photons which were
emitted when atoms were heated or an electric discharge passed through it. he found
though, that as soon as he went to a 2 electron atom such as helium the mathematics didn't
work. the reason the mathematics didn't work was because there were now not only
interactions between the electron and the nucleus, what charge is on the nucleus?
Alex:  Positive ... positive 2
Teach. Well in a hydrogen nucleus ...
Ken  Neutral.
Teach. It's not neutral, the whole atom is neutral ...
Alex:  Positive one.
Teach. What has positive 2 in the nucleus?
Tim:  Helium
Teach. Thanks, so once he went to the helium atom, there were interactions between the electrons -
and they were repelling - as well as attracting towards the nucleus. The mathematics
worked when there was only one variable and Nils Bohr's theory broke down. Then along
came the quantum mechanics description developed by Erwin Schrodinger and Louis de
Broglie
Jon  What is quantum theory?

The discussion went on to talk about quantum theory but contained no items of relevance to atoms
and particles.
Appendix 8

Kinetic Theory Pretest
This kettle is boiling as it is heated by a gas flame.

Try to answer each of these questions

(a) What is happening at A (the interface between the water and the steam)?

Why? How?

(b) How would you describe the arrangement of the water molecules \( H_2O \) in

(i) the water?

(ii) the steam?

(c) What is happening at B (where the steam coming out of the whistle forms a cloud)?

Why? How?

(d) At A, what temperature is the

(i) steam

(ii) water

(iii) Does the temperature vary anywhere inside the kettle?
3.

No air can get into or out of the flask

(a) How would you describe the structure of the air (gas) in situation A?

(b) What has happened in situation B?

(c) How do your ideas about the air in the flask in A compare to your ideas about the air in B?

(d) What is air pressure? Explain its cause(s).
This 250 mL tumbler was filled with ice plus a small amount of water. It has been standing on a table in the kitchen for 15 minutes. The air in the room is at 20°C. Try to explain the following observations.

(a) What do you think is 0°C, the water, the ice or both? Explain.

(b) If all the ice has melted after 25 minutes, describe what you think has happened to the temperature of the ice, the water, the mixture over the total 40 minutes. A graph may be useful.

(c) How would you describe the difference between structure of the ice and the water?

(d) Why are there droplets of water on the outside of the tumbler?
Appendix 9

Atomic Structure and Bonding Pretest

Note: For copyright reasons Appendix 9 (pp 333-334 of this thesis) has not been reproduced.

(Co-ordinator, ADT Project (Retrospective), Curtin University of Technology, 8.1.03)
Appendix 10

Atomic Structure and Bonding Test

Note: For copyright reasons Appendix 10 (pp 336-339 of this thesis) has not been reproduced.

(Co-ordinator, ADT Project (Retrospective), Curtin University of Technology, 8.1.03)
Appendix 11

Organic Chemistry Pretest
ORGANIC CHEMISTRY WORKSHEET

1. An compound is said to be an ORGANIC compound because

2. Which of these substances then, would be classified as ORGANIC? (Circle if organic, underline if you're unsure, leave unmarked if inorganic)

   \[
   \begin{array}{cccccc}
   C_8H_{13}NO_2 & CaSO_4 \cdot 5H_2O & K_2CO_3 & AgBr & CO_2 \\
   ZnO & Al(HCO_3)_3 & CH_3COOH & NH_2CONH_2 & CCl_4 \\
   NH_3 & \text{diamond} & C_60 \text{ (a fullerene)} & COCl_2 & H_2O \\
   \end{array}
   \]

3. What then do you understand by the term HYDROCARBON?

   What are two examples of hydrocarbons? (Give the common name and its formula)

4. Describe an atom of carbon. The best way is to use a diagram and some brief notes.
5. Two types of molecular models are space filling and ball-and-stick models like the ones on the bench. Which of these models do you think is the better representation of a molecule? (Circle the one you prefer)

Why do you prefer the model you circled?

6. Three bonding situations are shown in these diagrams. Briefly describe what you think the circled parts of these diagrams represent?
Appendix 12

Organic Chemistry Worksheet
ORGANIC CHEMISTRY WORKSHEET

1. An compound is said to be an ORGANIC compound because

2. Which of these substances then, would be classified as ORGANIC? (Circle if organic, underline if you're unsure, leave unmarked if inorganic)

<table>
<thead>
<tr>
<th>O₃SC₆H₅OH</th>
<th>BaSO₄</th>
<th>graphite</th>
<th>PbCl₂</th>
<th>Na⁺C₁₇H₃₅COO⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu(NH₃)₄²⁺</td>
<td>Mg(HCO₃)₂</td>
<td>C₂H₅OCH₃</td>
<td>NH₂CONH₂</td>
<td>CHCl₃</td>
</tr>
<tr>
<td>cyclopentene</td>
<td>H₂O⁺</td>
<td>Na₂CO₃ 2H₂O</td>
<td>octane</td>
<td>COCl₂</td>
</tr>
</tbody>
</table>

3. What then do you understand by the term HYDROCARBON?

How many different types of bonding are possible within HYDROCARBON molecules? Describe the different bond types as well as you can using words and/or simple diagrams. If you can, use actual examples.
6. Look again at the ball and stick models that we have been constructing and using.

Are these models accurate representations of the atoms and their bonds? Explain.

EXAMINE THE MODEL OF cis-1,2-dichloropropene

In what way(s) are the hydrogen, carbon and chlorine atomic models LIKE actual atoms?

i. 

ii. 

iii. 

In what way(s) are the hydrogen, carbon and chlorine atomic models UNLIKE actual atoms?

i. 

ii. 

iii. 

In what ways are the carbon-carbon bonds and the carbon-hydrogen bonds LIKE actual atoms?

i. 

ii. 

iii. 

In what ways are the carbon-carbon bonds and the carbon-hydrogen bonds UNLIKE actual atoms

i. 

ii. 

iii.
Describe an atom of carbon. The best way is to use a diagram and some brief notes.

The type of molecular models that we have been making in class are called ball-and-stick models like the ones on the bench. Examine each model and write its IUPAC name in the space provided.

A.  

B.  

C.  

What is the difference between the carbon-carbon bonds between A and C that is different in B?

How could you describe or explain this difference? Use any method you believe is useful.
Appendix 13

Final Year 11 Interview Protocol
Thanks ............. for giving up a few minutes to talk to me about your ideas about chemistry.

Do you mind if I tape record our discussion?

I understand that you've just finished the organic chemistry unit?

What is organic chemistry about?

[aim to elicit idea of the chemistry of carbon compounds]

If organic chemistry is about carbon compounds (or, molecules containing carbon) what do you think compounds and molecules are made of?

[aim to elicit idea atoms]

I'd like you to tell me what you think an atom looks like.

Can you draw me a diagram of your mental picture of an atom?

Tell me what you're doing as you draw your atom.

What are these parts [nucleus, electrons ...]

Look at the diagrams on the other side of this piece of paper.

These are some of the ways that people have described atoms.

Which one best suits your idea of what an atom would look like?

Circle the diagram that is best for you.

You can circle more than one - number them in order of preference.

I have here a model of an organic molecule [1,2-dichloroethane - CH₂Cl-C₂Cl] You can examine it.

Why does it have this shape?

[aim to elicit tetrahedral due to mutual repulsion of four C-H bonds]

Here is another organic molecule. [trans-1,2-dichloroethane - CHCl=CHCl]

How is this molecule different to the previous one?
If no mention of shape difference, ask
Is this molecule the same shape as the previous one? [it is planar, 2-dimensional]
Why is this molecule shaped like this?
[balloon analogy may be given]

Here is a third molecule [ ethyne (acetylene) - HC≡CH - linear ]
How would you describe this molecule's shape?
Why does this molecule have this shape?

SPACE FILLING MOLECULES
These three models are of the same compounds.
These models are called space filling models.
Which model type is more appropriate? Ball-and-stick or space-filling?
Why?
Do either of these model types accurately describe a molecule?
Why? or why not?

If no analogy mentioned Did Mr Harrison use any other models to explain these shapes?

If single, double bond differences have not been mentioned
Have another look at the models of 1,2-dichloroethane and trans-1,2-dichloroethene.
How are these two molecules different?
How are the carbon-carbon bonds different?

On this other sheet of paper, there are diagrams of these same three molecules showing the bonds as a — or as electron dot diagrams.
Are the electrons situated between the atoms like this?

If no, then How are the bond electrons arranged between the atoms?

IS THERE ANYTHING MORE YOU CAN TELL ME?
1,2-dichloroethane

trans-1,2-dichloroethene

ethyne