Science and Mathematics Education Centre

Secondary Students' Understanding of the Gene Concept: An Analysis of Conceptual Change from Multiple Perspectives

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"This thesis is presented as part of the requirements for the
award of the Degree of Doctor of Philosophy
of the
Curtin University of Technology"

September 1997

ABSTRACT

A journey into the past century of genetics history reveals transformations of the concept of the gene through notions of discrete units that obeyed Mendelian laws to the modern bewildering gene concept. We can no longer say that a gene is a sequence of DNA that continuously and uniquely codes for a particular protein - it is the phenotype that defines the gene, rather than the other way around. Research into learning in genetics has largely focussed on issues such as problem solving and the process of meiosis. The central concept of the gene, however, has had little attention. How do students learn about the concept of the gene during an introductory high school genetics course? Is it possible to justify an analogy between the historical development of the concept of the gene and student learning? Can student learning about the gene be described as conceptual change and what are the factors that might influence this process? These are the issues that are addressed in this thesis.

The general purpose of this study was to investigate Year 10 students' learning about the concept of the gene. The theoretical framework is embedded in the personal and social paradigms of constructivism and a multidimensional interpretive framework for conceptual change was utilised, enabling the data to be interpreted from ontological, epistemological and social/affective perspectives.

A total of eight classroom sites were used to collect data as a series of linked case studies. Data from three of these cases were used to investigate Year 10 student learning about the concept of the gene and one of the cases was used to make an in-depth examination of individual student learning and conceptual change. The larger series of eight cases was drawn upon to provide data to support assertions made about the factors influencing conceptual change. Methods of data collection included classroom observations, student interviews, teacher interviews, student work-sheets and classroom quizzes. Traditional notions of research rigour were side-stepped for different standards that better suit the paradigm of naturalistic or constructivist inquiry. Credibility, transferability, dependability and confirmability were enhanced by a thorough system of triangulation at the data source and collection level and at the data interpretation level for each of the research questions. Theory triangulation also was utilised through the multidimensional framework for conceptual change. In addition, methodology and case studies with a thick description that allow the readers to proceed on their own tracking and interpretation process are provided.

The results of the research reported in this thesis are examined from several different perspectives. From an ontological perspective, Year 10 student learning about the concept of the gene is described by a proposed learning pathway that consists of four ontologically distinct models. The majority of the students in the classes, however, did not progress the entire length of the pathway, rather they completed their introductory genetics course with an "active particle gene" conception. This is the second model in the pathway. In other words, few students were found to have a modern conception of the gene.

From an epistemological perspective of conceptual change, six students' post instruction conceptions of genes were classified as being intelligible, plausible or fruitful to the learner. For example, at the end of the genetics course, Alastair had an "active particle gene" conception that he viewed as intelligible and plausible and Douglas had a "productive sequence of instructions gene" conception that was intelligible, plausible and fruitful. The student learning investigated in this study was described as conceptual change of the weaker kind that proceeded in an evolutionary manner because the new conceptions involved detailed explanations of the gene concept and were reconciled with old conceptions.

A social/affective perspective revealed information about how the teaching approach and student interest in genetics influenced the process of conceptual change. Lack of student interest in submicroscopic explanatory phenomena and algorithmic approaches to problem solving were found to inhibit learning about the gene concept. The nature of the content was another perspective used to examine conceptual change. The process aspects of genetics content were said by teachers to be difficult to teach, and students found it difficult to link together ideas taught in genetics such as the double helix structure of DNA, the genetic code, protein synthesis and phenotypic expression. The different levels of representation in genetics content confused students; for example, Anna was unable to differentiate between submicroscopic DNA structure and symbolic representations of the genetic code such as the letters A, T, C and G.

Implications from the study are that for students to construct a better understanding of the concept of the gene, teachers and curriculum writers should use the gene as a central organising concept in genetics courses and explicitly encourage students to build links with other genetics concepts. Improvements need to be made in the way that teachers teach genetics processes so that students are actively involved in thinking about the processes, especially by making the connections between the structure and function of genes. In addition, students need to be involved in learning strategies that will help to raise the status of sophisticated models of genes in their cognitive structures.

Having the multidimensional framework for conceptual change as the interpretive framework and utilising different perspectives of conceptual change enabled triangulation of the theoretical interpretations of the data. This can be likened to creating a three dimensional picture of a learning situation rather than the equivalent of a linear, or two dimensional representation of a complex three dimensional phenomenon. A major implication for conceptual change research from this study is that the multidimensional framework has the potential to enable researchers and teachers to better understand the process of conceptual change in many fields. The thesis concludes with a discussion of the limitations of the study and future directions for research.

ACKNOWLEDGMENTS

First and foremost I would like the thank my supervisor, Professor David Treagust, for being a mentor, and a wonderful teacher. David has guided me from a neophyte researcher through the doctoral thesis program with patience, persistence, encouragement and wisdom. He has given me enough freedom to pursue my interests while at the same time directing me to remain within the boundaries of rigorous research that will contribute to the knowledge base in science education. David has encouraged a collaborative research environment from which I have greatly benefited and I would like to thank Rod Thiele, Sue Stocklmayer, Allan Harrison and Louise Tyson for the many hours of enlivened discussion and debate.

The environment at the Science and Mathematics Education Centre (SMEC) for post-graduate students is most conducive for intellectual stimulation and supportive companionship. I would like to thank Professor Barry Fraser, the director of SMEC, for encouraging this environment and specifically I would like to thank my SMEC room-mates, Cath Milne, David Geelan, Wendy Speering, Joan Gribble, Allan Harrison and Louise Tyson for the camaraderie over the past few years.

I would like to thank my parents, Wilma and Harry, for instilling in me a love of teaching and, most importantly, a love of learning.

My husband, Adam, has given me unquestioning support and a great deal of encouragement throughout my doctoral research. I thank him for his belief in me, his acceptance of me for who I am and for the many hours when he has listened to me talk about my research. I thank my children, Yul and Miika; through their playful vitality they have had the ability to distract and refresh my mind.

I would like to extend my thanks to Curtin University Child Care Centre staff. With the outstanding child care and support provided by the Centre, I have had the peace of mind to be able to pursue my studies.

Last, but not least, I thank the teachers and students who have participated in this research and the Principals who allowed me to enter their schools for the purpose of data collection.

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CHAPTER 1
INTRODUCTION AND OUTLINE

> Young children and scientists have much in common. Both are interested in a wide variety of objects and events in the world around them. Both are interested in, and attempt to make sense of, how and why things behave as they do.
>
> (Osborne & Freyberg, 1985, p. 1)

The Genesis of this Study

As a high school student, I loved genetics. I thrived on doing investigations where I had to find out who in my family could roll their tongue, who had a widow's peak, or who had attached ear lobes. It was interesting finding out things about myself and my family. I felt I understood myself better and gained insight into my shared inheritance. I relished doing the problems about red and white cows, even though I had never seen a "red" cow, about round and wrinkled pea seeds, and red, white and pink snapdragons. I was good at solving the problems because they were consistent and predictable; it was rewarding to get them all right.

At university, genetics became a little more mundane. It was reduced to estimating the locus of genes from the rate of crosses with other genes on the same chromosome. Problems that were once again rewarding to get right, but never-the-less somewhat removed from the inheritance of characteristics in my family in which I had originally been interested. We did look at the genetics of real organisms, but I remember the dark rings under my eyes from spending hours in the botany laboratory counting the pollen of certain species of plants native to Western Australia. I've forgotten the significance of that particular exercise, I think it had something to do with the research interests of one of our lecturers.

As a teacher I loved teaching genetics. One of my most vivid memories was when the Principal of a Catholic Girls' School in which I was teaching, Sister Mary, walked past my Year 12 Biology class. The students were laughing and chatting in loud anticipation of the investigation we were about to conduct to find out the students' blood groups. Of course, this was in the days when such investigations were still permitted. Sister Mary came into my class to find out what all the excitement was about and I invited her to stay. She eagerly accepted. During the pre-lab, I demonstrated the use of sterile blood lancets and showed the students how to prick a finger to get a few drops of blood to which they could add clotting agents to determine their blood group. Even though I had done this experiment many times before, and I knew it didn't really hurt, I still felt my heart quicken as I was about to stab my own finger. The students squirmed and groaned and Sister Mary mocked them for their lack of stoicism. To my absolute horror, one of the more bold members of the class suggested that Sister Mary could be the first to demonstrate composure while inflicting a stab wound in her finger for the purpose of scientific endeavour. I gulped and racked my brains to think of an excuse that would allow Sister Mary to exit the class with her pride still intact. To my surprise, she swabbed her finger, picked up a blood lancet, removed the wrapper and without any hesitation or sign of inhibition stabbed herself and drew blood that would have been enough for the entire class to do their experiments. Sister Mary's blood group was O positive, the most common kind, her intrepid spirit was of a rarer class.

I found doing such a practical exercise on human blood groups was a good way of introducing ideas like multiple alleles to my students. Once the students had worked out their blood groups and had become familiar with the A, B and O alleles, it could be used as an example of other more complicated concepts in genetics. People with the different blood groups A, B, AB and O have different terminal sugar molecules on the antigens on the surface of their red blood cells. The genes responsible for these blood groups produce specific enzymes which add the different terminal sugars to the antigens on the blood cells. I found this was a relatively simple example of a metabolic pathway where students could understand how genes and their code for a particular protein, in this case an enzyme, could have an effect on the characteristics of a human. It helped my students to link the ideas of the gene, protein synthesis, and characteristics or phenotype. The exercise also was a great stepping stone to examining protein synthesis in more detail.

In 1990, the biology syllabus in Western Australia was changed. I was surprised when I attended an in-service course and was told that protein synthesis, among other things, had been removed from the Year 12 course and replaced with the single objective that students should be able to "give a functional definition of a gene and explain the relationship between genes and chromosomes" (Secondary Education Authority, 1996, p. 71, objective 3.2). My blood groups exercise, that we now did with screened blood from the biological supplies company, had largely become redundant because, according to the syllabus, students didn't need to know about protein synthesis any more. It wasn't clear to me as a teacher what a "functional definition of a gene" meant because such an important concept had been reduced to a very simplistic objective. Did it mean that students should simply understand that genes control characteristics, or should they know more? I didn't know.

As a researcher I was fortunate enough to interview other biology teachers about the teaching and learning of genetics. One teacher's story struck a resonate chord with what had been my own thoughts back in the early 1990's.

> I think students have got to see the link between the gene and the protein. Otherwise they don't really know, there's a sort of a gap between the DNA and the characteristic like hair colour or eye colour. In fact, I remember it myself, when I learnt that, or found that out. It made genetics understandable because I could never understand the link between the DNA and what was actually happening to the organism in terms of its characteristics. So when I realised that, I kind of thought, well that makes sense. So I think kids need to know that too.

While other teachers were worried about teaching all the "new genetics" such as genetic engineering, I was more concerned about the fundamental concept of the gene. If students didn't understand the basic structure and especially the functioning of genes, surely the rest of genetics and biology would make little sense. What do students think a gene is? How do they learn about the gene and how can teachers help them to understand this fundamental and difficult concept? It is from these humble ponderings of a high school biology teacher that this thesis essentially began. When I was given the opportunity to become a doctoral student it was with little hesitation that I chose genetics and specifically the gene concept on which to focus my research attention.

Context

This thesis is one part of a series of research studies conducted by a collaborative research group at the Science and Mathematics Education Centre at Curtin University of Technology. The leader of the group is Professor David Treagust. Other members of the group have been Professor Treagust's students, and initially included Dr Susan Stocklmayer and Dr Rodney Thiele, who have both completed their doctoral studies and subsequently moved to other institutions. The current members of the group are Dr Allan Harrison, Louise Tyson and myself, Grady Venville. The initial focus of this research group was analogies and models and their use in science classrooms. To thoroughly investigate teachers' use of analogies and models, it was found that student learning in classroom situations had to be monitored. Research available on students' conceptions reveals that many investigations of learning in science are of the conceptual change type, that is, a considerable reorganisation of the existing knowledge is required to facilitate understanding of the concepts presented in the classroom (Duit, 1991b). As a consequence, the focus of the research group gradually shifted to the role of analogies and models in conceptual change learning and then further still to focus on conceptual change itself.

In the same way that the research group's focus changed, the focus of this thesis also has changed. The initial purpose was to investigate the role of analogies and models in the process of conceptual change in genetics. The first part of the study was to investigate conceptual change in genetics and secondly, the role of analogies and models in the conceptual change process. As the study progressed over the past three years, it became clear that the focus would be on conceptual change in genetics and particularly on the concept of the gene. Little research has been reported on conceptual change in genetics and investigating conceptual change in classroom situations turned out to be a convoluted and complex agenda. Subsequently, the role of analogies in the conceptual change process took on a smaller, though still important, aspect of the study. As a consequence, much of the data collected has been omitted from this thesis in order to maintain clarity and cohesion of the final document. Conference presentations and publications which report these data, as well as data included in this thesis, are listed in Appendix 1.

Purpose

The general purpose of this study is to investigate students' learning about the concept of the gene. In other words, what happens to students' image of a gene in their cognitive structures when they are being taught genetics? A conceptual change perspective is utilised to analyse student learning about genes, to ascertain if conceptual change takes place and if so, to describe the process of conceptual change. Part of the purpose of this study is to investigate the factors influencing student learning about genes and the process of conceptual change and also to describe the utility of using different theoretical perspectives of conceptual change for analysing classroom learning situations.

Background and Rationale

Teaching and Learning Genetics

Genetics emerged as a new scientific discipline in the early 20th century revolutionising our thinking about heredity and reproduction. Classical genetics established the foundations upon which modern molecular biology has been built. An understanding of the theories and concepts behind modern genetics is necessary for fundamental understanding of the discipline of biology as a whole and essential for some associated aspects of biology such as the theory of evolution, adaptations, populations and ecology. Kindfield (1992) says that she sees genetics "not as one of many branches of biology but more as a central organising feature of biology that has relevance in all subdisciplines and can be studied at all levels of organization" (p. 39). Additionally, understanding in the field of genetics by the general public is important in establishing modern attitudes to biology and comprehending the social and scientific consequences of research in molecular genetics in this biotechnological era. An understanding of the majority of genetics concepts such as meiosis and genetic engineering is, in turn, dependent on students' understanding of the basic unit of heredity, the gene, its structure and most importantly, its function in the process of life.

Unfortunately, research has shown that, even after instruction, students often have basic ideas about genetics which differ from the current scientific model of heredity (Brown, 1990; Clough & Wood-Robinson, 1985; Hackling & Treagust, 1984; Hildebrand, 1985; Kindfield, 1991a, 1994; Smith, 1991; Wood-Robinson, 1994). One of the most significant findings of these studies is that students often do not understand the process of meiosis and the concept of the gametes as haploid cells which carry half the genetic information to the offspring. The related notion that the sperm and the egg both contribute information relevant to the determination of the phenotype of each feature of the offspring also is not well understood. For example, Deadman and Kelly (1978) investigated what schoolboys understand about evolution and heredity before they are taught these topics and found that "they had a firm idea of heredity as the transmission of characteristics from one generation to another but beyond this their understanding was shallow" (p. 10). Kargbo, Hobbs and Erickson (1980) found that "from age 7 to 13, [children] have a large number of novel ideas about the nature and the mechanism of inheritance." (p. 145). Kargbo et al.'s findings also suggest that a considerable number of children of all ages "believe that environmentally induced characteristics, such as a missing finger, can be transmitted to offspring under certain circumstances" (p. 137). Clough and Wood-Robinson (1985) came to similar conclusions that many students of all ages believe acquired characteristics are inherited, although the results suggest some improvement in understanding with age.

Hackling and Treagust's (1984) work is complementary to that of Deadman and Kelly, Kargbo et al., and Clough and Wood-Robinson because it scrutinises students' conceptions after a 10-week genetics course. They found that inheritance of acquired characteristics was believed by only 13% of Year 10 students after instruction and that 40% of students comprehended that such features are not inherited. Features of young people's understanding of inheritance described in a review of the literature by Wood-Robinson (1994) include the widespread belief that plants do not reproduce sexually, that there is an unequal contribution by the parents to the features of the offspring and that a belief in the inheritance of acquired characteristics is common.

Consequently, it is important that teachers become familiar with the areas where students have difficulty comprehending genetics and where they are likely to hold alternative, often naive, beliefs about related genetics entities and processes (Smith & Simmons, 1992). More importantly, it is imperative that teachers become familiar with teaching strategies which have the potential to produce high-quality cognitive representations of genetics structures and processes and to do this they need to understand how students learn in genetics. None of the studies discussed above, however, examined the changes that occur in students' conceptions over a course of instruction; that is, previous research has focused on students' conceptions at one point in time and not at the changes that occur over a period of time. Research in genetics learning has tended also to focus on how students solve genetics problems (Finkel, 1996; Slack & Stewart, 1990; Smith, 1988) and students' understanding of the role of meiosis in inheritance (Brown, 1990; Cavallo, & Schafer, 1994; Smith, 1991).

To date, little research has been conducted on students' understanding of the gene concept. Words such as gene, "DNA" and chromosome are frequently used in everyday language; however, the relationship between these structures and the role they play in heredity is often confused by learners (Martins & Ogborn, 1997; Pearson & Hughes, 1988; Smith, 1991). Johnstone and Mahmoud (1980) isolated genetics from other biology topics as a subject that students perceived as having maximum difficulty. Teachers also said that the gene was a concept which they thought was giving their students most trouble (Johnstone & Mahmoud, 1980). More recent research has reflected the findings of Johnstone and Mahmoud. Hackling (1982), for example, investigated 100 above-average Year 10 (14 and 15 year old) students' understanding of genetics concepts after they had completed an introductory genetics course. Hackling found that 58 per cent of the students said that genes determine features, but only 27 per cent identified the gene as a unit of genetic information. Clough and Wood-Robinson (1985) reported that of the 84 students (aged between 12 and 16 years) whom they interviewed, half discussed inheritance without giving any genetic explanation, a third suggested that a genetic entity of unspecified nature was passed on at fertilisation to determine phenotypic features, but only seven per cent of the students indicated a good understanding of the nature of gene function.

Pearson and Hughes (1988) identify several problems with the term "gene". For example, the term "cistron" is used in molecular biology and the term "gene" is used synonymously elsewhere and the term "gene" is often used to describe the specific form of a gene that should be referred to as an "allele". Smith and Sims (1992) labelled the concept of the gene as being more formal, with fewer perceptible examples and attributes than concrete concepts. Taking into consideration the difficulty for concrete operational students to understand formal concepts, the proposition that they be eliminated from the high school curriculum was considered (Smith & Sims, 1992). In conclusion, however, these authors pointed out that concrete operational students are capable of correct reasoning about formal concepts if teachers provide hands-on, direct, concrete examples such as illustrations, diagrams and models. Wood-Robinson (1994) reviewed the literature and concluded that current knowledge about young people's understanding of inheritance shows that variation in mammals and humans is seen as being associated with parentage, though the concept of some genetic entity passing from one generation to the next is often absent.

Recently, Martins and Ogborn (1997) describe how different metaphorical models for genes were assimilated and constructed by 14 primary school teachers. They describe two models, the basic model where a gene is thought to be equivalent to an entity or particle and the second where a gene is thought to be like a sequence of instructions. None of these studies discussed here, however, specifically focus on students' understanding of the concept of the gene and none investigated student learning of this concept or conceptual change within genetics.

Constructivism

The theoretical and interpretive frameworks of this thesis can be described as being embedded in the personal (or radical) and social paradigms of constructivism (Gergen, 1995; von Glasersfeld, 1995). Most cognitive scientists now work with a constructivist model of knowledge which has been summarised in a single statement by Bodner (1986, p. 873) as "knowledge is constructed in the mind of the learner". Constructivism is a theory of knowledge that contrasts with traditional epistemological theories that knowledge has to be a representation of reality. In contrast, constructivists believe that the only world we can know is the world of our own experience (von Glasersfeld, 1993). This theory contests the belief that knowledge can be transferred to a passive receiver. Rather, knowledge is the result of an active construction process, "it has to be actively built up by each individual knower" (von Glasersfeld, 1993, p. 26). Bodner emphasises that from a constructivist view the most vital factor influencing learning is that knowledge is constructed on the basis of a student's pre-existing cognitive structure. Bodner's view is that the construction of knowledge is a search for a fit rather than a match with reality and that each person builds their own view of reality.

Constructivism has been an important theory for research and practice in science education. There are, however, many forms of constructivism such as personal, radical, social, critical and contextual (Geelan, 1997; Good, 1993; Solomon, 1994). Conceptual change learning theory is used in this study as a theoretical and interpretive framework and as conceptual change theory is embedded in constructivism as a theory of knowledge it is important to clarify the kind of constructivism that forms a scaffold for this thesis. Geelan (1997) suggests that conceptual change pedagogy lies within the personal constructivist paradigm. Personal constructivists accept the ontological reality of the external world, but emphasise the idea that individuals construct knowledge for themselves (Geelan, 1997). In other words, personal constructivists believe that a real world exists outside our minds, but we only see and perceive this world through our own experiences, hence we construct our own individual understanding of the nature of the external world.

Bliss (1995) claims that "Piaget was one of the early proponents of constructivism, seeing children as constructing their own knowledge through their own activity, or in Piagetian terms through the processes of assimilation and accommodation" (p. 147). These processes stress the individual's construction of models of the world and hence can be regarded as consistent with personal constructivism. Assimilation was used by Piaget to describe the process whereby new ideas and information are gradually incorporated into a person's mental schemes (Bliss, 1995; Piaget, 1950). Accommodation, according to Piaget, was the adjustment process whereby mental schemes were modified to allow for the assimilation process (Bliss, 1995; Piaget, 1950). Piaget thus saw accommodation and assimilation as concomitant processes, "every assimilation involves some accommodation, and every accommodation involves some assimilation" (Bliss, 1995, p. 147).

Solomon (1994) explains why Piaget's ideas did not, at the time, trigger constructivism as we know it in science education today. She says it was because Piaget's language was inappropriate and the attitude of the day far too judgemental. Solomon (1994) suggests that constructivism only encroached on the science education field when "it acquired a new vocabulary to match new intentions" (p. 3). This happened, according to Solomon, with the publication of Driver and Easley's (1978) paper in *Studies in Science Education* that was a review of related literature on concept development and which "created the tools for the accelerated rise of constructivism in science education" (p. 3).

Bliss tells the story of how Piaget's ideas had evolved by the mid 1970s, and most of the research in science education had converted to a constructivist view of learning. "As our knowledge grew about the surprising ways in which pupils construe their world, so, for science educators, it became important to find appropriate ways to help pupils change their ideas" (Bliss, 1995, p. 149). This was the beginning of international research on students' conceptions that then began to focus on ways to change students' pre-instruction conceptions to conceptions that would "fit" better with accepted scientific beliefs.

While the conceptual change theoretical framework of this thesis has its roots deeply embedded in the personal constructivist paradigm, the water that brings nourishment to those roots can be described as social constructivism (Gergen, 1995; Solomon, 1987). Just as a tree will not flourish without water, knowledge will not flourish within an individual without social interaction (Solomon, 1987). The social constructivist paradigm is seemingly contradictory to the personal constructivist paradigm because it emphasises the importance of such things as social exchanges with other people, context dependent experiences, and more remotely, language, culture, and media influences. Richards (1995) simplifies the issue by saying that the personal or radical constructivist, "focuses on the individual act of construction on the learner, and the social constructionist focuses on the group conversation. ... On a surface level, one can say the radical constructivists see only the individual and do not account for the behaviour of the group, and the social constructionists see only the group and do not account for the behaviour of the individual." (p. 58-59). The two paradigms can, on the other hand, be seen as complementary. Even though the social constructivist emphasises the social effects on the construction of scientific ideas, the individual is still seen to be the one to construct her or his own understandings which is consistent with personal constructivism (Solomon, 1987). Confrey (1995, p. 225) goes further to say that "[e]xperience and context intermingle" - we need to recognise both the individual and social aspects of knowledge and how they shape each other and that we need to seek an appropriate balance. Confrey suggests that we consider a new theory of self where the differences of personal and social constructivism are resolved and elements of both theories are included. According to Confrey, such a new theory will be "one in which diversity plays a more significant role, and in which the individuality of the child is tempered by the responsibility of community and culture" (p. 225).

Conceptual Change

In describing constructivism as a theory of knowledge, Tobin (1990, p. 30) states that, "knowledge is constructed and adapted as a result of successive experiences and reflections". It is this process of construction and adaptation that can be seen as conceptual change. More expressly, Spada (1994, p.113), says that "conceptual change is a process which leads from one coherent mental structure to another, which represents the world more adequately". What exactly conceptual change is, how it can be identified and the best ways of enhancing it are still topics keenly debated by educational researchers. White (1994a) for example, debates the difference in meaning of *concept* and *conception* and describes what most other researchers refer to as *conceptual change* as *conceptional change.*

Several theories of conceptual change have emerged over recent years, one of the most influential in the field of science education being the conceptual change model (Posner, Strike, Hewson & Gertzog, 1982; Strike & Posner, 1992). Other theories of conceptual change include Thagard's (1991, 1992) continuum theory, Vosniadou's (1994) framework theory and presuppositions view of conceptual change, and Pintrich, Marx and Boyle's (1993) motivational perspective of conceptual change. Each of these theories of conceptual change and others is discussed in detail in Chapter 3.

The conceptual change model (Posner et al., 1982; Strike & Posner, 1992) was based on an analogy between the construction of individual scientific understanding and the development of scientific theories. The model discusses conceptual change of two types, accommodation and assimilation, but the terms have different meanings to those of Piaget. The first type, *accommodation* (later referred to as *conceptual exchange* by Hewson and Thorley, 1989) is described as being a radical overhaul of existing conceptions in order to incorporate new knowledge. The second type, *assimilation* (later referred to as *conceptual capture* by Hewson and Thorley) is described as being a more common and simple process of incorporating new knowledge with existing concepts. This model classifies the status of conceptions as being intelligible, plausible and fruitful to the student. For conceptual change to occur students first must be dissatisfied with old conceptions and then the new ideas must meet the conditions of intelligibility, plausibility and fruitfulness to be successfully incorporated into their working conceptual framework. Because of this explicit, hierarchical classification of the status of students' conceptions, the conceptual change model has been used in several studies concerned with the process of conceptual change (see for example, Demastes & Good, 1996; Hewson & Hennessey, 1992; Hewson &

Hewson, 1992; Southerland-Demastes, 1993; Treagust, Harrison, Venville & Dagher, 1996).

The bimodal nature of the conceptual change model comes into question in the light of research conducted by Thagard (1991, 1992). Rather than the accommodation and assimilation forms of conceptual change, Thagard suggests a continuum of varying degrees ranging from simply adding a new instance to the knowledge base of a concept, to fundamental conceptual reorganisations. Between these extremes, Thagard also identifies other kinds of conceptual change including adding weak and strong rules, adding relations and concepts and reorganising hierarchies.

Vosniadou (1994) adds further complexity to the notion of the process of conceptual change. She sees concepts as being embedded within larger theoretical structures that contain them. Conceptual change, according to Vosniadou, requires the revision of the entrenched presuppositions of the framework theory. She believes conceptual change is not a sudden shift from one theory to another, but a continuous process which happens as the different kinds of constraints of the framework theory are reinterpreted. Caravita and Hallden (1994) outline the limitations of the analogy between the construction of individual scientific understanding and the development of scientific theories and the related metaphor of the "science learner as a scientist" which permeate the works of scientific philosophers such as Thomas Kuhn, Imre Lakatos and Stephen Toulmin. Caravita and Hallden maintain that these important differences have been understated with the result that conceptual change has been isolated from the more global and complex process of learning. Thus, they argue that the aim of learning science should not be to abandon old ideas in favour of new ones, but rather to extend a repertoire of ideas about the physical and cultural world, and to refine its organisation and coherence. Further still, Pintrich, Marx and Boyle (1993) question the "cold" models of conceptual change and propose that motivation is one of the most important factors influencing the progress and process of student learning as conceptual change.

This is by no means an exhaustive discussion of the theories of conceptual change (see Chapter 3 for more detail), but the point can be made that contrasting views of what conceptual changes are and how they can be identified exist within the field of science education. Despite this range of theories, empirical researchers have tended to remain within the constraints of one theory, often their own, when interpreting data. Undoubtedly, each theory has its merits and deficiencies when utilised as an interpretive framework for empirical research. Using several theories of conceptual change to interpret the same data would have the effect of identifying the salient aspects of each and perhaps, give a better understanding and explanation of the teaching - learning situation at hand. The intention of this study was to explore the different theoretical perspectives of conceptual change described in the literature in order that the most appropriate and useful theories could be utilised to describe student learning about genes.

Research Questions

Four research questions addressed the components of the purpose of this thesis. The responses to the four questions are primarily addressed in Chapters 6, 7, 8 and 9 respectively. Chapters 2 - 5 provide the background literature, the pilot study and the methodology while the final Chapter, 9, summarises the results by directly addressing each of the research questions.

Research Question 1

What happens to Year 10 students' conceptions of the gene when they learn genetics?

This question is approached on a collective and individual basis; an ontological perspective of conceptual change is utilised to describe what happens to students' conceptions of the gene when they learn about genetics. Subsumed within this question are subsidiary questions; what conception of the gene do students have before a genetics course?, what conception of the gene do students have after a genetics course?, and what are the differences between the two?

Research Question 2

When Year 10 students learn genetics, do the changes, if any, that occur in their conceptions of the gene constitute conceptual change, and if so, how can these conceptual changes be described?

At the outset, no assumption of change existed but there was an expectation that change in students' conceptions would be observed. Learning that does and does not constitute conceptual change and the different ways that conceptual change can be described have been introduced in this chapter and are discussed in more detail in Chapter 3. This question directs attention to the issue of whether the observed learning in genetics constitutes conceptual change, and if it does, what form do the conceptual changes take?

Research Question 3

What factors influence the process of conceptual change when students are learning about genes?

This question draws attention to factors in addition to cognitive aspects of conceptual change such as classroom contextual factors and the nature of the content that might influence the process of conceptual change.

Research Question 4

How can different theoretical perspectives of conceptual change be optimally used to describe the changes that occur in students' conceptions of the gene and how is this significant for conceptual change theory?

This is a theoretical question that focuses on conceptual change theory. Embedded are questions about the utility of various perspectives of conceptual change as an interpretive framework for classroom-based research and about the direction of conceptual change research for the future.

Significance of the Study

Genetics is an interesting and much talked about subject among people and myths are common (Jones, 1993). Sensationalised media coverage of recent genetic engineering projects and poor instruction within schools have probably both contributed to the formation of alternative frameworks and misunderstandings about genetics held by students and the population at large. As already stated, understanding by the general public in the field of genetics is important in order to comprehend the social and scientific consequences of research in molecular genetics. Additionally, it is important for students to have a good grounding in high school genetics for a wide variety of occupations and, where appropriate, as a foundation for tertiary study. This research will enhance teachers' and researchers' understanding of the way that students learn about genes and has the potential to improve teachers' classroom approach to teaching genetics which, in turn, can enhance student understanding.

Enhancing student learning and understanding is surely a major objective of science teachers everywhere. Unfortunately, a "sad situation" (Duit, 1991b, p. 65) has been revealed worldwide by research, namely that science instruction very often has limited success. This presents a major challenge to science teachers, and much recent research is relevant to the classroom in terms of enhancing student conceptual change. It is now widely accepted that students hold naive alternative conceptions prior to instruction and conceptual change teaching is often necessary for significant learning to take place (Guzzetti, Snyder, Glass & Gamas, 1993). As already discussed, the process by which conceptual change takes place and the best ways of enhancing it, however, are still topics under much debate by educational researchers (White, 1994a). By exploring the different theories of conceptual change and searching for consistency between them and the data collected in this research, the intention was that considerable steps could be made towards a better understanding of the process of conceptual change. This information is of great significance to teachers and educational researchers in their quest for improved conceptual change teaching.

Overview of the Thesis

Introduction and Overview - Chapter 1

Chapter 1 briefly describes the genesis of this thesis in the teaching experience of the author and outlines the context of the study in a collaborative research group at Curtin University of Technology. In this chapter, the background and rationale are presented, the research questions are posed and the significance of the study is argued. An overview of the thesis is presented here in Chapter 1 because a traditional thesis format is not followed. The purpose of the overview is to clarify the structure of the thesis and enhance the readability and cohesion of the final document.

Literature Review - Chapters 2 and 3

Chapters 2 and 3 essentially make up the literature review and background information for this thesis. Chapter 2 traces the history of the concept of the gene and concludes with a series of metaphors that outline the author's personal conception. Because this thesis concentrates on student learning of the gene concept, the purpose of Chapter 2 is to explore the development of this concept from an historical perspective. It is appropriate that this concept should be explored from an historical perspective because the analogy between the historical development of scientific ideas and the development of those same scientific ideas in students' minds is one that is well known to those who work in the conceptual change field (Duit, 1995; Fisher, 1983; Helm & Novak, 1983; Nussbaum, 1983; Posner et al., 1982; Wandersee, 1985). Consequently, in the first part of Chapter 2, information presented in historical literature is used to construct a picture of the ideas about the concept of the gene held by researchers throughout the history of genetics. The picture is not intended to be a complete documentation of the history of genetics, rather the purpose is to create an image of the way that the gene concept developed.

In the second section of Chapter 2, the researcher uses a series of analogies and metaphors taken from the literature and textbooks to describe her own conception of the gene. The purpose of this section is to disclose the author's image of a gene, hence putting the reader in a position of knowing the researcher's personal construction of the concept under investigation. This is not a complete description because details of concepts related to, but more peripheral from the gene concept, such as DNA replication, transcription, translation, the idea of homologous pairs of alleles and the effects of the environment on the phenotypic expression of genes have been omitted. This was done so that the focus was maintained on the core ideas of gene structure and function.

In the same way that Chapter 2 provides the background to the gene concept, Chapter 3 provides the background to theories of conceptual change that emerge from the research literature. Firstly, a definition is teased from the literature by examining how different researchers define and bound the process of conceptual change. The second issue to be examined is the idea of initial conceptions and whether they are discarded, maintained or altered by the conceptual change process. Next, the notion of the status of students' conceptions is explored and the contrasting ideas that conceptual change can be revolutionary or evolutionary and global or domain specific are presented from the reviewed literature. Two further issues discussed include the age of the individual learner and the nature of the content and the relevance of these to the conceptual change process. The teaching approaches for conceptual change that have been presented in the literature are described and, finally, factors thought to influence conceptual change are examined. The issues explored in Chapter 3 provide the background to the pilot study which is presented in Chapter 4 and the background to the theoretical framework of this thesis which is presented in Chapter 5. Although Chapters 2 and 3 present the main body of the reviewed literature, salient aspects of the literature are expanded upon in relevant places in subsequent chapters.

Pilot Study - Chapter 4

In Chapter 4, a pilot study is described that utilised different theoretical perspectives of conceptual change to analyse the role of four analogies in classroom learning situations. A supermarket analogy for the classification of living things was described using the Posner et al.'s (1982) view of conceptual change as having the role of a *sense maker*. A car cooling system analogy for human temperature homeostasis was found to play the role of a *memory aid* and was best explained by considering Vosniadou's (1994) framework theory and mental models perspective of conceptual change. A fluid mosaic analogy for cell membranes was found to play the role of a *transformer* and was best explained by Chi, Slotta and deLeeuw's (1994) ontological category perspective of conceptual change. Finally, a bucket and pump analogy used to teach the structure and function of the heart was described as a *motivator* and was viewed through the motivational perspective of conceptual change of Pintrich et al. (1993). The pilot study concludes that each of the learning situations was best explained by a different perspective of conceptual change and that these perspectives had much to tell us about the "normal" shifts in conceptual understanding as well as "radical" conceptual change. A review of this pilot study has subsequently been published (Venville & Treagust, 1996).

The pilot study was pivotal in the development of the multidimensional interpretive framework for conceptual change that is used in this thesis and which is presented in the methodology section, Chapter 5. There is a chronological and logical progression from the pilot study to the theoretical framework presented in the methodology, hence the pilot study is included in this thesis before the methodology.

Methodology and Theoretical Framework - Chapter 5

Chapter 5 outlines the research approach taken in this study. The research is carried out within the constructivist research paradigm. The approach taken to the notion of theory is one of being inductive, with the expectation that theory will be grounded in the data. There is no assumption, however, that the researcher goes into the research process without any preconceived ideas; rather the researcher is very clear about the theoretical framework being used to inform the interpretive process. A multi-dimensional interpretive framework is outlined with particular attention to the ontological, epistemological and social/affective perspectives of the framework. This framework forms the basis of interpretation in the study with Chapter 6 utilising an ontological perspective of conceptual change to interpret the data, Chapter 7, ontological and epistemological perspectives, and Chapter 8 a social/affective perspective of conceptual change, as well as other theoretical perspectives.

The research strategy described in Chapter 5 is the case study. A total of eight classroom sites were used to collect data as a series of linked case studies (Hitchcock & Hughes, 1989; Stake, 1994). Three of these cases are used for the analysis of Year 10 students' learning about genes in Chapter 6 and one of these cases is used to make an even closer examination of individual student cases of learning and conceptual change. The larger series of eight cases is utilised to provide data to support the assertions made in Chapter 9 about the factors influencing conceptual change. Methods of data collection such as classroom observations, student interviews, teacher interviews, student work-sheets and classroom quizzes are described as part of the case study research strategy.

Traditional notions of research rigour such as internal and external validity, reliability and objectivity are side-stepped for different standards that better suit the paradigm of naturalistic or constructivist inquiry. Credibility, transferability, dependability and confirmability are enhanced by a thorough system of triangulation at the data source and collection level and at the data interpretation level for each of the research questions (Guba & Lincoln, 1989; Patton, 1990). In addition, the researcher presents methodology and case studies with a "thick description" (Guba & Lincoln, 1989, p. 241) that allows readers to proceed on their own tracking and interpretation process, coming to their own conclusions concurrently with the researcher.

The ethical approach guiding this thesis is outlined as a set of codes in Chapter 5. The list includes a code of informed consent, a code of exchange of information, a code of confidentiality and a code of trustworthiness that the researcher has embraced throughout the research process.

Results and Discussion - Chapters 6, 7 and 8

The results and discussion are presented in a series of three chapters. Chapter 6 is the first of the series and presents the development of a learning pathway of models that reflects the student learning about genes observed in three Year 10 science classes. Chapter 6 largely addresses research question 1, that is, what happens to Year 10 students' conceptions of the gene when they learn genetics? An ontological perspective of conceptual change based on the work of Martins and Ogborn (1997) and Mariani and Ogborn (1990, 1991) is used to interpret the data and inform the development of the learning pathway.

The second chapter in the series of results and discussion is Chapter 7 that focuses on one class case study from the three classes investigated in Chapter 6. Chapter 7 largely addresses research question 2, that is, when Year 10 students learn genetics, do the changes, if any, that occur in their conceptions of the gene constitute conceptual change, and if so, how can these changes be described? The classroom procedure followed by the teacher, Mr Counter, is described in detail and the learning of six students from the class, Alastair, Douglas, Beth, Jacinta, Tan, and John, is investigated. The purpose of these student case studies is to compare and corroborate the learning pathway developed in the previous chapter with individual learning patterns. The individual students' pre- and post-instruction conceptions are compared with the models in the learning pathway that were developed from an ontological perspective of conceptual change. In addition, an epistemological perspective of conceptual change, based on a series of works by Posner et. al. (1982), Strike and Posner (1992) and Hewson (1981, 1982, 1996) is used to determine the post-instruction status of the students' conceptions as being intelligible, plausible or fruitful. The discussion in Chapter 7 looks at the utility of the pathway of models in describing students' learning about genes and the advantages and difficulties in classifying the status of students' conceptions. The discussion also considers whether or not conceptual change is observed in the students' learning and how the changes can be described.

The third chapter in the series of results and discussion, Chapter 8, analyses the factors that influence conceptual change by drawing on literature from an array of areas in science education such as content (White, 1994b), motivation and interest (Hidi, 1990; Pintrich, Marx & Boyle, 1993), teachers' use of analogies (Glynn, 1991; Treagust, 1995; Venville & Treagust, 1996), students' modelling ability (Grosslight, Unger, Jay & Smith, 1991; Harrison & Treagust, 1996), and linkage across concepts (Fensham, Gunstone & White, 1994; White, 1994b). Chapter 8 addresses research question 3, what factors influence the process of conceptual change when students are learning about genes? The data presented in this chapter are drawn from the three Year 10 classes studied in detail in Chapter 6; however, additional data collected as part of the series of eight case study classes of this thesis, such as Year 12 Biology classes, are used to further exemplify the issues raised. The five factors that influence conceptual change discussed in this chapter are the teaching approach; student interest; the process aspects of genetics content; linkage between ideas; and levels of representation. This does not suggest a finite list of factors that influence conceptual change, but the five factors discussed in Chapter 8 are the most salient and easily demonstrated by the data collected. These five factors are not mutually exclusive, the ideas presented under each heading often overlap with the ideas presented under other headings.

Conclusions and Implications - Chapter 9

The final Chapter summarises the conclusions of this thesis by addressing each of the research questions outlined in this first chapter. Research question 4 is answered by examining the results presented in Chapters 6, 7 and 8. In the second section of

Chapter 9, the historical development of the gene concept presented in Chapter 2, is brought into juxtaposition with the student learning elicited in this study. Similarities and differences between the historical development of the gene concept and student learning are discussed in the light of the "learner as scientist" metaphor made popular by conceptual change literature (Posner et al. 1982; Wandersee, 1985). The similarities include the tendency of some students not to distinguish between a gene and the characteristic and the understanding that the gene is a material entity on a chromosome while at the same time using the gene concept as an abstract calculating unit. The most obvious difference is the lack of a "modern" notion of the gene in the Year 10 students' post-instructional conceptions. The implications of the results of this study for the teaching of genetics are proposed and these include the use of the gene as a cental organising concept in genetics courses, improving the teaching of genetics processes and more explicit linking of genetics concepts. The implications for research in conceptual change promote the importance of utilising multiple theoretical dimensions to analyse the data (Tyson et al., 1997) and the utility of an orientational grounded theory approach (Patton, 1990). Finally, the possibilities for further research in this area are discussed including the investigation of students' conceptions of genes at different ages and the application of the multi-dimensional framework of conceptual change to analyse classroom data on other scientific concepts.

This first chapter, which has introduced this study and presented an overview of each of the chapters, is intended to provide a mental map that can easily be followed throughout the thesis. Chapter 2 will take the reader on a journey through the historical development of the gene concept and present the researcher's own conception of the gene in the form of a series of metaphors. The second part of the literature review, presented in Chapter 3, examines nine issues on conceptual change.

CHAPTER 2
EXPLORING THE CONCEPT OF THE GENE

> The concept of the gene is and always has been a continuously evolving one.
> (Portin, 1993, p. 173)

Introduction

Bowler (1989) suggests that "the crucial issue in the history of genetics is: How did the notion of fixed units eventually emerge?" (p. 23). The major focus of this thesis is student learning of the concept of the gene and hence the primary purpose in this chapter is to explore the development of this concept from an historical perspective. This is an appropriate thing to do because the analogy between the historical development of scientific ideas and the development of those same scientific ideas in students' minds is one that is well known to those who work in the conceptual change field (Caravita & Halldén, 1994; Nussbaum, 1992; Posner, Strike, Hewson & Gertzog, 1982, Wandersee, 1985). The issue of whether or not such an analogy is a useful one to make is further discussed in Chapter 9 in the light of the findings of this study. In this Chapter, however, the historical perspective is pursued. This chapter is the first of two chapters that make up the literature review of this thesis. The second section of the literature review, Chapter 3, focuses on conceptual change.

One would expect that genetics, being a relatively new science, would be a fairly easy topic to research and describe in an historical sense. On the contrary, apart from a few chronological milestones, the history of genetics is a morass of interconnected areas of research such as embryology, evolution, cytology and breeding experimentation. There are many personalities such as Mendel, Weismann, Correns, von Tschermak, Morgan, Johannsen, deVries, Bateson, McClintock, Watson and Crick, all of whom made important contributions in their particular areas of genetics. To make matters even more confusing, several of the leading geneticists changed their views during their life-time (Mayr, 1982).

Overview of the Chapter

Studies of the history of genetics (Bowler, 1989; Dunne, 1965; Mayr, 1982; Sturtevant, 1966; Tudge, 1993) generally describe four main periods to the present. These four periods can be referred to as pre-Mendelian, Mendelism, classical genetics and molecular genetics. In addition to these periods, Mendel himself usually has a chapter or at least a major section devoted to his achievements. Consequently, the first part of this chapter is divided into six sections - pre-Mendelism, Mendel, the rediscovery of Mendel's experiments, Mendelism, classical genetics and molecular genetics - within which a picture is constructed of the ideas that the researchers of the period had about the concept of the gene. This picture is not intended to be a complete documentation of the history of genetics, rather the purpose is to create an image of the way that the concept of the gene has developed. This picture is purely a secondary interpretation of the ideas presented in books and other literature written by people with a much more intimate knowledge of the history of genetics. The paragraphs below are presented in a roughly chronological order; however, it is important to understand that many of the theories co-existed, reinvented and altered as time went by.

The second part of this chapter examines the different concepts of the gene over the past century, discusses a philosophical question of whether the gene concept was one that was invented or discovered and finally, the researcher's personal conception of a gene is presented as a series of analogies. The researcher considers it important to be explicit about her own conception of the gene concept so that readers can be confident in making judgements about this thesis by knowing the nuances of the researcher's own conception. The use of analogies to convey the conception is consistent with the constructivist theoretical framework of this thesis, that we can only know a representation of the world around us. Analogies have been chosen because they highlight the second-hand nature of our knowledge of these sub-microscopic entities and they hint at the non-permanent and fluid way that the researcher views knowledge about genes. With the use of analogies, the researcher wishes to convey the clear impression that her conception of the gene is simply "her conception" and not a statement of what she believes to be a true or unambiguous representation of a scientific fact.

Pre-Mendelism

It is difficult to know where to start describing some of the theories about heredity before Mendel, as there were many. Most of them are fascinating, and, seen from our point of view with knowledge of twentieth century molecular genetics, could be described as ridiculous. It is more challenging, however, to put aside our modern knowledge, to try and recreate the world of scientists of past paradigms and attempt to make sense of the information they had at hand. Of course, it is impossible for us to do so entirely, but we can still enjoy a journey through the history of heredity before Mendel.

Aristotle

Aristotle theorised about heredity as he did about many other scientific topics. He was not the first to do so, however, and much of his discussion was centred around a criticism of Hippocrates theory of heredity (Sturtevant, 1966). Aristotle had a very masculine interpretation of the heredity world around him by supposing that the menstrual blood developed into the embryo, but, it was a non-physical influence from the male semen that was the active power in determining the offspring's physical characteristics. Aristotle did account for female characteristics that might occur in the offspring by suggesting that the menstrual blood might interfere with the influence of the male's semen (Bowler, 1989). What was important about Aristotle's theory is that he thought it was not the actual characters which were inherited but only the potentiality of producing them (Sturtevant, 1966). Today this seems obvious, but according to Sturtevant (1966), it was an important conclusion and something that wasn't fully appreciated even by the early Mendelians. As far as the concept of the gene is concerned, this is an important step to have been made because it renders possible the idea of a gene carrying the potentiality of a characteristic. It was, however, a long time after Aristotle that this idea was fully realised.

Preformation

Vitalism is a term that has been given to the theory of life that was prevalent before about 1700. This view assumed that the body had to be vivified, or given life by an external, non-physical force that left the physical body when an organism died. The Christian notion of the soul is consistent with vitalist theory. Religion played an important role in scientific theory at this time and around 1700 a theory called preformation had become popular among scientists. There were many variations of preformation; however, the basic notion of this theory was that an embryo grows from a preformed miniature created originally by God. This theory was consistent with the religious influences of the period. Another influence on the acceptance of this theory was the development of microscopes in the late 1600s. Microscopes were used to observe embryos which showed that parts of the embryo had developed before they had become visible to the naked eye. This suggested a preformed organism that simply had to grow and mature.

One of the more radical forms of preformation theory that appeared around the end of the 17th century and was popular through the 18th century (Bowler, 1989) was that the miniature organism existed in the female's egg before fertilisation and even before the mother was born. The scientists of this more radical form of preformation theory believed that all organisms grow from miniatures or 'germs' created by God at the beginning of the universe. The germs are stored up inside females, one inside another, like a series of Russian dolls. Fertilisation was said to give one of the germs the chance to grow.

Was there any notion of a 'gene' in this theory of preformation? "The claim that all organisms grow from germs originally created by God makes nonsense out of any attempt to trace individual characters from one generation to the next" (Bowler, 1989, p. 31). If scientists believed that God was responsible for determining the original 'germ', the idea that the developing embryo was controlled by material entities such as the gene would not have even been contemplated.

Epigenesis

An alternative theory to preformation that first appeared in the mid 1600s was termed epigenesis (Bowler, 1989). This basis to this theory was that the embryo grows by the sequential production of its various parts over the course of time. Generally, however, there was no explanation of a mechanism for this successive production of parts. This theory, unlike preformation theory, was agnostic because it was not dependent on the presence of a God. Maupertuis, the first person to describe polydactyly (the presence of a sixth finger or toe), believed the embryo grows by epigenesis. He described in his book *Venus physique* (1745; reported in Bowler, 1989) his twin semen theory. The twin semen theory argued that both parents contributed semen that, when mixed, forms the basis of the embryo in the mother's womb. Maupertuis accounted for segregation of the dominant polydactyly gene by "elementary particles". This idea seemed to be on the right track to the concept of a gene, however, Maupertuis had no immediate followers (Dunne, 1965).

Lamarkism

Lamark's theory of evolution described in his book *Philosophie Zoologique* (1809, reported in Dunne, 1965) and his idea that acquired characteristics could be inherited was widely accepted by naturalists through into the 19th century. Lamark also promulgated the idea that spontaneous generation provided the ultimate source of all living things.

Atomistic View

Another view of inheritance that gained popularity during the 19th century was the atomistic view. This theory suggests that each part of the body produces small particles that remember the structure of that organ. The particles all move from the various parts of the body to the sexual organs. The material in the egg or semen is a complex mixture of all the particles from all over the body and when the embryo forms it has within it all the particles that remember the structure of the body part of the parent from where they came (Dunne, 1965). An example of one naturalist's theory that can be described as being atomistic is Spencer (Dunne, 1965). Spencer discussed the idea of "physiological units" to explain facts of reproduction and differentiation and development. Spencer's idea of "physiological units" that could be vehicles of transmission as well as directors of development comes remarkably close to our present day idea of what genes do (Dunne, 1965). The incorporation of the inheritance of acquired characteristics, which is consistent with Lamark's ideas, is, however, in marked contrast with our present day thinking. Other naturalists, Darwin, for example, had similar atomistic ideas like Spencer's during the same period.

Darwin's (1868, reported in Dunne, 1965) theory of heredity, pangenesis, is a less well know part of his work. Darwin's idea of "gemmules" was similar to Spencer's "physiological units". Darwin's theory was that the cells of the body throw out extremely small and numerous "gemmules" which were thought to circulate throughout the body and self reproduce. The gemmules would then travel from the various parts of the parent body to the sexual organs. Fertilisation involved the blending together of both parent's gemmules. The form of the embryo would be a blend of characters from both mother and father (Bowler, 1989). In some cases an uneven mixture of gemmules would result in the domination of one parent's feature over the other and allow for characters to be passed to subsequent generations even though undeveloped in the parent generation (Bowler, 1989). Even though Darwin's theory of pangenesis was not generally accepted (Sturtevant, 1966), his ideas about gemmules did serve a useful purpose in that they played a role in suggesting the particulate theories of Weismann and of de Vries which were instrumental in 1900 for the appreciation of Mendel's work. (See later for a discussion of Weismann and de Vries's contribution to the notion of a gene.)

Mendel

> Most histories of genetics agree that the new science was established through the 'rediscovery' of Gregor Mendel's work in 1900 (eg.. Dunne, 1965; Sturtevant, 1966). As a result, Mendel has been awarded the status of a 'hero of discovery'. The basic generalizations upon which genetics is founded are still known as Mendel's laws, and the story of his life has become part of the mythology of science, endlessly depicted in popular books and even in TV programmes. ... And yet Mendel is an anomalous hero of science because his discovery was ignored during his own lifetime. His posthumous fame has been enhanced by the aura of tragedy generated by the image of a brilliant scientist who could not get his contemporaries to understand the significance of what he was doing. (Bowler, 1989, p. 93)

Dunne (1965) poses the question, "What in fact had Mendel discovered?" The question is answered by referring to Mendel's original paper published in 1866 in the journal of the Brno Natural History Society, which, Dunne claims, "illustrates the crucial importance, in a scientific inquiry, of the proper framing of the question at issue" (p.6). The purpose of Mendel's investigation, according to Dunne, was to account for the regularity of appearance of hybrids that had been observed in crosses between different varieties of the same species. In other words, Dunne believed that Mendel discovered (or at least demonstrated) a set of statistical rules because that is what he set out to do. Dunne says that "such questions had, as Mendel points out, never been asked before" (p. 6). The "rules" that Mendel demonstrated with his experiments with pea plants were the law of segregation and the law of independent assortment.

Bowler (1989) questions the traditional view that Mendel's purpose was the discovery of laws of inheritance. Bowler refers to several papers that reinterpret this section of history and claim that "the real purpose of Mendel's experiments was not to create a new model of heredity, but to resolve the old question of whether or not new species can be produced by hybridisation" (p. 103). This explains the "long neglect" of Mendel's work because it wasn't aimed at a model of heredity. According to Bowler, it was only the interpretation by early Mendelians at the turn of the century that transformed Mendel's experiments into the groundwork for modern genetics.

Mendel's work also has been questioned because of the remarkable agreement between his statistical results and the expected results. It has been suggested that Mendel disregarded results that were not in agreement with his predictions or that his assistants, trying to please Mendel, modified the results slightly to better represent expectations. Accounts of this phenomenon are reported in Bowler (1989), Sturtevant (1966) and Tudge (1993).

What was Mendel's concept of the gene? Was he the first person to visualise the modern concept of the gene? This is a question that is addressed by most historians of genetics, however, there is considerable diversity in their answers. Sturtevant (1966) claims that, "Mendel usually used the word *Merkmal* for what we now term gene, and this was translated as *character*, often appearing as *unit character*" (p. 32). Was a *Merkmal*, as Sturtevant says, really the same as what we now term gene? Tudge (1993) claims that Mendel used the word, *Anlagen*, for genetic factor and demonstrated that:

> the characteristics of a plant ('characters') were determined not by vague pervasive philtres that could be mixed like inks. Instead, each character was determined by a discrete 'factor' (Mendel used the German *Anlagen* for 'factors'). These are the factors that we now call *genes*. (Tudge, 1993, p. 13)

Mendel's factors could be considered as purely mathematical abstractions which served a purpose in predicting hybridisation experiments. However, Mayr (1982) speaks of Mendel's speculation about genes as if he made a conscious decision to not give too much attention to the nature of the genetic material.

> Mendel kept his speculation about the nature of the genetic material to a minimum, a wise decision on his part, considering the rudimentary understanding of nucleus and chromosomes in 1865. He referred in his experiments to traits ("Merkmale") and characters ("Charaktere"), essentially restricting himself to the phenotypic level, even though the symbols A, Aa, a used by him are generally considered to refer to the constitution of the genotype. He used the term "elements" ten times in his concluding remarks, several times very much as we would now use the word "gene," but he had no clear concept concerning the genetic material. (Mayr, 1982, pp. 735-736)

Bowler (1989) says that reinterpretations of Mendel's work suggest that in Mendel's description of his pea experiments he does not make any explicit reference to the concept of paired material particles equivalent to the genes of modern Mendelism. This is in marked contrast to Mayr's (1982) claim that Mendel "used the term 'elements' ... several times very much as we would now use the word 'gene'" (p. 736). Bowler is of the opinion that Mendel was able to think in terms of paired *characters*, but not in terms of paired *particles* and that he does not express the idea that the gametes contain one character-particle, and the fertilised egg two. An examination of a translation shows that both the words "factor" (p. 42) and "element" (p. 46) are used in Mendel's original work (Mendel, 1965). It seems that Mendel thought that the elements "assimilated" in the new zygote only to "liberate themselves from the enforced union" when the gametes of the hybrid generation are developed.

> In the opinion of renowned physiologists, for the purpose of propagation one pollen cell and one egg cell unite ... into a single cell, which is capable by assimilation and formation of new cells to become an independent organism. This development follows a constant law, which is founded on the material composition and arrangement of the elements which meet in the cell in a vivifying union. If the reproductive cells be of the same kind and agree with the foundation cell [fertilised ovum] of the mother plant, then the development of the new individual will follow the same law which rules the mother plant. If it chance that an egg cell unites with a *dissimilar* pollen cell, we must then assume that between those elements of both cells, which determine opposite characters some sort of compromise is effected. The resulting compound cell becomes the foundation of the hybrid organism the development of which necessarily follows a different scheme from that obtaining in each of the two original species. (pp. 45 -46). ... Since in the habit of the plant no changes are perceptible during the whole period of vegetation, we must further assume that it is only possible for the differentiating elements to liberate themselves from the enforced union when the fertilising cells are developed. (p. 47)

There is a great deal of confusion and contrast in the historical accounts with regard to Mendel's ideas about genes. What is clear is that the re-discovery if Mendel's work at the turn of the century was a pivotal point in the evolution of this concept.

The Re-discovery of Mendel's Experiments

Several reasons why Mendel's work was neglected are given in historical accounts; for example, the journal in which he published was not widely circulated, Mendel himself did not have a network of personal contacts within the scientific community, or Mendel was simply ahead of his time (Dunne, 1965; Sturtevant, 1966; Tudge, 1993). Bowler (1989) argues that Mendel was not ahead of his time because, as described above, his intention was not to promote a new theory of heredity. More specifically, Mendel's work provided answers to problems that were beyond the prevailing conceptual framework. Bowler claims that only when the framework changed was it possible for biologists to look back at Mendel's work and appreciate it's significance. Sturtevant (1966) suggests several advances which helped to make Mendel's results acceptable:
1) The germplasm theory created an emphasis on the effects of germinal material on the body rather than the reverse.

2) There was a challenge of the inheritance of acquired characteristics as a result of the above emphasis.
3) There was a striking increase of knowledge of the cytological details of fertilisation and cell division.
4) There was increasing emphasis on the importance of discontinuous variation.

Others claimed that the third point listed above, that is developmentalism or embryology of the 19th century, was the challenge that took the study of heredity into the 20th century.

> The embryologists paved the way for an exploration of how the process of inheritance might work because their discoveries served as a channel by which the newly emerging cell theory could be applied to the phenomenon of reproduction. Von Baer's identification of the mammalian ovum was the first step in a recognition of how the process of fertilisation takes place, while von Baer and many others traced the complex process by which the single cell of the fertilized ovum multiplies in the early stages of growth. Whatever the teleological assumptions of the early nineteenth-century embryologists, their work fed into the great development of cytology that created the empirical framework within which the concept of nuclear preformation - and hence the theory of the gene - would be formulated. (Bowler, 1989, p. 45)

Germplasm Theory

The outstanding figure of the time between Mendel's experiments and their rediscovery at the turn of the century was August Weismann (Sturtevant, 1966). Weismann was a professor of zoology and worked on the embryology of Diptera. Weismann's ideas about the germ line were significant because it led to an emphasis on the effects of the hereditary material on the body of an organism, and not the effects of the body on the hereditary material. In Weismann's germplasm theory, the plans for the entire body are contributed only by the sex organs, unlike previous pangenesis theories of Spencer and Darwin where all structures and organs throughout the body contribute copies of themselves to a sex cell (Strickberger, 1976). This in turn led to a challenge of the hypothesis of the inheritance of acquired characters (Sturtevant, 1966). Weismann's famous experiment where he cut the tails off twenty-two generations of mice demonstrated that there was no decrease in tail length at the end of the experiment and that the hypothesis of the inheritance of acquired characters was unfounded (Strickberger, 1976; Sturtevant, 1966).

Weismann's later theoretical work on the importance of the nucleus on cell theory was of greatest significance to genetics (Sturtevant, 1966). Between the years of about 1882 and 1885 a series of investigators established the foundation knowledge about the behaviour of the chromosomes in mitosis and meiosis (Sturtevant, 1966). Weismann adopted these ideas and suggested that the chromosomes are the bearers of the hereditary material (Sturtevant, 1966). Weismann's theory was explained in great detail and widely discussed; however, it was not generally accepted because it did not offer a basis for experimental testing because it was so hypothetical (Sturtevant, 1966).

During this period, Francis Galton, a cousin of Darwin, developed a different approach to the study of heredity. Firstly, he cast doubt on Darwin's theory of pangenesis by performing blood transfusion experiments between different strains of rabbits showing that gemmules did not collect information from the various organs of the body. Secondly, Galton had strong feelings for the importance of quantitative studies and demonstrated that on average, people inherit 1/4 of their characteristics from each parent, 1/16 from their grandparents and 1/64 from their great-grandparent, and so on (Sturtevant, 1966).

de Vries

In 1900 Mendel's work was discovered by three scientists working independently; the Dutch biologist Hugo de Vries; the German botanist Carl Correns; and the Austrian Erich Tschermak. de Vries was greatly influenced by Weismann work and added the essential idea that the inherited units, which he called *pangens*, are each associated with a single character, and that these units may be recombined in various ways in the offspring (Dunne, 1965; Sturtevant, 1966). This was clearly in agreement with Mendel's ideas and helps to explain why, about a decade later, deVries was one of the people who discovered and appreciated Mendel's paper. de Vries published three papers on Mendelism in 1900 (Dunne, 1965). The first paper to be published does not mention Mendel, though it used some of his terminology (Sturtevant, 1966). The third paper does mention Mendel, but only on the last page. The second paper, but apparently the first to be submitted, gives full credit to Mendel for his discovery (Sturtevant, 1966). de Vries later stated that he had worked out the Mendelian laws by himself, and was then led to Mendel's paper. However, there is the suggestion that de Vries at first did not intend to reference Mendel and changed his mind only when he found that Correns was going to refer to him (Sturtevant, 1966).

Correns

Carl Correns grew hybrids of maize and of peas through several generations and arrived at the Mendelian ideas in 1899. Correns reported his work with peas in May 1900, after he had seen de Vries' account. He fully referenced Mendel but disagreed with deVries in that he thought there were cases that did not conform to the Mendelian rules (Sturtevant, 1966). Dunne (1965) claims that of the three rediscoverers, Correns had the broadest view of the problems and principles of genetics. Dunne claims that Correns was the only one who observed, interpreted and emphasised the recombination of independent pairs of characters in Mendel's work. It was Correns who first identified the segregation of alleles with the reduction division in meiosis (Dunne, 1965).

von Tschermak

Erich von Tschermak's interests were on the effects of crossing and inbreeding on vegetative vigour, following the work of Darwin (Dunne, 1965; Sturtevant, 1966). He published two papers on the Mendelian laws in 1900. The first published paper does not clearly indicate a real understanding of Mendel's ideas but the second does, being written after von Tschermak had seen de Vries' and Correns' papers (Dunne, 1965; Sturtevant, 1966). The traditional story of simultaneous rediscovery of Mendel's laws is now surrounded with controversy (see Bowler, 1989 for an account of this controversy).

Bowler (1989) discusses the possibility that the discovery of Mendel's laws could be described as a scientific revolution.

> Did the rediscovery of Mendel's laws spark off a dramatic revolution in scientific thinking on heredity? It certainly introduced a new factor into the debates, and one that would eventually play a vital role in eliminating the old ideas of soft [inheritance of acquired characters] and blending inheritance. But if there was a revolution it took well over a decade to be completed, so the early version of Mendelism can be seen at best as only a first step in the right direction. ... Historians now recognize that the development of genetics was far more complex than a simple recognition of the particulate nature of heredity. The new theory took some time to emerge, and many of the early Mendelians did not foresee concepts we now take for granted. ... The emergence of Mendelism was more than a conceptual revolution; it required the establishment of an entirely new branch of biology devoted to the study of topics that had hitherto been parcelled out among other fields. (Bowler, 1989, p. 112)

Mendelism

During the early period after the rediscovery of Mendel's laws, from the turn of the century to about 1910, scientists were preoccupied with evolutionary controversies and with doubts as to the universal validity of Mendelian inheritance. However, particulate inheritance slowly became accepted, and the idea of inheritance of acquired characteristics was finally abandoned. The period was dominated by de Vries, Bateson, and Johannsen, who have often been designated as "the early Mendelians" (Mayr, 1982, p. 732). The term *genetics*, proposed by Bateson in 1909 was generally accepted during this period for this new science dealing with inheritance (Mayr, 1982).

Prior to about 1910 there was no clear distinction between a genetic factor (gene) and a character. In other words, when biologists spoke of a unit character, it did not really matter whether he or she meant the underlying genetic basis or its phenotypic expression (Mayr, 1982). Johannsen was responsible for the important distinction and coining of the terms phenotype and genotype (see Dunne p. 92 for a more detailed account). Johannsen also was responsible for the introduction of the word *gene* in 1909. Dunne (1965) reports on Johannsen's definition of a gene.

> The gene is thus to be used as a kind of accounting or calculating unit [*Rechnungseinheit]*. By no means have we the right to define the gene as a morphological structure in the sense of Darwin's gemmules or biosphores or determinants or other speculative morphological concepts of that kind. Nor have we any right to conceive that each special gene (or a special kind of gene) corresponds to a particular phenotypic unit-character or (as morphologists like to say) a "trait" of the developed organism. (Johannsen, 1909, as reported in Dunne, 1965, p. 93)

Instead of providing a definition for the gene, Johannsen merely said the gene is to be used as a kind of accounting or calculating unit (Mayr, 1982). It is clear from these accounts presented above that biologists like Bateson and Johannsen refused to accept that the behaviour of chromosomes did in fact have anything to do with the passage of hereditary information (Bowler, 1989; Tudge, 1993).

During the decade of Mendelism (1900 - 1910), sex was shown to be a Mendelian character and it's relationship with the sex chromosomes was demonstrated by Stevens and Wilson (Brush, 1978). Correns, in 1907, provided the first experimental evidence that sex was determined by the uniting gametes (Dunne, 1965). From these ideas came the first evidence that genes were in fact parts of chromosomes. The British biologist, William Bateson, and his collaborators showed that Mendel's laws applied to animals as well as plants in a series of papers extending from 1902-1919 (Dunne, 1965). From that time, genetics dealt with the patterns of inheritance and has been termed "classical genetics" (Tudge, 1993).

Classical Genetics

The period called classical genetics is said to have began with the Morgan school. Morgan proposed "The Chromosome Theory of Heredity" which consisted of the view that chromosomes are made up of linear arrangements of genes in an order that can be mapped by experimental breeding methods (Dunne, 1965). This theory was to influence genetics for the next 25 years. The essential part of the theory was the recognition that the gene was the conceptual and physical element in the process of heredity (Dunne, 1965). In order to test and find supportive evidence for the new theory, Morgan set up the 'fly room' at Columbia University, where vast numbers of *Drosophila* were bred and studied (Sturtevant, 1966). The classical genetics period was occupied much more intensively with problems such as the arrangement of the genes on the chromosome (Mayr, 1982).

Classical genetics dealt with the patterns of inheritance and consisted of various studies on a vast range of domestic plants and animals such as snails, *Primula,* and tobacco as well as the fruit fly, *Drosophila,* studied by Morgan (Tudge, 1993). The studies revealed that there were a great many complications with the simple patterns of inheritance proposed by Mendel such as the realisation that the same phenotype may be brought about by different genetic means, that the same genotype may result in different phenotypes, that many characters are brought about by more than one gene (ie., polygenic), and that most genes affect more than one character (pleiotropic) (Tudge, 1993). Mendel's rule of independent assortment also was complicated by genes carried on the same chromosome or the phenomenon of linkage.

What was the classical geneticists view of a gene? Even though the gene had been recognised as physically existing on the chromosome, according to Tudge (1993), for classical geneticists:

> the genes themselves, Mendel's "factors', are conceived simply as abstractions - or as beads, threaded on chromosomes. Clearly, classical genetics is immensely powerful and, when combined with the evolutionary ideas of Darwin, provides a wonderfully unifying picture of the endless variety of life. But in genetics there is another, quite different line of inquiry to pursue: 'What exactly are genes, and how do they work?' (Tudge, 1993, p. 45)

Bowler (1989) is of the same opinion as Tudge and suggests that classical geneticists had a lack of interest in how the gene influences the developing organism. Bowler even goes as far to suggest that:

> Although linked to the chromosome, the 'material' gene was almost as abstract a concept as that advocated by earlier Mendelians such as Bateson. On this interpretation, the subsequent emergence of molecular biology as the study of what genes are and how they function constitutes a major breakthrough transcending the research tradition of classical genetics. Other historians see the classical geneticists' reluctance to tackle the question of gene expression as merely a tactical manoeuvre designed to set on one side questions that could not be answered with the techniques then available. (Bowler, 1989, p. 137)

As time moved on through the second World War, techniques improved and biologists started to concentrate more on questions other than those about the patterns of inheritance and the arrangement of genes on chromosomes. They started to investigate more seriously questions about what genes are made of and how genes make an effect on the characteristics of an organism.

Molecular Genetics

From the 1950s onward, and even into the 1990s, molecular geneticists used increasingly sophisticated technology to investigate more complex organisms. The distinctive purpose of molecular genetics, according to Cook-Deegan (1994), was to understand the functioning of genes through their structure. This strategy is described as "reductionist" (Cook-Deegan, 1994, p. 32) and is said to have been borrowed from physics. The initial study of gene structure started with proteins.

Associating Genes with Proteins

By the 1940s some biologists, like Francis Crick thought that the most logical thing that a gene could do would be to make proteins (Tudge, 1993). This idea had gained a foothold in the scientific community partly because of the vast variety of functions that proteins perform in the body. For example, it was understood at the time that proteins form the building blocks of much of the body; some proteins, such as insulin, serve as hormones, others act as receptors for initiating immune responses and make up antibodies. Most of all, though, it was recognised that proteins serve as enzymes, the natural catalysts of the cell, and help to regulate the cell's metabolic pathways (Berg & Singer, 1993). It was understood, therefore, that proteins have a pervasive influence on the structure and function of the cell and the body as a whole.

The idea that genes do make proteins can be traced back to several lines of thought (Tudge, 1993). The first is the recognition that enzymes are proteins. The first description of enzymes in the body can be attributed to a German chemist, Edouard Buchner in the late 1800s (Tudge, 1993). Work subsequent to Buchner's has shown that there are many thousands of different enzymes in nature and that most of those enzymes are proteins (Berg & Singer, 1992; Tudge, 1993). Garrod showed from experiments that investigated alkaptonuria* and other inherited diseases that "inborn errors" are caused by defects in particular enzymes. He also tentatively proposed the now famous idea of "one gene, one enzyme" (Tudge, 1993). In the first decade of this century, even before the word *gene* had been introduced, Garrod showed that the inheritance of certain human diseases followed Mendelian rules (Berg & Singer, 1992). Later, Garrod suggested that the heredity units controlled the production of enzymes (Berg & Singer, 1992). Beadle and Tatum working in the United States during the 1940s on orange bread mould supported the "one gene, one enzyme" idea (Berg & Singer, 1992). In the 1950s, Linus Pauling showed that the sickle cell anaemia gene caused a specific defect in haemoglobin, the protein that carries oxygen in the blood. Therefore, he was able to demonstrate that defective genes led to defective proteins other than enzymes. The saying, "one gene, one enzyme", was then broadened to "one gene, one protein" (Tudge, 1993).

Gene Structure

Around the 1940s, most biologists assumed that genes must not only make proteins but they must also be proteins themselves (Tudge, 1993). There was, however, another possibility, an acid that had been discovered in human pus cells in 1869 (Berg & Singer, 1992) and in the sperm of trout in 1871 (Tudge, 1993). Sperm are mostly nucleus, so the acid was called a nucleic acid. Analysis showed that the acid contained a deoxyribose sugar, and hence the full name, *deoxyribose nucleic acid* or DNA for short. In the 1920s, Robert Feulgen of Germany showed that DNA was confined to the chromosomes, and not a general part of the nucleus.

The general structure of proteins being made up of chains of amino acids was demonstrated in the early 1900s. It wasn't until the 1940s that it was realised there are only about 20 amino acids and that the behaviour and properties of proteins are determined by different combinations of amino acids and the three-dimensional

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* alkaptonuria is a relatively benign hereditary disease due to an autosomal recessive allele where the sufferer's urine turns dark when exposed to air. This is caused by the presence of homogentisic acid which is not broken down by the sufferer's liver (King & Stansfield, 1985).

structure of the protein molecule. Initially, it seemed that DNA could not possibly be responsible for producing the variety required to produce all the different kinds of proteins (Tudge, 1993).

According to Tudge (1993), there were two lines of inquiry that eventually demonstrated beyond reasonable doubt that DNA is the physical structure of genes. The first line of inquiry was during the 1920s by Frederic Griffith and then in the 1940s by Oswald T. Avery who worked on the bacterium *Pneumococcus* and showed that an exchange of information could occur between virulent and non-virulent forms of the bacterium so that the non-virulent form would re-acquire the quality of virulence. In 1943, Avery, MacLeod, and McCary showed that the material that passed between the bacteria was not protein, but was DNA (Cook-Deegan, 1994).

The second line of inquiry, that was pivotal in demonstrating the role of DNA in conveying hereditary information, involved viruses which attack bacteria, or bacteriophages. In 1952, two scientists, Alfred Hershey and Martha Chase showed that only the DNA of phages entered the bacteria that they attack (Tudge, 1993). The protein coat remained on the outside. The subsequent reproduction of phages within the bacterial host was controlled by DNA alone. More and more evidence showed that the hereditary information in genes was tied up in the DNA. Once this had been demonstrated beyond reasonable doubt, biologists started to ask different questions. For example, how can a molecule such as DNA, which has a basic structure of only four different components, be responsible for making molecules that have a much more complicated structure?

By the 1940s, it was known that DNA consists of chains of nucleotides consisting of a phosphate group, a sugar group and a nitrogen base. Other research revealed that the four different nitrogen bases of DNA, thymine, guanine, cytosine, and adenine, were not present in equal amounts, and the proportions of the four nucleotides were different in DNA from different species. In the 1940s, Erwin Chargaff showed that the amount of the base adenine always equalled the amount of thymine and the amount of guanine always equalled the amount of cytosine (Tudge, 1993).

The increasing use of the electron microscope after World War II showed that DNA molecules were thread-like. Another crucial technique was X-ray crystallography which played an important role in deducing the arrangement of atoms in crystals of DNA by firing X-rays at them. Maurice Wilkins and Rosalind Franklin began crystallography of DNA after 1949 at King's College, London. They showed that the DNA chains are arranged in a helix, with the nitrogen bases (adenine, cytosine, guanine and thymine) on the inside, and the sugar-phosphate backbone on the outside (Tudge, 1993). Finally, at Cambridge in 1953, James Watson and Francis Crick proposed that DNA consisted of two helical chains that ran in opposite directions, head to tail in the form of a double helix. Crick, Watson and Wilkins shared the Nobel Prize for Medicine in 1962; Rosalind Franklin died at a young age, in 1958, her contribution not recognised (Berg & Singer, 1992; Tudge, 1993).

Further examination of the fine structure of genes in the T4 bacteriophage virus during the early 1960s by Benzer (1962) demonstrated that the gene consisted of specific regions, or units, that were distinguishable by function, mutation and recombination. Benzer (1962) discussed the genetic units of various sizes: the small units of mutation and recombination and much larger cistrons (the functional units). The question of whether all, or only some, of these regions make up the gene is addressed by Benzer in the following quotation.

> The term "gene" is perfectly acceptable so long as one is working at a higher level of integration, at which it makes no difference which unit is being referred to. In describing data on the fine level, however, it becomes essential to state unambiguously which operationally defined unit one is taking about.
>
> (Benzer, 1962, p. 78)

For Benzer, the gene is made up of subunits of recombination, mutation and function, and it is important for scientists working at the fine structure level to acknowledge the sub-genetic units. However, it is acceptable to use the term gene collectively for these units when working at a higher level.

The Genetic Code

Tudge (1993) proposes that there are three sub-questions to the question, how does DNA work? The first: How does DNA replicate itself?; the second: How does DNA make a protein?; and third: How do the four nucleotides in DNA code for the 20 amino acids in protein? Watson and Crick hinted in their publication of the DNA structure that DNA would replicate itself by the two strands of the double helix splitting away from each other, each strand then forming a template on which a new double helix is constructed. Matthew Meselson and Franklin Stahl demonstrated that this is actually how DNA replicates in 1958 with experiments on *E. coli*. They were able to show that nucleotides from the surrounding medium line up against the two strands of the original DNA in complementary partners to form two double helix molecules.

How does DNA make protein? It seemed likely since Watson and Crick proposed their DNA model that RNA was an intermediate medium between the DNA in the nucleus and the ribosomes where proteins are manufactured. This idea came about from observations that RNA was in abundance in cells that make a lot of protein. As early as 1953 it was foreseen that DNA that had separated, or unzipped into its two strands, could then either replicate itself or make RNA which can leave the nucleus, travel to the ribosomes and supervise the production of proteins. This process of the production of RNA is now known as *transcription*. The process where the information stored in the RNA is then used to make proteins is called *translation*. The process of translation involves three kinds of RNA: messenger, ribosomal and transfer RNA. The messenger RNA is responsible for bringing messages from the nuclear DNA into the cytoplasm. The messenger RNA then co-operates with ribosomal RNA in order to assemble the amino acids in the correct order to form a protein. The transfer RNA is responsible for bringing the amino acids that are needed for the manufacture process to the ribosomes.

How do four nucleotides code for 20 amino acids? Sydney Brenner and Francis Crick and colleagues demonstrated at Cambridge in 1961 that the genetic code operated through triples of nucleotides in DNA. They worked with a phage which infects *E. coli* to show that there are three nucleotides codes for one amino acid in a protein chain. Their work also demonstrated how "frameshift mutations" occur by throwing the coding sequences of triplets of nucleotides, or *codons*, out of sync. Exactly which sequence of three nucleotides coded for which amino acid was worked out in the early 1960s, especially by Marshall Nirenberg and Heinrich Matthai. By June 1966, it was know that 61 of the 64 codons coded for amino acids and the other three coded for 'stop' signals: "In short the genetic code was cracked" (Tudge, 1993, p. 69).

Different Gene Concepts

Mayr (1982), Falk (1986) and Portin (1993) specifically concentrate on the development of the concept of the gene in the past century; however, each of these authors present different interpretations. The first of the four concepts of the gene that Mayr (1982) believes to have existed in the period since Mendel portrays genes as the building blocks of the organism. Darwin's gemmule theory and de Vries pangens ideas are examples of this concept. Secondly, Mayr asserts that the concept of genes being enzymes, catalysing chemical reactions in the body, was very popular in the late 1800s, particularly with Weismann. Thirdly, around the middle of the 20th century, Mayr suggests that genes were seen as a means of energy transfer to some biologists. Finally, Mayr says that the gene was viewed as "the conveyor of highly specific information" (p. 807). Mayr suggests that after the discovery of the structure of DNA and transcription and translation, this concept of the gene became the modern standard concept.

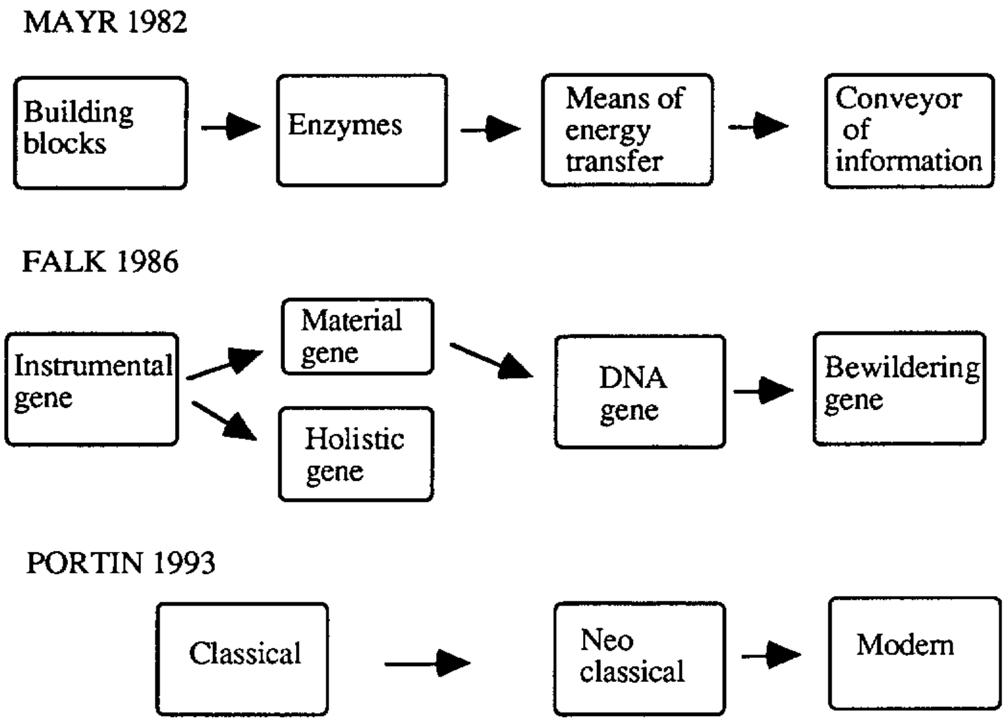


Figure 2.1: Historical developments in the concept of the gene over the past century as portrayed by three authors, Mayr (1982), Falk (1986) and Portin (1993).

In contrast to Mayr's four concepts, Falk (1986) outlines five concepts of genes that he believes have been of the most importance this century (Figure 2.1). These include the instrumental gene, the material gene, the holistic gene, the DNA gene and the bewildering gene. Falk's instrumental gene is something which he believed the researchers of the earlier part of the century understood as discrete units that obeyed the basic Mendelian laws and were allocated the potentiality for a single trait. Falk (1986) describes this concept of the gene as "instrumental reductionism" (p. 141) and suggests that it was a useful and flexible concept for the development of genetic research as exemplified by the Morgan school.

The second concept of the gene that Falk (1986) discusses is the material gene which he explained coincided with the realisation that genes are located on chromosomes and therefore are material entities. Once this was accepted, researchers started to look at the function of genes, for example Beadle and Tatum's work in the 1940s investigating how genes determine properties. The slogan "one gene - one enzyme" therefore developed within this concept of a material gene and soon research about gene function led back to the analysis of gene structure. The material gene eventually was seen to consist of three elementary units; the cistron - responsible for the function or production of proteins: the recon - units of recombination; and the mutons - units of mutation.

Parallel to and at the opposite extreme to the existence of the "instrumentally reduced" material gene, Falk (1986) describes an holistic concept of the gene supported by biologists such as Goldschmidt during the period of the 1920s and 1930s. Goldschmidt thought genes were abstractions that had been important to the early geneticists but were no longer so. Goldschmidt thought the chromosomes and loci (the position of the gene along the chromosome) were more important than the genes and visualised the chromosomes as a continuous genetic substance. Falk suggests that this image prevented Goldschmidt from achieving the insight necessary to understand the functional concepts of heredity.

It was the material gene concept, according to Falk (1986), and the related ideas about the function (one gene - one enzyme) and structure (cistron, recon, muton) that led to Watson and Crick's discovery of the double helix. This discovery was the turning point from the material gene concept to what Falk (1986) entitles the DNA gene concept. This period also saw the description of the structural and regulatory gene concepts by Jacob and Monod (Falk, 1986). When research expanded to the study of eucaryotes, rather than procaryotes, many of the assumptions about genes that came with the DNA gene concept began to be questioned. Falk (1986) describes Britton and Kohne's discovery in 1968, that much of the DNA in eucaryotes is highly repetitive and redundant, as the turning point to the new notion of the bewildering gene.

The Bewildering Gene

The concept of the bewildering gene described by Falk (1986) coincides with many discoveries that contradicted the concept of the discrete, material, gene. For example the discovery that segments of DNA may code for two different polypeptides defies the "one gene - one protein" slogan. This slogan has subsequently been changed to "one gene - one polypeptide" in some textbooks (Cook-Deegan, 1994). Another example Falk (1986) discusses is the discovery of unstable or "jumping genes" by Barbara McClintock. Falk suggests that this discovery was largely ignored because the genetic community believed genes were a "specific and discrete sequence of DNA with well defined and specific modes of function, her concept of genes, unstable both in their location and function, was too disruptive to accept" (p. 164). According to Falk, it is only possible to accept the ideas of McClintock in the present climate. Within this present concept of a bewildering gene, Falk argues that we return to something akin to the ideas that Mendel and Johannsen had, that the phenotype defines the gene, rather than the other way around.

> What is a gene?... Clearly we can no longer say that a gene is a sequence of DNA that continuously and uniquely codes for a particular protein. For situations in which a stretch of DNA is responsible for production of one particular protein, current usage is to regard the entire sequence of DNA, from the first point represented in the messenger to the last point corresponding to its end, as comprising the 'gene', exons, introns, and all. In cases where the sequence representing proteins are overlapping or have alternative forms of expression .. Instead of saying "one gene - one polypeptide," we may describe the relationship as "one polypeptide - one gene." Thus we may regard the sequence actually responsible for production of the polypeptide (including introns as well as exons) as the gene, while recognizing that from the perspective of another protein, part of this same sequence may also belong to its gene. (Lewin, as quoted in Falk, 1986, pp. 168-169)

Portin (1993) contests that the gene concept has been continuously evolving, however. In order to understand the development of the concept of the gene, Portin discusses three major periods - classical, neoclassical and modern (Figure 2.1). The classical view is similar to Falk's material gene in that the gene is viewed as an indivisible unit of genetic transmission, recombination, mutation and function. The neoclassical view of a gene, according to Portin, developed in the early 1940s in conjunction with the discovery of intragenic recombination and the establishment of DNA as the chemical basis of the gene. The neoclassical view saw genes consisting of the units called cistron, muton and recon. Portin discusses the colinearity hypothesis of this time which states that one cistron produces one mRNA which in turn produces one polypeptide. Since the 1970s, with the advent of DNA technologies, the modern concept of the gene has prevailed. Portin (1993) states that discoveries such as repeated genes, split genes and alternative splicing, assembled genes, overlapping genes, transposable genes, complex promoters, multiple polyadenylation sites, polyprotein genes, editing of the primary transcript and nested genes have left us with a "rather abstract, open, and generalized concept of the gene, even though our comprehension of the structure and organization of the genetic material has greatly increased" (p. 173). Nevertheless, Portin's modern conceptualisation of a gene is similar to Falk's bewildering gene because the criteria utilised to define the gene at other times in history are insufficient.

The Gene: A Discovery or Invention?

The picture painted in much of this description of the development of the concept of the gene is of a series of discoveries by scientists searching for the truth. The impression is that this search has resulted in the unfolding of the facts and the documentation of the realities of genetics and inheritance. This too is the impression presented in many student textbooks where some of the personalities, particularly Mendel, Watson, and Crick, are presented as scientific heroes who were able to uncover the facts and truths about genetics (see Evans, Ladiges, & McKenzie, 1995, or King & Sullivan, 1991, for example). More recently, however, the independence and objectivity of science has increasingly been questioned by such authors as Bowler (1989), Mayr (1982) and Tudge (1993). It must not be ignored that although many earlier books on the history of genetics did highlight a "discovery science" perspective of genetics, this image was questioned. In the final chapter of Dunne's (1965) book, for example, he raised the notion of "inventing" genetics and highlighted the importance of "scientific ideas" in contrast to "scientific facts".

> It has been said that Mendel discovered the principle of segregation of alleles - as though the principle had existed and had waited to be uncovered. ... However, the disclosure of these facts (such as the proportion 3:1) did not lead to the development of genetics, while the *idea* of segregating elements did. The idea was a product of Mendel's imagination and was independently arrived at by Correns and de Vries and perhaps by others. "Inventing" or "conceiving" ... would perhaps more nearly describe the introduction of a new idea.
>
> (Dunne, 1965, p. 209)

Bowler (1989) challenges the orthodox view of the history of genetics on three levels, that of conceptual, professional and ideological. On the conceptual level, Bowler suggests that the history of genetics is not so much the accumulation of facts but the development of new conceptual schemes.

> Acceptance of Mendel's laws thus depended not on the discovery of facts, but on the creation of a new conceptual scheme within which laws of that kind could make sense. But once we accept that genetics emerged as part of a conceptual revolution, it becomes obvious that Mendel's fellow biologists would not have been able to recognize implications that would only become apparent over thirty years later. (Bowler, 1989, pp. 7-8)

On the professional level, Bowler argues that science must be seen as a social activity and suggests that in genetics there were social constraints on the kind of theorising permitted within the new discipline. Constraints such as the need for university positions, journals, government and industrial funding for the creation of an entirely new discipline. "The growth of science does not represent an open-ended assault on the unknown: it is shaped by the theoretical models considered acceptable by the community that defines the field of study" (p. 9). At the third, ideological level, Bowler boldly suggests that the "conceptual revolutions" (p. 9) that occurred in genetics were in accordance with social developments on a wider scale. On this ideological model, Bowler suggests that "new laws or theories are not simply discovered, ... they are invented to satisfy the cultural values of the scientists and of the public with whom they must interact" (p. 10). Bowler points out that the rediscovery of Mendel's laws coincided with the emergence of 'hereditarian' social and political policies. These policies were based on the theme that human abilities are rigidly determined by heredity. That is, human intelligence and moral capacities, for example, of the various human races were fixed by their biological make-up. Jones (1993), in a similar way to Bowler, implies that people such as Galton, who believed in eugenics, influenced the progress of research in genetics, particularly in the first half of the 20th century.

> Galton and his followers felt free to invent a science of human inheritance which accorded with their own prejudices. They believed that our duty to our genes outweighs that to those who bear them. (Jones, 1993, p. 12)

Tudge (1993) also clearly questions the objectivity of science in such statements as the following:

> Yet the notion that science is entirely objective has been perpetrated by successive generations of philosophers, as if there was simply some 'method' which, when applied, provided inexorable truth. To be sure, there is a pattern to science which is not seen so clearly in other disciplines. ... The findings and ideas of science are not unequivocal and perennial truths. They are only the best ideas that scientists are able to put forward on the evidence and with the means available at any one time. But they have a robustness, none the less - a testability - which is not so easy to discern in the ideas of history, say, or literary criticism. (pp. 371-372)

As an example of what Tudge describes as "the best ideas that scientists are able to put forward" he describes the paradigm of all modern biology as:

> Neodarwinism: the fusion of Darwin's ideas with Mendel's. ... Mendelian genes are translated into living bodies - the phenotype - upon which Darwinian natural selection can act. Basically, genes make proteins, which shape bodies, which are then exposed to the rough and tumble of natural selection." (p. 338)

Tudge tantalises his readers by describing challenges to this modern paradigm of biology. He says that although the existing paradigm takes us a very long way, it doesn't provide all the answers. For example, he suggests that many biologists are not satisfied that genes on chromosomes are the only thing responsible for the development of "the subtly interacting three-dimensional totality of the organism" (p. 338). Tudge then delves into areas of science and philosophy that some describe as 'new wave' or even 'mysticism' and describes three areas of research that purport to fill the gaps between the genetic code and protein synthesis, and the final, whole organism. The first of the ideas, which has ancient resonance, is that of an external life force or 'vitalism' which must reach the body in much the same way that radio waves reach a radio and make it work. The second area suggests that different parts of the organism signal to each other in ways that are not to be explained purely in terms of the chemical signals, such as hormones, that have so far been described in embryology and biochemistry. Thirdly, Tudge explains the idea of 'complexity' that suggests that apparently chaotic interactions can lead to simple forms. Tudge uses an analogy with water swirling around rocks - a chaotic event - and the formation of a whirlpool - a perfectly simple form. Proponents of this theory suggest that the order of the body arises from the confusion of genetic information because there is innate orderliness within the confusion.

Why does Tudge discuss these theories on the edge of conventional science? His point is that the current explanations of the mechanisms of how organisms are constructed are inadequate and it is probably necessary to venture into unconventional ideas in science to make further progress in our scientific understanding. Some of these ideas may, in the future, give us further answers; some, or even all of them, may not. These descriptions of 'new wave' areas of research suggest that scientific activity is not well represented as a search for truth, and gives credence to Tudge's idea that science is more about "testability" and that "scientists progress by making guesses (hypotheses) about the way the world works and then testing those hypotheses by experiment" (p. 371).

So were genes discovered or invented by scientists? The discussion above indicates that it was probably both invention and discovery that led to today's concept of the gene. Certainly there has been some great scientific endeavour to construct a picture of the physical structure and biochemical processes related to genes. However, there is no denying the role of external pressures, such as social and political, in science and the ways that these pressures help to mould the scientific thought of the day (Cook-Deegan, 1994; Watson, 1968). The gene is undeniably a physical entity, but the importance that has been placed on that particular entity has certainly been shaped by forces other than purely scientific inquiry. It is difficult to place ourselves outside the paradigm of today and hypothesise about what might have been if the social climate had been different, but the section of DNA which we call the gene may not have been as important in different circumstances. We can simply imagine a scientific world where the section of DNA we call a gene may never have been given a name or had any significance if patterns in inheritance other than "fixed units" (Bowler, 1989) had been given greater precedence.

What is a Gene to Me?

In this section, I change to first person because I am going to explain my own conception of a gene as a teacher and a researcher. I make no attempt at objectivity because it is a purely personal exploration of the concept of the gene and what it means to me. I consider this section a necessary part of this thesis because it will disclose my image of a gene, hence putting the reader in a position of knowing the researcher's personal construction of the concept under investigation. I make no pretence at expertise, I have simply gleaned my knowledge of genes from readings of textbooks and historical accounts in the field of genetics as an undergraduate and postgraduate student. Nor do I pretend that this is a complete description of the gene concept. There have been whole books written about genes (see Berg & Singer, 1992 for example), and in order to keep this section to a manageable length I have omitted detailed descriptions of related concepts such as DNA replication, transcription, translation, the idea of homologous pairs of alleles and the effects of the environment on the phenotypic expression of genes.

I will explore the concept of the gene and what it means to me by asking myself two primary questions: What are genes? and What do genes do? Even though the questions separate the ideas of gene structure and function I have made this division purely for the practical purpose of writing. I see the structure and function of genes, as with most biological concepts, as being inextricably linked. I choose to answer these questions using a series of borrowed metaphors and analogies that I have encountered through my readings for this thesis. Each of the analogies and metaphors that I have chosen to present here has, in some way, helped to redefine my conception of a gene, and together I believe they present a powerful image.

What are Genes?

Genes are entities in the nucleus of cells that play an important role in inheritance, in controlling cell function and in the development of individuals. As a biology teacher, I have often looked at cells through light microscopes, but it has never been possible for me to observe genes. It is, therefore, difficult for me to visualise the size of genes. Cook-Deegan (1994) uses an analogy between the cell and the world to describe the relative sizes of the subcellular entities involved with genetics (Figure 2.2). The advantage of this analogy is that it gives me a rough notion of the very small size of genes because I am better able to visualise the difference in size between the Earth and a street address than between a cell and a codon. Although the analogy gives me an idea about the size of genetic entities, it does not help me to understand the relationships between genetic entities such as genes, chromosomes and DNA.

Genes are made up of the chemical deoxyribonucleic acid, a name which, luckily for teachers of biology, is often shortened and referred to as DNA. Last year, I was tutoring a student, Hannah, in senior biology. When we were on the topic of genetics I asked her to explain to me the relationship between genes, chromosomes and DNA. A fundamental and easy question, I thought. I realised as Hannah struggled to verbalise or draw an acceptable answer to the question that it was not. In order to help Hannah, I borrowed an analogy from one of the teachers whom I had observed during the data collection stage of this thesis. I explained to Hannah that chromosomes are made up of chains of genes. The chromosomes could be likened to a silver chain and that the genes were like the links along the chain. The DNA is the chemical that the chromosomes and genes are made of just like the silver that a chain is made of. In humans, I explained, we have 46 chromosomes in each nucleus of each cell, so it's like having 46 chains of genes. As I was describing the analogy to Hannah, and even though it helped to clarify the relationship between genetic entities, I was really concerned about the misleading ideas the silver chain analogy could be instilling in her mind. For example, I knew that genes are not discrete sections of a chromosome lined up like links on a chain. Regardless of the limitations of the analogy, I could justify my choice in that it was a good starting point for my student. I believe the silver chain analogy helped Hannah to construct an initial conception, of something that she was really confused about. And, it was something that she could modify as she learnt more. I remember telling Hannah that chromosomes aren't exactly like silver chains, but I don't know if she really appreciated what I was saying. Hannah was more excited about finally being able to visualise a meaningful relationship between the three ideas, gene, chromosome and DNA.

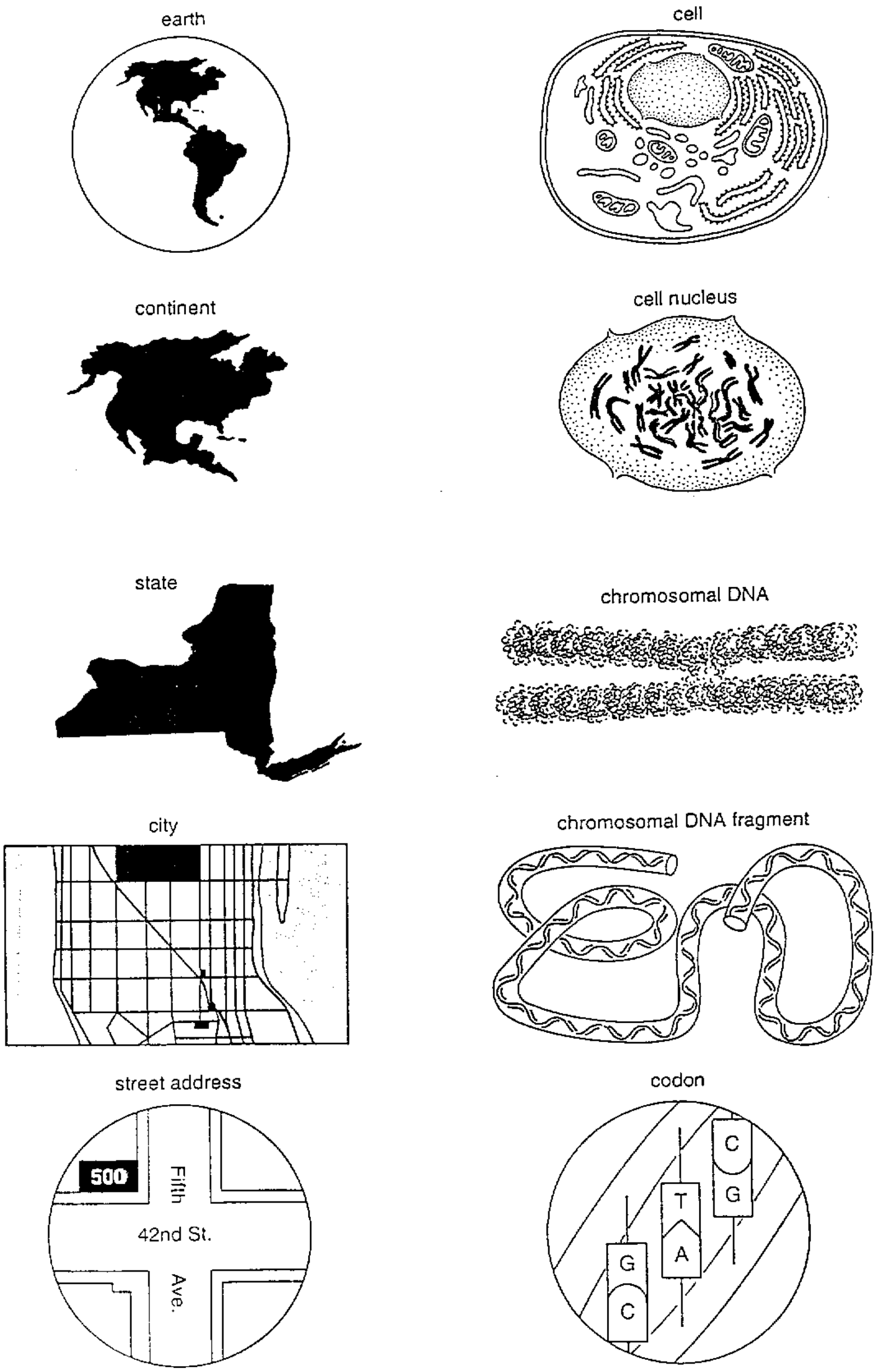


Figure 2.2: An analogy presented in Cook-Deegan (1994, p. 24) gives a rough sense of the relative sizes of the subcellular entities involved in genetics.

I would like to include the silver chain analogy in my conception of a gene, even though I know that it is a poor one. As with my teaching of Hannah, I think it is a good starting point. I have come across several metaphors which create a less discrete and more living, moving idea of a gene than a link in a chain. These metaphors serve to further modify the conception that I am constructing on these pages. Falk (1986), for example, describes the concept of a "bewildering gene" and explains the difficulty in pinning down a gene to a particular segment of DNA. Falk suggests that the only way of actually defining the segment of DNA that we can call a gene is by looking at the gene from the perspective of its function. That is, a gene is the "string of DNA" that is used to produce something or do something. Such a string of DNA, however, may come from lots of different places on chromosomes, some parts may move around and there might be pieces of DNA that are associated with more that one gene.

> Today the gene is not just *the* material unit, or *the* instrumental unit of inheritance, but rather *a* unit, *a* segment that corresponds to *a* unit-function, as defined by the individual experimentalist's needs. It is neither discrete - there are overlapping genes, nor continuous - there are introns within genes, nor does it have a constant location - there are transposons, nor a clearcut function - there are pseudogenes, not even constant sequences - there are 'consensus' sequences, nor definite borderlines - there are variable sequences both "upstream" and "downstream". (p. 169) ... At the present time the referent of 'gene' cannot be more precisely specified than as 'a string of DNA'. (Falk, 1986, p. 170)

Tudge's (1993) metaphor of a "restless genome" is similar to Falk's (1986) "bewildering gene" metaphor. However, to me, Tudge's ideas are a little more radical than Falk's, especially in the idea that viruses can connect and interchange DNA in the genomes of different organisms.

> The seventeenth-century vision of a clockwork universe seems to apply reasonably well to the arithmetical certainties of Mendelian genetics, or even to the 1960s vision of the genome, with its orderly ranks of genes. But the vision we have now, of a restless genome, innately anarchic, always prone to change, linked (perhaps) to other genomes by viruses, seems to re-awaken the ancient and poetic vision of life as a candle-flame: never the same for two instances of time, definable only in general terms. (Tudge, 1993, p. 75)

The metaphors presented so far have yet to provide an image of the chemical make-up of genes. Genes are made up of DNA, but what is DNA and what does it look like? The structure of DNA, as most people know, can be described as being like a twisted ladder. Although the analogy is somewhat inadequate in many regards, like the silver chain analogy, I think it is a good starting point.

> Studies of DNA crystals show a pattern which indicates that the DNA molecule consists of two polynucleotide strands spiralling around a sugar phosphate 'backbone'. One way to picture it is as a ladder held at one end and twisted. An A [adenine] of one strand pairs with a T [thymine] in the other, and a G [guanine] of one strand pairs with a C [cytosine] in the other (Figure 2.3a). The bases together with the bonds are like the steps of the ladder. The sequence of bases in one strand is *complementary* to that in the other strand. Bases can occur in any order within a strand: if a particular base is A the next base in sequence could be A, G, T or C. The polynucleotide strands spiral symmetrically in three dimensions to form a *double helix* (Figure 2.3b). (Evans, Ladiges & McKenzie, 1995, pp. 229-230)

Although this analogy provides an image of the general structure of DNA it falls short of highlighting the significance of the double helix structure.

The structure of DNA is important because the structure renders possible a code. The code contains messages with instructions which ultimately control the structure and function of individual cells and organisms. The genetic code is described by Jones (1993) in an analogy with written language.

> The language of the genes has a simple alphabet, not with twenty-six letters, but just four. These are the four different DNA bases - adenine, guanine, cytosine and thymine (A,G, C and T for short). The bases are arranged in words of three letters such as CGA or TGG. Most of the words code for different amino acids, which themselves are joined together to make proteins, the building blocks of the body. (Jones, 1993, p. 4)

The analogy with written language highlights the significance of the double helix structure; that it is a code that conveys a message about the sequence of amino acids in proteins.

Jones (1993) describes another analogy which paints a different picture of DNA and the genes within them. I really enjoy the journey along DNA that Jones creates in the following geographic analogy, but I transform in my mind Jones' image into an Australian geography, the geography I know better than any other.

> We can get an idea of what the physical map [of our genome] looks like with a geographical analogy. Imagine the journey along the whole of your own DNA as being equivalent to one from Land's end to John O'Groat's via London. This is about a thousand miles altogether (which means that it's American equal would be roughly equivalent to a trip from New York to Chicago). To fit all the DNA letters into a road map on this scale, there have to be fifty DNA bases per inch, or about three million per mile. The journey passes through twenty-three

DNA consists of deoxyribose sugar, phosphate and nitrogen-containing bases. The molecule is a double helix of two polynucleotide strands with a strict pairing relationship between the bases of complementary strands. Adenine pairs with thymine, guanine pairs with cytosine.

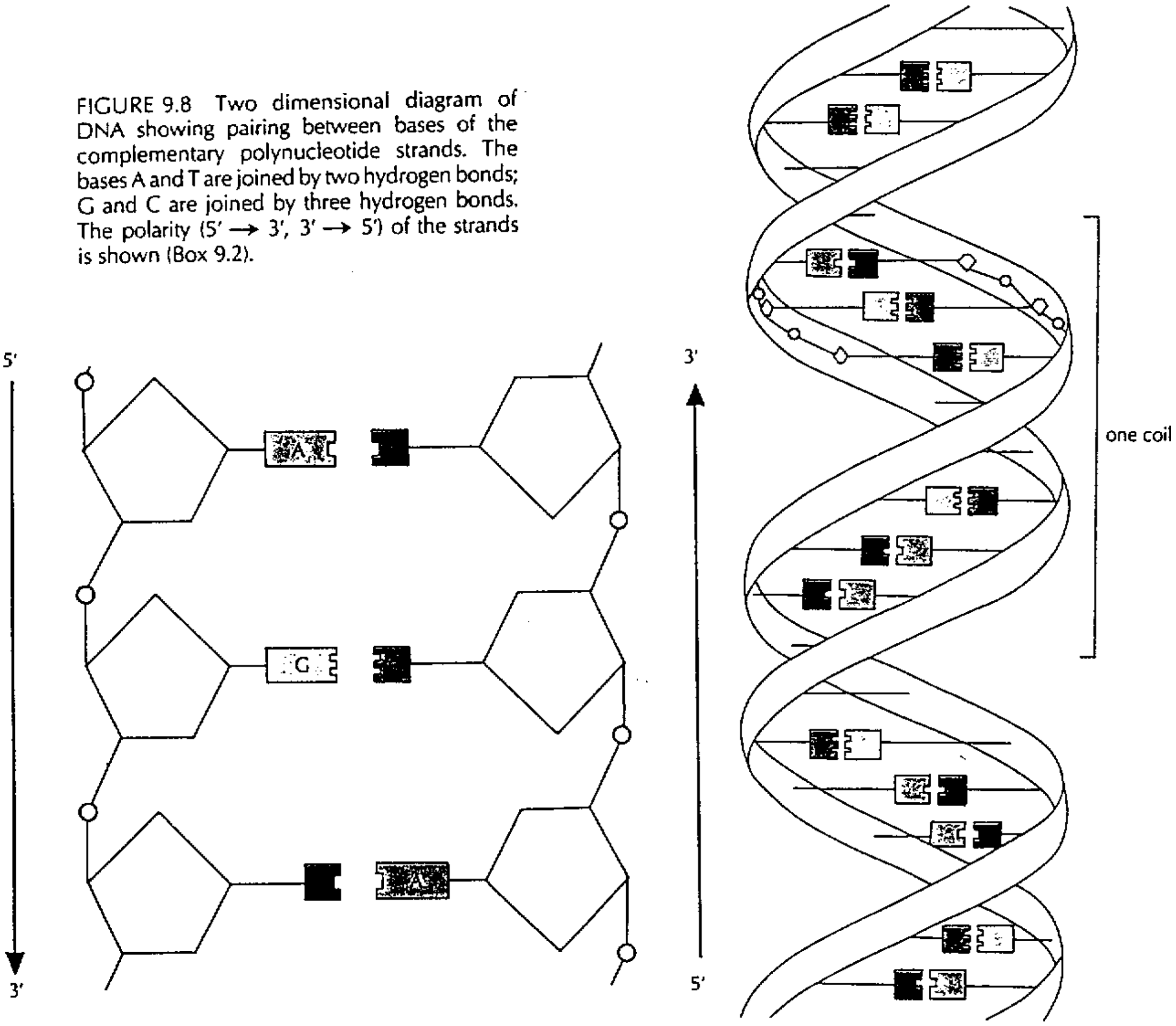


FIGURE 9.8 Two dimensional diagram of DNA showing pairing between bases of the complementary polynucleotide strands. The bases A and T are joined by two hydrogen bonds; G and C are joined by three hydrogen bonds. The polarity (5' → 3', 3' → 5') of the strands is shown (Box 9.2).

FIGURE 9.9 The DNA molecule, showing how the two complementary strands intertwine. There are ten bases per strand in each helical coil. The ribbon-like strands consist of the phosphate-sugar backbone and the horizontal rungs are the base pairs. Symbols are as for Figure 9.7.

a.

b.

Figure 2.3: Diagrams presented in *Biology Two* (Evans, Ladiges & McKenzie, 1995, p. 230) that demonstrate the double helix structure of DNA.

> counties of different sizes. These administrative divisions, conveniently enough, are the same in number as the twenty-three chromosomes into which human DNA is packaged. ... The scenery for most of the trip is very tedious. Like much of modern Britain it seems to be totally unproductive. About a third of the whole distance is covered by repeats of the same message. Fifty miles, more or less, is filled with words of five, six or more letters, repeated endlessly next to each other. ... Yet more of the genome is given over to occasional long and complicated messages which seem to say nothing. ... Much of the inherited landscape is littered with the corpses of abandoned genes, sometimes the same one again and again. The DNA sequences of these 'pseudogenes' look rather like that of their working relatives, but they are riddled with decay and no longer produce anything. ...
> After many miles of dull and repetitive DNA terrain, we begin to see places where something is being made. These are the working genes. ... Many functioning genes are arranged in groups making related products. There are about a thousand of these 'gene families' altogether. ...
>
> Another surprising aspect of the map of ourselves is that genes are of very different sizes, from about five hundred letters long to more than two million. In nearly all genes, the working segments are interrupted by lengths of non-coding DNA. In very large genes (such as the one which goes wrong in muscular dystrophy) the great majority of the DNA codes for nothing. The non-coding DNA participates in the first part of the production process, but this segment of the genetic message is snipped out of the messenger RNA before the protein is assembled. This seems an extraordinary way to go about things, but it is the one which evolution has come up with. (Jones, 1993, pp. 68-71)

Jones' (1993) geographic analogy puts the gene into context within the genome by conveying the idea that different genes are working at different times. None of the analogies so far describe adequately what genes do.

What Do Genes Do?

In high school textbooks, I often have seen genes described as blueprints for the cell's structure and function. One such analogy was extended in the textbook *Biology Two* (Evans, Ladiges & McKenzie, 1995) to describe the processes of transcription, translation and protein synthesis as being like the manufacture of a product in a factory (Figure 2.4).

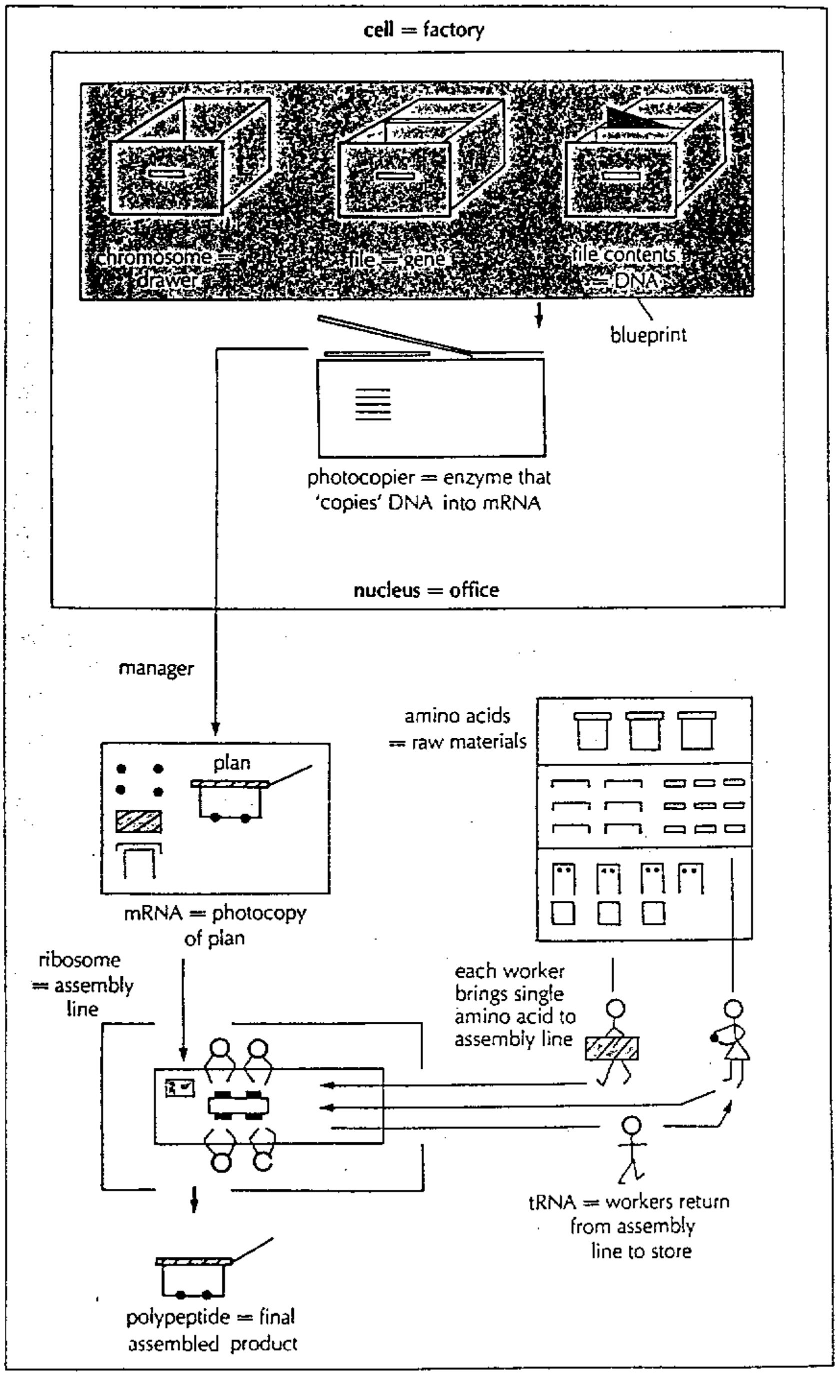


FIGURE 9.17 From a starting blueprint to the end product. Polypeptide synthesis in a cell can be likened to the manufacture of a product in a factory.

Figure 2.4: An analogy presented in *Biology Two* (Evans, Ladiges & McKenzie, 1995, p. 234) that describes polypeptide synthesis in a cell as being like the manufacture of a product in a factory.

> How is DNA involved in protein production? Consider the enzyme amylase, which catalyses the reaction in which starch is broken down to maltose. How does the DNA specify the particular sequence of amino acids to make the enzyme? If we think of it as a manufacturing process, how are the raw materials at the beginning of an assembly line converted into a product at the other end? In a factory there is a plan or blueprint in the office that defines the product, and specifies what parts are required for its manufacture and in what order they should be assembled. A manger surveys the plan and informs the workers of what is required and when their tasks should be carried out to produce the desired product.
>
> The formation of a polypeptide (enzyme) follows a similar route (Figure 2.4). DNA provides the blueprint found in the office (nucleus) of the factory (cell). The polypeptide is the end product. Amino acids are the raw material used in the construction of the polypeptide. We now need to identify the 'manager' who can read the plan and the 'workers' who are directed to bring the correct raw material (amino acids) to the appropriate site (the ribosome) in the factory where the product (polypeptide) is assembled. (pp. 234-235)

The analogy is continued in *Biology Two* and identifies and describes the role of the 'manager' or messenger RNA and the 'workers' or transfer RNA. The strength of this analogy is that the metaphor of a blueprint promotes the idea that genes are instructions on how to produce something.

For the third time, I apologise for using such an analogy that I know has serious limitations. I maintain that this is a good place to start, however, and in compensation I will include further analogies and metaphors that will serve to further develop and paint a more sophisticated picture of my concept of gene function. Tudge (1993) says that the blueprints metaphor is one of science's misleading myths because genes are not passive bystanders in the life of cells. He suggests instead a modern, active administrator metaphor that highlights the responsiveness of genes to their environment, and the active role they have in the cell's activities.

> DNA is an active administrator of the modern kind: sleeves rolled up, frenetically and intimately involved in the second-by-second running of the cell from conception to the grave, and extremely sensitive to events all around it. (Tudge, 1993, p. 78)

Dawkins (1989) suggests a "recipe" rather than a blueprint metaphor, as does Schmidt (1994), to describe the function of a gene. The advantage of the recipe metaphor is that it describes how each cell, given the same genetic information, can have a unique structure and function.

> All cells contain the same genetic information. So what makes a hair cell hairy or a bone cell bony? Imagine a bustling metropolis, sustained by myriad restaurants. At the heart of each is a busy kitchen with a table upon which lie volumes of a huge, ancient cookbook. Every restaurant relies on the same cookbook. Yet each uses a different selection of recipes-some churn out hamburgers exclusively, while others cook up exotic dishes such as moo-shoo pork and profiteroles. The various menus are created by mysterious behind-the-scenes chefs who specialise in particular cuisines.
>
> Bizarre as it sounds, this kitchen scenario is a good analogy for what appears to be going on in the nuclei of living cells. The recipes are genes, the cookbook chromosomes and the chefs transcription factors-protein molecules that bind to DNA with the effect of switching genes on or off. ... Burley's vision [Stephen Burley at the Howard Hughes Medical Institute and Rockerfeller University in New York] is that one day, scientists will be able to use transcription factors to control the expression of these healthy replacement genes. "Like having brakes and a gas pedal," says Burley, "you could rev up the transcription level or turn it off if it turns out to be harmful to the patient." (Schmidt, 1994, pp. 32-33)

It is easy to fall into the trap of assuming that single genes have affects on single characteristics because that is the way that genes are often portrayed in the media and in textbooks. Dawkins (1989) provides an excellent analogy with nitrate fertilisers to explain the effects of genes on the development of organisms and the expression of characteristics which dispels the idea of one gene, one characteristic.

> Expressions like 'gene for long legs' or 'gene for altruistic behaviours' are convenient figures of speech, but it is important to understand what they mean. There is no gene which single-handedly builds a leg, long or short. Building a leg is a multigene cooperative enterprise. Influences from the external environment too are indispensable: after all, legs are actually made of food! But there may well be a single gene which, *other things being equal,* tends to make legs longer than they would have been under the influence of the gene's allele.
>
> As an analogy, think of the influence of a fertilizer, say nitrate, on the growth of wheat. Everybody knows that wheat plants grow bigger in the presence of nitrate than in its absence. But nobody would be so foolish as to claim that, on its own, nitrate can make a wheat plant. Seed, soil, sun, water, and various minerals are obviously all necessary as well. But if all these other factors are held constant, and even if they are allowed to vary within limits, addition of

> nitrate will make the wheat plants grow bigger. So it is with single genes in the development of an embryo. Embryonic development is controlled by an interlocking web of relationships so complex that we had best not contemplate it. No one factor, genetic or environmental, can be considered as the single 'cause' of any part of a baby. All parts of a baby have a near infinite number of antecedent causes. But a *difference* between one baby and another, for example a difference in length of leg, might easily be traced to one or a few simple antecedent differences, either in environment or in genes. It is *differences* that matter in the competitive struggle to survive; and it is genetically-controlled differences that matter in evolution. (Dawkins, 1989, p. 37)

It is easy to understand that every cell of an organism has the same set of genes, but understanding how cells become differentiated is more difficult. To answer questions about growth and differentiation and how a baby and an adult can look different and have the same genome, Tudge (1993) uses a computer analogy:

> From all that I have said, the general mechanism of change is obvious. As the organism grows and matures, different suites of genes become active, or are switched off. The soldier with his strange oaths has the same genome as the mewling infant, but different genes are active within that genome. The analogy between genes and blueprints may be misguided, but it is tempting to compare the genome to a computer program, which issues a *series* of instructions, each waiting on the one before. (Tudge, 1993, p. 84)

I hope that this presentation of some of my favourite analogies and metaphors has conveyed, in a reasonably rich way, my own personal construction of the concept of the gene. It is important, however to keep the following words of Tudge (1993) in mind.

> No analogy works exactly, however. There is nothing quite like life except life itself. (Tudge, 1993, p. 84)

Each of these analogies has strengths and weaknesses for the constuction of my gene conception. Together, however, and presented with the associated critique, I hope the strengths are maximised and the weaknesses minimised to create an image as close as possible to "life itself".

In summary, I see genes as small entities in the nucleus of cells that play an important role in inheritance, development and cell function. Their role is primarily carried out by the control of the production of proteins, including enzymes. Genes, along with other molecules make up chromosomes in the nucleus, like the links along a silver chain. However, the gene is a bewildering concept because it is not necessarily discrete like a link on a chain, nor does it have to be continuous, a gene can move and its function may not be clear cut. Genes are made of the chemical DNA which has a double helix structure that is like a twisted ladder. The rungs of the ladder are made of complementary base pairs that entail a code. The code is like the letters of the English alphabet, but there are only four, not 26. The code contains messages about how proteins can be manufactured. Genes manufacture proteins in a similar way to the production of a product in a factory. DNA is active, not passive like a blueprint, in the way it administers the cell's functioning. Rather than a blueprint, I see genes as being like recipes and transcription factors like chefs that decide which recipe to make. Suites of genes become active at different stages in an organism's life in much the same way that a computer program issues a series of instructions. The effect of genes on characteristics is similar to the effect of nitrogen on the growth of a wheat plant. It is not possible for a gene to single-handedly create a characteristic, like curly hair. Building curly hair is a "multi-gene cooperative enterprise" (Dawkins, 1989, p. 37) with influences from the environment. One gene may, however, tend to make the hair curlier than it would have been under the influence of an alternative allele.

This chapter is the first part of the literature review of this thesis. Here, we have travelled on a journey through the historical development of the concept of the gene and the researcher has shared with the reader her own conception of a gene. The next chapter, Chapter 3, is a continuation of the literature review, but the focus is on conceptual change, the theory of which is the foundation of the theoretical framework of this study.

CHAPTER 3

A LITERATURE REVIEW OF CONCEPTUAL CHANGE

> When thinking of conceptual change it is helpful to recognise that the same word "change" is used in different ways. One might talk, as in the fairy tale, of a frog changing into a prince when the princess kisses the frog. In this case, there is only one entity before and a different one after; the frog is no more after the change, there is only a prince. Here change means extinction of the former state. A second example might be Jane's savings account. Her money earns interest and the balance grows; she spends money and the balance falls. Here change means an increase or decrease in the amount of something. A third example might be an election for political office with the incumbent being beaten by the challenger: there has been a change of mayor. Both people continue to live in the city, but only one person is mayor. The incumbent loses status, while the challenger gains it. In this case, there is no extinction; change means an exchange of one entity by another. (Hewson & Hewson, 1992, p. 61)

Introduction

Of the many aspects that are debated in the conceptual change literature, nine issues are described and developed in this second part of the literature review of this study. The issues discussed are centred around the following questions: 1) What do researchers call conceptual change?, 2) What happens to initial conceptions?, 3) What is the status of students' conceptions?, 4) Is conceptual change revolutionary or evolutionary?, 5) Are conceptual changes global or domain specific?, 6) Is the age of the individual relevant to a theory of conceptual change?, 7) Is the nature of the content important when considering a theory of conceptual change?, 8) What teaching approaches are there for conceptual change?, and 9) What other factors influence conceptual change? By addressing each of these questions, the literature on conceptual change is reviewed and presented in a structure that is relevant to the research conducted in this thesis. Several of these issues have been discussed and published (Tyson et al., 1997) in a joint paper by the research group at the Science and Mathematics Education Centre.

Four research perspectives of learning have emerged from research into science education (Eylon & Linn, 1988). These four perspectives, which focus on different aspects of the learner and the processes of learning and instruction, are referred to as concept learning, developmental, differential and problem-solving perspectives. An examination of these perspectives reveals some common ground: The content of science and the manner in which links between ideas are organised play an important role in the learning process. The procedures used by the learner to represent and organise knowledge, and the learner's epistemology and ability level are all crucial factors that influence the manner in which students learn. The conceptual change model (Posner et al., 1982) forms a part of the concept learning perspective in which students' existing knowledge, as well as the content and characteristics of new ideas, has an important role in the learning process.

Conceptual change is a research agenda that evolved from the alternative conceptions movement that rapidly expanded during the 1980s (Wandersee, Mintzes & Novak, 1994). It differs from other learning theories in that it is an outgrowth of constructivist epistemology in which the growth of knowledge is viewed as a constructive process that involves actively generating and testing alternative propositions.

Posner et al. (1982) established a theory that attempted to explain how "people's central, organising concepts change from one set of concepts to another set, incompatible with the first" (p. 211). They proposed two types of conceptual change - *assimilation* which describes the process "where students use existing concepts to deal with new phenomena" and *accommodation* which describes when "the student must replace or reorganise his [sic] central concepts" (p. 212). In focussing on this second type of conceptual change, the authors describe four conditions that must be fulfilled for this type of change to occur. They also describe five features of a student's conceptual ecology that influence the conceptual change process.

A decade later, the theory was revised (Strike & Posner, 1992) due to the over-emphasis on rational aspects of learning in the initial theory and acknowledgment of the importance of affective and social issues for conceptual change. In this revision, Strike and Posner proposed a wider range of factors that needed to be considered when attempting to facilitate conceptual change learning. The set of features comprising the conceptual ecology of the learner was subsequently expanded (Strike & Posner, 1985, 1992), but the centrality of the conceptual ecology in the change process was most recognised in 1992. Strike and Posner (1992) introduced the notion that alternative conceptions may not necessarily pre-exist but "may be generated on the spot as a consequence of instruction" (p. 158). They point out that all parts of the conceptual ecology, including scientific conceptions and misconceptions, must be seen as dynamic and in constant interaction and development" (p. 160). A further revision in the 1992 paper was their acknowledgment of the active role played by social and motivational factors in the learning environment.

The original theory has received considerable attention in the science education literature and many studies have used it as a theoretical framework even though these studies rarely have focussed explicitly on the conditions of conceptual change (Hewson & Thorley, 1989). Many studies (Chi, Slotta & deLeeuw, 1994; Hewson & Thorley, 1989; Jensen & Finley, 1995) continue to examine the manner in which students' conceptions change and refer to the term 'conceptual change' as a theoretical framework. This is a crucial issue, as is shown later, because alternative theories of conceptual change have emerged along with new terminology. The goal of this chapter is to examine the main issues that are discussed in the conceptual change literature in order to set the scene for the theoretical framework for conceptual change that is developed in Chapter 5. The pilot study presented in the next chapter also utilises various theoretical perspectives of conceptual change and this chapter provides a comprehensive background for that piece of research.

What do Researchers Call Conceptual Change?

Before the term "conceptual change" is examined it is important to clarify the terms "concept", "conception" and "model". Throughout this thesis a concept is defined as "a conglomerate of connected ideas which can explain a certain class of problems or situations" (Schwedes & Schmidt, 1992, p. 188). Conceptions are defined as "tangible inside-head constructs" (Linder, 1993, p. 294) that are "fundamental beliefs about how the world works which individuals form in response to experiences and in concert with others" (Dykstra, 1992, p. 44). The difference between the two terms is that a concept is a general word to denote any number of connected ideas associated with a particular word, whereas a conception is the specific set of connected ideas that one person has at one particular time about a certain concept. Conceptual change is related to the changes that occur over time in the conceptions that a learner has for a particular concept. In Chapter 6 a series of models is presented. The term "model", in this situation, is used "to describe the content of thinking" (Bliss, 1995, p. 157). In other words, the models represent or describe a person's conceptions.

A review of the literature on conceptual change published through the eighties and early nineties reveals a range of associated terminology capable of confusing even the most devoted reader. Terms such as assimilation and accommodation (Posner et al., 1982; Strike & Posner, 1992; Smith, Blakeslee & Anderson, 1993), weak restructuring and strong restructuring (Carey, 1985), branch jumping and tree switching (Thagard, 1991), conceptual capture and conceptual exchange (Hewson & Hewson, 1992), differentiation and reconceptualisation (Dykstra, 1992), and enrichment and revision (Vosniadou, 1994) emerge from the conceptual change literature. Are these various terms recognising discernible differences in terminology for essentially the same aspect, or is there little consonance between the various terms used to describe conceptual change? To date, with the exception of Dagher (1994) who has overtly suggested that "while different terms are used to describe the types of change, these terms share common ground" (p. 608), few theorists have compared or even considered the similarities or themes that run through these different perspectives of conceptual change. In this first section, Dagher's comparison of the kinds of conceptual changes described by various theorists is extended and elaborated and the similarities and differences are discussed.

The most striking theme that runs through the various descriptions of conceptual change is that there are "big" changes and there are "small" changes. On closer examination of these descriptions, a dichotomy of two levels emerges, as illustrated in Figure 3.1. At the most basic level, there are changes which can occur to the conceptual structure which involve the simple addition of knowledge. This kind of conceptual change is described in various ways, either as rote memorisation (Hewson, 1981, 1982), as knowledge accumulation that does not involve restructuring (Carey, 1985), as enrichment by the mechanism of accretion (Vosniadou, 1994), or as belief revision (Thagard, 1991). Alternatively, there are changes to the conceptual structures which involve some kind of change to the existing conceptual structures rather than simple addition. This kind of conceptual change is also referred to in various ways, revision (Vosniadou, 1994), conceptual change involving more than mere belief revision (Thagard, 1992), and knowledge accumulation that involves restructuring (Carey, 1985). The latter kind of learning is most commonly described as conceptual change and is divided into strong revision and weak or lesser revision by most theorists (see Figure 3.1). Figure 3.2 extends Dagher's (1994) comparison of various descriptors for these degrees or kinds of conceptual change.

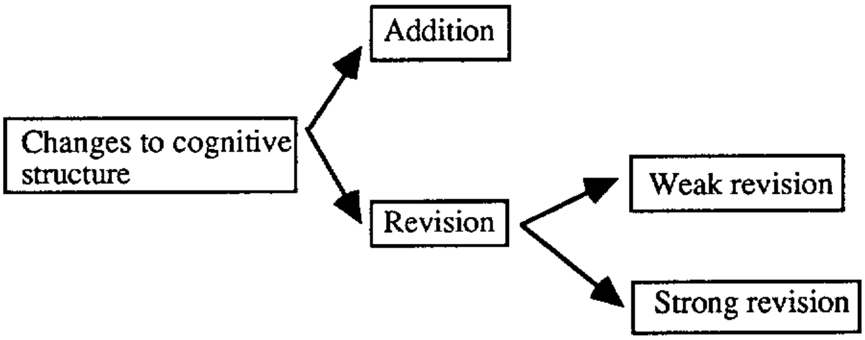


Figure 3.1: A generic model of the dichotomy of levels or kinds of conceptual change.

Thagard's (1992) description of conceptual change does not immediately seem to fit into this generic dichotomy because it is of a continuum of varying degrees of conceptual change as listed in Figure 3.2. He does, however, distinguish between the first three changes as "straightforward kinds of belief revision" (p. 115) and the last two changes as "holistic replacements" (p. 116), that is, "changes that are very difficult to make on a piecemeal basis" (p. 115) and in this sense they can be classified into similar degrees of conceptual change as the other descriptions.

White (1994a) distinguishes between the most basic level of addition of knowledge and revision or conceptual change (he uses the term "conceptional change"). He says that "additions are easy to teach and learn, and trivial in that they rarely involve reconstruction of the rest of your knowledge about the concept, let alone of other concepts" (p. 118). To learn that Indian elephants have the same number of toes on front and back feet while for African ones the number of toes is different is an example of addition of knowledge to the concept of "elephant". Conversely, White describes conceptual change as "major shifts, that typically involve detailed explanations of phenomena [that] ... have far-reaching effect on the total meaning we place on a term" (p. 118). An example of the revision kind of conceptual change is when a student learns how rainbows result from reflection, refraction and dispersion of light.

It is interesting that, as explained above, Posner et al. (1982) use the terms assimilation and accommodation to describe the weak and strong kinds of revision. Their work clearly and explicitly focused on the stronger kind of conceptual changes that they called accommodation and, in 1985, Strike and Posner reassert that their discussion of conceptual change is "more oriented to accommodation than to

Theorist Degree of Conceptual Change	Posner et al. (1982) Strike & Posner (1992)	Hewson (1981, 1982, Hewson & Hewson (1992)	Carey (1985)	Vosniadou (1994) Vosniadou & Brewer (1987)	Thagard (1992)	Chi et al. (1994)	White (1994)	Schwedes & Schmidt (1992)	Tiberghien (1994)	Dykstra (1992)
addition	accretion	rote memorisation	knowledge accumulation that does not involve restructuring	enrichment (accretion)	belief revision • add instance • add weak rule • add strong rule	no change in ontological membership of concept	addition	addition to pool of rules and ideas around nucleus (hard core of concept)	addition to experimental field of reference (experimental facts, devices and measurements	differentiation
weak revision	assimilation	conceptual capture	weak restructuring	revision at the level of specific theory	• add partial relation • add kind relation • add new concept	a concept's membership is shifted across parallel categories within a major ontological tree	conceptual change: change to the knowledge a person associates with a concept	pool of rules and ideas around nucleus (hard core of concept) is altered or cognitions in pool are attached to core concept	semantic conceptual change: deep modification of structuring of objects and events: but theory not radically changed	class extension
strong revision	accommodation	conceptual exchange	strong restructuring	revision at the level of framework theory	•branch jumping •tree switching	a concept's membership is shifted from one major ontological tree to another (eg. matter to process)	conceptional change (conceptions are systems of explanation cf. concept)	nucleus (hard core) of concept is completely changed for another	theoretical conceptual change: change at the theory level (explanatory system) especially causality	reconceptualisation

Figure 3.2: A comparison of language used by various researchers to describe degrees or kinds of conceptual change.

assimilation" (p. 216). In the 1985 paper, however, they say that "we regard the distinction between accommodation and assimilation as a matter of degree" (p. 216). Strike and Posner (1992) do not mention assimilation but describe accommodation as being equivalent to Piaget's notion of an accommodation in that it is "meant to apply to concepts that play a generative or organising role in thought" (p. 148). It is particularly confusing that Hewson (1981, 1982), who is a coauthor of the Posner et al. (1982) paper, refers to the weaker and stronger types of revision as "conceptual capture" and "conceptual change" respectively. Another confusing issue is that the Hewson (1981, 1982) papers were written after, but published before, the Posner et al. (1982) paper. So why did Hewson (1981, 1982) use different terms to Posner et al. (1982) to describe essentially the same thing? A footnote in Hewson's (1981) paper explains.

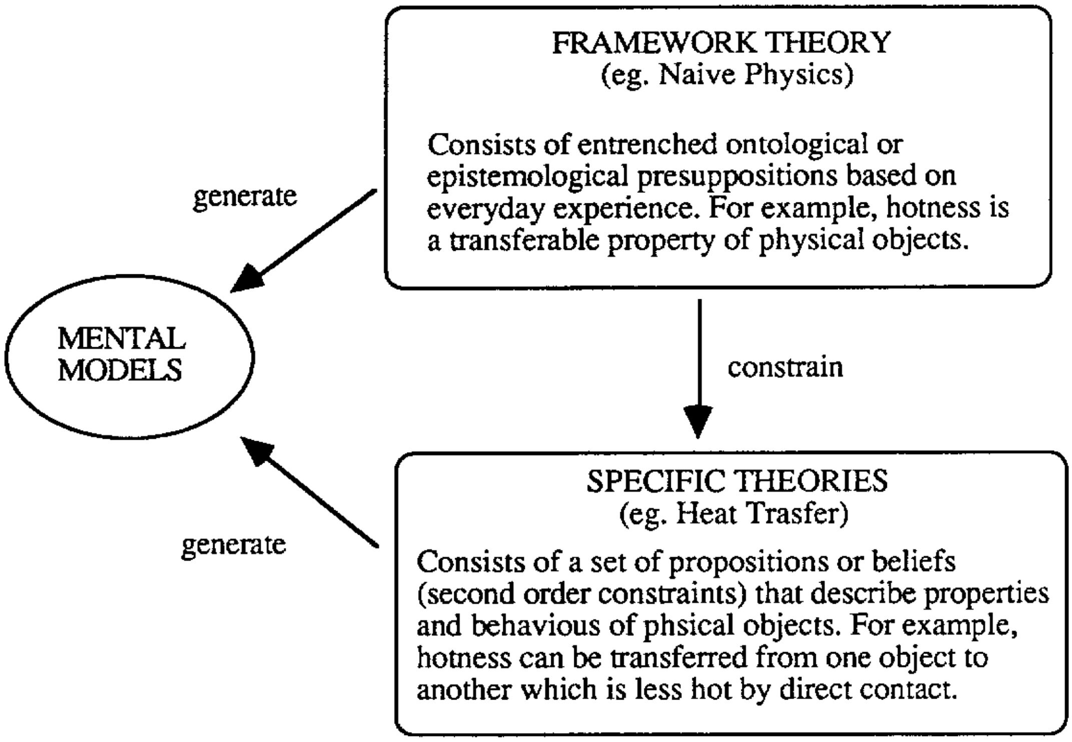
> PSHG [Posner, Strike, Hewson & Gertzog, 1982] used the terms 'assimilation' and 'accommodation' for conceptual capture and conceptual exchange respectively. They acknowledged that these are Piaget's terms, but indicated that in using them they intended no commitment in his theories. I have introduced the terms conceptual capture and conceptual exchange firstly to eliminate all confusion on this count and, secondly, because current dictionary usage places them closer to their intended meaning. (p. 386)

Hewson's claim to help "eliminate all confusion on this account" is debatable because the introduction of different terminology is confusing in itself. Another question also arises; is the difference between Hewson's ideas of conceptual capture and conceptual exchange simply a matter of degree, as was the difference between Posner et al.'s assimilation and accommodation? We can turn to the analogical parables, introduced at the beginning of this chapter, that Hewson and Hewson (1992) used to describe different kinds of change. Hewson and Hewson (1992) say that the second parable, that of Jane's saving's account, or increase - decrease change, is an example of conceptual capture - the weaker kind of conceptual change. The third parable Hewson and Hewson (1992) describe, the election of an new mayor, is said by them to represent conceptual exchange. But is not this example of exchange simply an extreme case of the increase - decrease kind of change that Hewson and Hewson describe as conceptual capture? Indeed we can see that it is. From these parables, therefore, it does seem that the distinction between conceptual capture and conceptual exchange, like the distinction between Posner et al.'s assimilation and accommodation, is simply a matter of degree.

Not only are there differences between the Posner and the Hewson descriptions of different degrees of conceptual change, Figure 3.2 displays a wide range of other terminology that can be found in the literature. The likely reason why there is such a range of terminology for the different degrees of conceptual change can be traced back to each of the theorist's background commitments and theories of conceptual structures. For example, the Conceptual Change Theory (Posner et al., 1982; Strike & Posner, 1992) is based on an analogy between the construction of individual scientific understanding and the development of scientific theories and the related metaphor of the "science learner as a scientist" which permeate the works of scientific philosophers such as Thomas Kuhn and Imre Lakatos. It is suggested that scientists have a background of central commitments which organise their research; likewise students have a background of central commitments which organise their learning. Conceptual change occurs when these central commitments require modification. The scientists and the students alike must acquire new concepts and a new way of seeing the world. In this regard radical conceptual change or *accommodation* is analogous to Kuhn's scientific revolution.

Vosniadou (1994) argued in her theoretical framework that concepts are embedded within larger theoretical structures that constrain them; specific theories of a given conceptual domain are constrained by a global framework theory which consists of entrenched ontological or epistemological presuppositions. Because Vosniadou's theory of cognitive structures is built up around two levels, the specific theory level and the framework theory level (Figure 3.3), it naturally follows that her theory of conceptual change involves knowledge revision at each of these levels shown in Figure 3.2.

Thagard's (1992) description of concepts as complex computational structures that establish hierarchies is an important aspect of his perspective of conceptual change. Thagard's view of concepts, described as enriched but still far from a genuine theory, leads to the hypothesis that conceptual change can come in varying degrees. Rather than a hierarchy, Schwedes and Schmidt (1992) theorise that a "concept has a central nucleus, the hard core, and a pool of rules and ideas around it which are more or less connected with the nucleus" (p. 188). It logically follows, therefore, that Schwedes and Schmidt see changes that occur to the pool of rules and ideas as being revision of the weaker kind and changes that occur to the central nucleus, or hard core of a concept, as revision of the stronger kind (Figure 3.2).



Consists of entrenched ontological or epistemological presuppositions based on everyday experience. For example, hotness is a transferable property of physical objects.

Consists of a set of propositions or beliefs (second order constraints) that describe properties and behavious of phsical objects. For example, hotness can be transferred from one object to another which is less hot by direct contact.

Figure 3.3: Diagrammatic representation of Vosniadou's theoretical framework of cognitive structures.

It is perhaps unfortunate that each of the theoreticians has developed their own terminology, but it is equally valuable to appreciate that there is common ground between the various perspectives of conceptual change. Conversely, it is essential to establish the critical differences that occur between these theoretical perspective's of conceptual change. Examination of Figure 3.2 raises a further question; why has Posner et al.'s conceptual change model dominated the field of science education up to the present time? The answer possibly lies in the aspect of their work which explicitly takes into consideration students' epistemological commitments to their conceptions, providing the researcher with tools to work with by introducing the conditions of conceptual change, namely - intelligibility, plausibility, fruitfulness and dissatisfaction.

Creating links is an important feature of conceptual change theory, otherwise there is no difference between conceptual change and simple rote learning. Some process of evaluating the new ideas is important, and such an evaluation process is what makes Posner et al.'s conditions of conceptual change relevant to all types of changes. Posner et al. view conceptual changes from an epistemological and not just a knowledge perspective, and it is the epistemological perspective that makes it different from Carey's (1985) or Vosniadou's (1994) examination of conceptual change. Although Carey and Vosniadou are aware of student's epistemological commitments they do not explicitly consider changes in students' cognitive structures from an epistemological perspective. The conditions of conceptual change as proposed by the conceptual change theory (Posner et al., 1982) are discussed later in this chapter under the heading "What is the status of students' conceptions", and in Chapter 7.

A question which arises from this analysis so far is, at what level can we call changes to cognitive structures conceptual change? Posner et al. (1982) and Strike and Posner (1992) are firmly of the opinion that only revision of the strong kind, or what they call accommodation, can be considered as conceptual change. On the other hand, Hewson and Hewson (1992, p. 62), Hewson and Thorley (1989) and Thorley (1991) argue that much of the conceptual change theory can and should be applied to weaker revisions as well.

> Processes of conceptual capture and conceptual exchange are both examples of *conceptual change.* Conceptual exchange has gathered most of the attention in the recent literature, perhaps because it is difficult to achieve, and has only recently been seen to be important. Yet we believe that both are significant aspects of conceptual change, and have a common explanation in the terms of the conceptual change model. (Hewson & Thorley, 1989, p. 543)

Dagher (1994) supports this position and suggests that "restricting worthwhile conceptual change to the radical type is equivalent to restricting worthwhile science to revolutionary science" (p. 609). This researcher concurs with the view that both levels of revision be referred to as conceptual change and that the conditions of the conceptual change models are applicable to both these levels. Throughout this thesis, therefore, both the weak and strong forms of revision, but not addition (Figure 3.1), will be referred to as conceptual change. The broader term, learning, will be used to refer to all levels of changes described in Figure 3.1 that can occur to cognitive structures, including addition and revision.

What Happens to Initial Conceptions?

There appears to be a consensus that conceptual change is concerned with restructuring of existing knowledge but the perceived 'fate' of this existing knowledge has changed subtly over the past decade. The condition of dissatisfaction discussed by Posner et al. (1982) implied that a non-scientific conception held by a student would be replaced or extinguished if the four conditions of the conceptual change model were met. This inspired a number of teaching strategies including conceptual conflict instruction (Hewson & Hewson, 1984) designed to help foster dissatisfaction and remove alternative conceptions held by students. Many researchers are now of the view (Garnett, Garnett & Hackling, 1995; Gunstone, 1994) that cognitive restructuring may occur without extinguishing prior conceptions. Duit (1994) states "There is no single study listed in the leading bibliographies of research on students' conceptions ... in which a particular students' conception of the above deep rooted kind could be totally extinguished and replaced by a new idea ... old ideas basically stay 'alive' in particular contexts" (p. 8).

Indeed, Linder (1993) challenged conceptual change models that have students giving up one conception and adopting an alternative. For Linder, the importance of context in shaping a conception is paramount.

> Refinement is not, I argue, change; it is rather the active delimitation and extension of conceptions, in other words establishing boundary conditions (the context) for applicability. In science itself, there is much conceptual dispersion. It is the essence of context that facilitates divergent conceptualisation, for example, how else could we simultaneously conceptualise the very different concepts of time vis-a-vis Galilean and special relativity contexts? (p. 295)

Driver, Asoko, Leach, Mortimer and Scott (1994) suggest that a model of learning which involves the replacement of old conceptions with new ones ignores the possibility of students having multiple conceptions each of which may be useful in a particular context. Mortimer (1995) expands upon this by proposing the notion of a conceptual profile that makes it possible to use different ways of thinking in different domains and that a new concept does not necessarily replace an old one. Schwedes and Schmidt (1992) present a specific example of such a phenomenon in a case study of Marc who participated in a series of interviews and teaching lessons. The purpose of the case study was to investigate the conceptual change from the very common preconception in the domain of simple electric circuits of current consumption to the concept of an electric circuit where the interdependence of current, voltage and resistance is realised. Schwedes and Schmidt observed that after the intended conceptual change had taken place:

> [W]e can still observe Marc falling back to his old theories as he tries out his ideas to account for the different phenomena. The old concept of current consumption does not immediately vanish and in every new situation both the old and the new concept are in competition. However we can observe that when the old concept does not work, the new concept is quickly at hand. The

> more successful application of the new concept takes place, the more stable it becomes. (p. 199)

The observation by Schwedes and Schmidt that the old conception is not immediately extinguished and is in competition with the new conception clearly leads to a discussion of the status of competing conceptions.

What is the Status of Students' Conceptions?

Posner et al. (1982) focussed explicitly on the status of students' conceptions arguing that in order for a new conception to be incorporated into a student's schema, the status of the conception must be raised by fulfilling a number of conditions. The conditions necessary for conceptual change to occur are *dissatisfaction* with existing conceptions, *intelligibility* of the new competing conception, *plausibility*, and *fruitfulness*. Posner et al. imply that in raising the status of a new conception the above conditions will be fulfilled in a linear manner starting with the dissatisfaction of the existing scientific conception and proceeding through to the fruitfulness of the new conception. Hewson (1982) suggests that competing conceptions must both fulfil the conditions of intelligibility and plausibility before dissatisfaction can be established with either of the conceptions. For Hewson, dissatisfaction is the key to the change in status of a conception. The descriptors - dissatisfaction, intelligibility, plausibility and fruitfulness - are used in Chapter 7 to classify the status of students' conceptions of the gene concept. Within the context of this study, therefore, a more detailed description of these terms is presented in Chapter 7, where it is directly related to the analysis of the data.

The issue of changing status of conceptions also has arisen with the more recently published literature on multiple representations (Spada, 1994) and the notion of a conceptual profile (Driver et al., 1994; Mortimer, 1995). Caravita and Halldén (1994) use the phrase "flickering status of conceptions" to describe the manner in which an individual will select a conception that is appropriate to a particular context. They describe change as involving "a set of ways of thinking about a conceptual domain, which are elicited in specific contexts of action and discourse. It results in an opportunistic differentiation among contexts of interpretation" (p. 89). Two questions that need to be addressed by conceptual change researchers relating to the status of students' conceptions include: How can the change in status of a conception be measured?, and How static is the status of a scientifically correct conception once it has been achieved?

For many researchers, the change in status of a conception is measured in terms of whether or not it is a part of the student's knowledge schema. If a student draws a solid sphere as a model of the atom in a pre-test and then following instruction draws a nucleus surrounded by spherical orbits then the status of the ball conception may be labelled as low and the 'orbital' conception as high. This type of change would be labelled conceptual change by many researchers. Other researchers (Hewson & Thorley, 1989; Treagust et al., 1996) examine the epistemology of the students' conceptions in terms of the conditions of the conceptual change model in order to determine status. For example, a conception that a student considers to be intelligible, plausible and fruitful is of high status whereas a conception that is only intelligible is of low status. For researchers using this epistemological perspective, conceptual change occurs when a new conception has fulfilled the intelligibility, plausibility and fruitfulness conditions.

The early work on conceptual change assumed that prior conceptions held by the learner would be eliminated perhaps through a process of creating dissatisfaction in which the student questioned the fruitfulness of the existing conception. The status of the existing conception would be lowered and then the process of raising the status of the new conception would begin. A successful student would be viewed as one who had low status for alternative conceptions and high status for scientifically correct conceptions.

Published theoretical papers on conceptual change that propose the existence of multiple explanations (Mortimer, 1995) and empirical studies that demonstrate the co-existence of scientific and everyday explanations (Scott, 1992) raise the possibility of the status of conceptions being more fluid than was originally implied. An extract of an interview cited by Scott highlights this possibility:

> Sharron was interviewed about the relative status of her original (macroscopic, continuous) and developing particle ideas:
>
> Teacher: Which of these two explanations [macroscopic or particle] do you think you'd be inclined to use, you know in everyday life?
> Sharron: Erm, that one [macroscopic].
> Teacher: The first one you did?
> Sharron: Mmm. To someone who's er, sort of, don't know...like if I were talking to my mum or summat should I say sort of particles she wouldn't really know what...
> Teacher: So are you saying that you, you wouldn't give up that kind of explanation ?

Sharron: Well not to someone who...em, didn't know what the, it means. Like say my mum or someone. (p. 222)

Sharron explicitly told her teacher that she would use her macroscopic explanation if she was talking with her mother in an everyday situation even though she found the particles explanation a better one in the more scientific context. Evidence like this excerpt from Sharron's interview demonstrate the coexistence of everyday and scientific conceptions and suggests a certain fluidity that allows the status to change in different contexts.

Is Conceptual Change Revolutionary or Evolutionary?

The question of whether conceptual change, particularly that of the strong kind, is revolutionary or evolutionary is an interesting debate. The question probably arose in the first place because Posner et al.'s (1982) original theory of conceptual change was formed from an analogy with Kuhn's work on scientific revolutions. In addition, Posner et al.'s description of a student's successful accommodation of special relativity may have suggested a fairly straight forward linear process; however, this was purposefully oversimplified. As an example of the revolutionary kind of conceptual change, Schwedes and Schmidt (1992) described the process of accommodation of Ohm's concept of electricity over the incorrect consumption theory in a case study of a student, Marc. Schwedes and Schmidt describe a concept as consisting of a cental "nucleus" which is the same for all individuals holding that concept and a pool of rules and ideas around it which can vary from individual to individual. They concluded from the study that:

> To achieve conceptual change through teaching, it is important to know the structure of the old and the new concept including the nature of their nuclei. Conceptual change then means changing the concept's nucleus. Conceptual change is not an evolutionary process, in small steps, from one concept to the other, but it means the installation of a totally new cognition. (p. 199)

In contrast to Schwedes and Schmidt's (1992) revolutionary view of conceptual change, Posner et al. are careful to point out that they see conceptual change as "radical but not abrupt" (p. 223). For them, accommodation is best thought of as a gradual adjustment of conceptions where the end result is a substantial reorganisation in the learner's central concepts. They do not see a logical progression from one commitment to another, rather they speak of "much fumbling about, many false starts and mistakes, and frequent reversals of direction" (p. 223). In the same vein, Nussbaum (1989) discusses Toulmin's historical description of evolutionary conceptual changes in science which is contrary to Kuhn's revolutionary perspective.

Nussbaum believes Toulmin's description best reflects his own research where "[t]he records of each study's conceptual change suggest that it forms an evolutionary pattern in which the student maintains substantial elements of the old conception while gradually incorporating individual elements from the new one" (p. 288).

Vosniadou (1994) also does not see conceptual change as a sudden shift from one theory to another, but a continuous process which happens to the framework theory. For Thagard (1991), the level at which conceptual change occurs determines whether it is part of an evolutionary or a revolutionary process. Adopting a new conceptual system as in tree switching or branch jumping (Thagard's strong kinds of conceptual change) is seen by him to be more holistic and revolutionary than the evolutionary change made up of piecemeal belief revision such as adding a new instance or weak rule (weaker conceptual change). Villani (1992) suggests that students and scientists change portions of their theories one at a time, and that in time, these changes manifest themselves as theory changes: "minor changes gradually introduced into guiding assumptions may turn out to be very important ... a real conceptual change" (p. 228).

In a similar vein to Villani, Duschl and Gitomer (1991) argue for a developmental view of conceptual change that is consistent with studies in the history of science that have documented changes that are piecemeal in character rather than global and holistic. Such a perspective, according to Duschl and Gitomer, would offer "different criteria for deciding what to teach and how to teach" (p. 839). To this end, Duschl and Gitomer develop a broadened and integrated view of assessment and instruction that they call a *portfolio culture* that creates opportunities for teachers and students to confront and develop their scientific understanding.

Concept substitution (Grayson, 1996) is also more evolutionary than revolutionary because it emphasises changing the faulty items in the student's conceptual ecology. Concept substitution is a strategy for promoting conceptual change that encourages the student to substitute an incorrect physics term they have for a correct intuition. For example, Grayson suggests students can substitute the term "heat transfer" for the intuition they call "temperature" when they recognise that a block of aluminium feels colder than a block of wood. The focus of this strategy is not on trying to remediate "incorrect" ideas but rather to "help students place their correct ideas into an acceptable scientific framework" (p. 160). Earlier, Hashweh (1986) took a similar stance observing that many items in the conceptual ecology were acceptable, the issue was to find and change the discordant pieces. Duit (1995) describes conceptual change as ranging on a scale from revolution to evolution and suggests that "major reconstruction of the already existing conceptual structure may be avoided and substituted by [a] process of continuous differentiation of key issues" (p. 9). Consequently, the rapidity and intensity of conceptual change is likely to be dependant on other factors such as the instructional strategies utilised and the nature of the content.

Are Conceptual Changes Global or Domain Specific?

Are conceptual changes only relevant to the domain of content that they were made in or do they have implications for the kind of thinking and reasoning students have in other areas? In other words, can conceptual changes be global or can they only be domain specific? This question has its roots in Piaget's well known ideas about general reasoning and his stage theory of cognitive development where changes from pre-operational to concrete operational or from concrete operational to formal thinking were thought to affect the organisation of knowledge in all specific domains. According to Bliss (1995), "Piaget never intended his stage theory to be the most important aspect of his work" (p. 147) and this aspect of his work, as well as others, has been challenged in many regards. One of these challenges has been a realisation that domain-specific knowledge is important rather than general schemes (Bliss, 1995). Metz (1995) also challenges the Piagetian assumptions of science curricula at the primary school level for emphasising "concrete" activities such as observation, ordering and categorisation. Metz suggests that this practice has its roots in ideas about developmental constraints on children's thinking and contends that when a close examination is made of both Piagetian and non-Piagetian literature they support the feasibility of children's science including abstract ideas and the planning of investigations and analysis of results.

Carey (1985) critiques Piaget's theory of operational development because she believes that Piaget and his colleagues accept evidence to support domain-general changes when in fact they reflect domain-specific structural reorganisations. She does not argue that there are no domain-general changes in the developing child's conceptual system, rather she outlines four different kinds of domain-general conceptual changes (Carey, 1983). She does, however, claim that domain-specific changes need to be studied in their own right, and this would be the key to understanding general developments. Carey (1983) describes concepts such as causality and the appearance-reality distinction and refers to them as foundational concepts in a range of domains, pointing out, however, that the development of these foundational concepts is intricately tied to the domain-specific theory changes. She therefore denies that "immature notions of causality, in general, place any domain-independent constraints on the conceptual structures of children of young ages"

(Carey, 1985, p. 194). Keil (1991) concurs with this perspective and argues that evidence for "shifts across all domains is hard to come by, it seems much easier to make the case on a domain-by-domain basis" (p. 241). That is, he believes that domain-general changes do occur, "but contrary to older accounts, it does not occur at the same time for all concepts" (p. 241).

Perkins and Salomon (1989) examine the research over the past 30 years that has addressed the question of whether cognitive skills, such as problem solving, decision making, and insightful invention, can be said to be general strategic knowledge or specialised domain knowledge. They found that the literature sways from the generalist to the specialist perspectives and then hovers somewhere in between. Perkins and Salomon conclude that it is difficult to separate the two, that is, "all specific applications of anything general need to configure to the context" (p. 23). The implications of this position for education, according to Perkins and Salomon, are that there needs to be "intimate intermingling of generality and context specificity in instruction" (p. 24). That is, attempts to teach general cognitive skills should focus on bringing together context-specific knowledge with general strategic knowledge. "It gets beyond educating memories to educating minds, which is what education should be about" (p. 24). These findings raise questions for the conceptual change research agenda. For example, is the capacity to undergo conceptual change a general cognitive skill that can be applied to different contexts?; is it possible that some students are more open to conceptual change and can apply this skill in different contexts? Currently, there are no answers to these questions, but the literature certainly suggests that these would be worthwhile questions to investigate.

Is the Age of the Individual Relevant to a Theory of Conceptual Change?

Throughout the lifespan of an individual, there are periods that may be characterised by the development of different physical and cognitive skills. A sketch of these developmental periods might be as follows: Infancy (birth to 18 months), early childhood (18 months - 6 years), childhood (6 - 12 years), adolescence (12 - 17 years), early adulthood (17 - 40 years), middle adulthood (40 - 60 years) and late adulthood (60 + years) (Biggs & Telfer, 1981). There is increasing differentiation and integration of concepts as the cognitive structure grows and a cyclic form of development with periods of stability followed by instability is evident (Levinson et al., 1978).

Piaget categorised the development of intelligence from birth to age 15 years in four stages: a sensorimotor period from birth to age 2 years; preoperational from 18 months - 7 years; a concrete operations period from ages 7 to 11 years; and the commencement of formal operations ranging from ages 11 to 15 years. These age ranges are only approximate and have been subject to criticism, but the sequence of development is assumed to occur in every child. Indeed, a common interpretation of Piagetian theory that concrete operational thinkers reason on the basis of the perceptual and concrete has turned out to be challenged as preschoolers have been found to be able to reason on the basis of 'deep structural principles' when they have the requisite domain-specific knowledge (Metz, 1995). In Piagetian terms, the stage of formal operational thought is achieved when an individual is able to think about and form theories. Lawson (1994) has suggested that this stage might be characterised by reflective thinking whereby the individual is able to consider alternative theories and consider which is the most acceptable.

Perry's Model of Intellectual Development (Finster, 1989) expands upon this notion of adults' reflective thinking capacities. Perry describes a series of stages that individuals pass through as they move towards intellectual maturity. The first of these is referred to as *dualism* in which a student perceives that there is one correct answer to a problem, that truth is absolute and that uncertainty is temporary. Knowledge is considered to be right or wrong. In the second stage of *multiplism,* diversity and uncertainty are accepted and individuals are entitled to their own opinions. Then there is a period of *relativism* in which the student recognises that knowledge is contextual and relative. These first three positions are mainly concerned with epistemology and intellectual development whilst the final stage *commitment in relativism* is concerned with ethical issues and identity development.

If it is accepted that an individual's cognitive structure changes both qualitatively and quantitatively with increasing age (Bodner, 1986) then what are the implications of this for a generalised theory of conceptual change? Would Posner et al.'s (1982) conditions of intelligibility, plausibility and fruitfulness be applicable to all types of conceptions across all age groups? For individuals who have achieved a relativist stage of intellectual development, it may be that the status of their conceptions change depending upon the context in which they are operating. It would seem reasonable that as an individual develops his or her intellectual capacity, the importance of the metaphysical aspects of conceptual change will increase. If this is the case, then the age of an individual must be relevant to a theory of conceptual change.

Is the Nature of the Content Important for Conceptual Change?

The alternative conceptions movement has generated an interest in the content of science with an intense research effort that has focussed on the development of students' understandings of specific natural phenomena and scientific principles. White (1994b) has suggested that it is now time to consider a theory of content that distinguishes between different types of science content and explicates how each type may best be taught and learned. White identified an initial list of properties of content that may be important determinants of the teaching and learning of specific content areas. These properties are: openness to common experience, abstraction, complexity, presence of alternative models with explanatory power, presence of common words, mix of types of knowledge, demonstrable vs arbitrary, social acceptance, extent of links and emotive power. These suggestions have implications for a generalised theory of conceptual change, if indeed such a theory is possible. If the teaching and learning in specific content areas differs to some degree from others, then is the nature of the conceptual changes that occurs in each of these areas going to be the same?

Each of the properties of content that White (1994b) discusses may be important determinants of the kind of conceptual change that is required for the learning of a specific content area. For example, content that is not open to common experience must be made intelligible to students through some strategy other than reliance on the students' prior experience. Such strategies might include the use of models, diagrams, role plays or analogies as examined in three studies by Dagher (1994). Dagher suggests that a narrow conceptualisation of conceptual change may be the reason why analogies have sometimes been found to only have a modest contribution to conceptual change. In order to give a fair evaluation of the role of analogies in the process of conceptual change, Dagher suggests that researchers should also examine propositional and procedural knowledge and the affective and creative processes.

> The influence that analogies might have on "humanising" science is just as worthy of an outcome to explore as is any anticipated change in the scientific concepts themselves. (p. 611)

When the nature of the content is not open to common experience and models are to be used to help students understand the content, then a logical conclusion is for students to have well developed modelling abilities. Underdeveloped modelling abilities consistent with a naive realist epistemology were found in Grade 7 and Grade 11 students by Grosslight, Unger, Jay and Smith (1991) compared with experts who expressed ideas consistent with a constructivist framework. The high school students were more likely to think of models as copies of reality than as constructed representations of theoretical perspectives. The students' ideas about models did, however, become more sophisticated by increasingly including the idea that models have a purpose. Grosslight et al.'s study suggests that there is the possibility that high school students may see models presented by teachers as miniature copies of reality. These authors concluded that students need more experience with models and particularly with using models to solve intellectual problems and multiple representations of the same phenomena so that they are likely to develop a richer conception of models.

Another dimension of the content that White (1994b) refers to as "complexity" is the level of coherence and the number of concepts and principals in a topic. Fensham, Gunstone and White (1994) go further to claim that links between these concepts and principals are necessary for conceptual change to take place. Alternatively, when a content area has a high level of complexity, then linkage between concepts within the content is likely to be a criterion for conceptual change to take place because "the more complex the content, the greater the need to attend to integrating it and to showing and to perceiving its unity" (White, 1994b, p. 258). Whereas, if a content area has a low level of complexity, linkage is not as likely to be as important for conceptual change to take place.

A third and important dimension of content that White (1994b) proposes is demonstrable and arbitrary features needed to differentiate between propositions that are observable and those that cannot be proved by demonstration. Such a dimension may indeed have consequences for conceptual change; for example, children are more likely to respond "I don't know" when asked about a biological concept such as the function of the heart whereas for physical science concepts they are likely to hold some robust alternative conception (Chi et al., 1994). In a similar way to White's ideas about demonstrable and arbitrary propositions, Lawson (1994) has distinguished between the construction of descriptive concepts, for which defining attributes are observable, and theoretical concepts, for which defining attributes are not directly observable.

The different levels of representation in chemistry content (Bucat & Fensham, 1995) place demands on students who are expected to switch between three levels of representation - macro-visible behaviour; sub-microscopic, explanatory abstractions; and symbolic descriptions in the form of chemical formulas and equations. It is possible that if the nature of the content can be represented at different levels, this may influence the conceptual changes that occur in that content area. For example, a student may need to be able to recognise and work with the different levels of representation before conceptual change can take place, or the ability of a student to switch readily between these different levels of content may constitute a kind of conceptual change in itself. Conversely, would the inability of students to distinguish between the different levels of representation inhibit the conceptual change process?

A theory of conceptual change proposed by Chi et al. (1994) explicitly suggests that the nature of the content of science is a dominant feature that influences the conceptual change process. They proposed that scientific concepts belong to three or more distinctly different ontological categories - matter, processes and mental states. Chi et al, see the categories as being different from each other in a metaphysical sense and that when a student places a scientific concept such as electricity from one category to another, this represents a change in an individual's ontology. It could be argued that these categories are not just relevant to ontology. The categories could represent concepts that have different attributes; for example, concepts in the matter tree may be more concrete than abstract or more descriptive than theoretical than those in the process or mental states trees. Therefore, is it possible that the conceptual changes involved in learning about electricity or weight might be different from those required when learning about mass or density because the concepts have different attributes and belong to different ontological categories.

The issues relating to the nature of content raised by Chi et al. are as important as those related to metaphysics. Spada (1994) has suggested that a common position taken by a number of leading theorists in the field is that "a detailed description of the process of conceptual change in specific subject matter areas is the way to reach a better understanding of this process" (p. 114). He questions the plausibility of "one coherent and stable theory" that explains conceptual understanding and argues that Vosniadou's claim of a consistent mental model of the Earth, which is a concrete object, may not be transferred to an abstract notion such as force. Spada raised the possibility of the fruitfulness of the use of multiple mental representations of abstract concepts that can be selectively applied in appropriate contexts noting that in problem solving individuals have several strategies available between which they switch on a problem-by-problem basis.

What Teaching Approaches are there for Conceptual Change?

Overviews of conceptual change teaching approaches outlined and evaluated in the science education research literature have been presented by Duit (1994), Scott, Asoko and Driver (1992), and Smith, Blakeslee and Anderson (1993). The first two of these papers make similar distinctions between conceptual change pedagogical strategies which emphasise conceptual conflict and the resolution of the conflict by the learner and those strategies which build on learners' existing knowledge structures and extending. Duit refers to these strategies as discontinuous and continuous (Figure 3.4). Continuous pathways "start from aspects of students' conceptual structures that are already mainly in accord with the science conceptions or reinterpret students' ideas" (Duit, 1994, p. 11). Examples of this kind of strategy discussed by Duit or Scott et al. (1992) include bridging analogies to promote the learning within the field of mechanics (Brown & Clement, 1989), the use of analogical relations to help students understand the conservation of matter during evaporation (Stavy, 1991), and allowing students to arrive at a conscious understanding of the differences between everyday-life thinking and scientific thinking (Schecker & Niedderer, 1996).

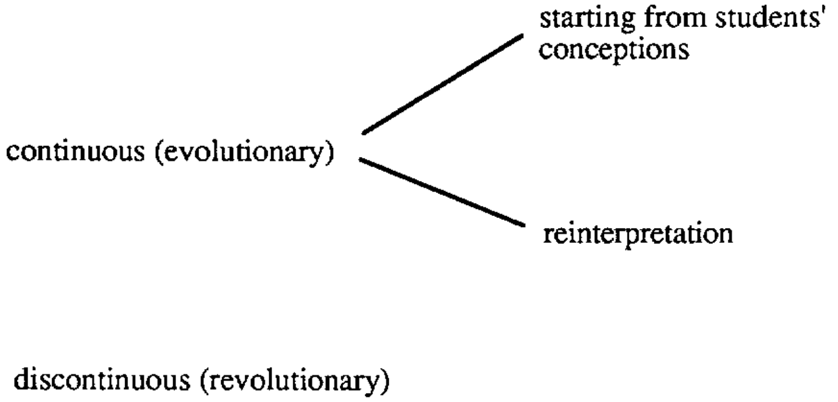


Figure 3.4: Pathways from students' conceptions towards science conceptions (from Duit, 1994, p. 22).

In the case of reinterpretation (Figure 3.4), resemblances between students' preinstructional conceptions also are the starting point but they are interpreted in a new way. In this case, the students are not told that their conception is wrong but they are told that what they have in mind can be referred to as something else. Examples of this strategy include Grayson's (1996) concept substitution illustrated in electricity and heat and temperature, and McDermott's (1984) conceptual change strategy where students are encouraged to reinterpret their pre-Newtonian notions of force as momentum.

Teaching strategies that follow a discontinuous pathway involve

> promoting situations where the student's existing ideas about some phenomenon are made explicit and are then directly challenged in order to create a state of cognitive conflict. Attempts to resolve this conflict provide the first steps to any subsequent learning. (Scott et al., 1992, p. 312)

Examples of this kind of conceptual change teaching strategy include the "Learning Cycle" (Lawson, Abraham & Renner, 1989), the "Constructivist Teaching Sequence" (Driver, 1989), a conceptual conflict teaching sequence which draws upon the Piagetian notion of accommodation (Nussbaum & Novick, 1982) and a "Generative Learning Model of Teaching" (Cosgrove & Osborne, 1985). For a more comprehensive review of these teaching strategies refer to Duit (1994), Scott et al. (1992) or Smith et al. (1993).

The demands upon the teacher for teaching for conceptual change are discussed by Scott et al. (1992) and they conclude that a teacher is required to:

- be aware of students' ideas and understandings relating to the topic under consideration.
- be aware of likely conceptual pathways for that topic.
- be sensitive to students' progress in learning.
- be able to generate learning tasks to support and encourage that progress in learning.
- be sufficiently confident in his/her own understanding of the subject topic to be able to appreciate, and respond to, differing points of view.
- be able to organise and manage a classroom which will allow for all of this to happen. (p. 327)

Research has shown that in classes where teachers use conceptual change-oriented instructional materials, students tend to perform better on post-tests and have higher performance on tests designed to assess conceptual change learning (Smith et al., 1993). However, implementing such strategies is not an easy task for teachers. Results from the same study showed that teachers need support from appropriately designed curriculum and instructional materials for successful implementation of conceptual change teaching strategies (Smith et al., 1993).

What Other Factors are Related to the Process of Conceptual Change?

In this discussion so far, factors that may influence conceptual change such as the age of the student and the nature of the content have been discussed. There are other factors that have been discussed in the literature that also need to be mentioned here. Posner et al. (1982) discuss students' conceptual ecology (Figure 3.5). The components of the conceptual ecology were said to influence the selection of a new central concept and thus are important determinants of the direction of an accommodation.

One criticism of the conceptual change model of Posner et al. and Strike and Posner (1985, 1992) is that it is overly rational and focuses only on student cognition without considering the influence of students' motivational beliefs and classroom contextual factors on conceptual change (Pintrich, Marx & Boyle, 1993). For these reasons it is interesting to compare and contrast Pintrich et al.'s views with Posner et al.'s views of the classroom, contextual, motivational, and cognitive factors that they see as being related to the process of conceptual change (Figure 3.6).

Pintrich et al. present a much broader range of factors that are related to the process of conceptual change, such as the authenticity of tasks presented in the classroom, the kind of evaluation, the level of personal interest and self-efficacy as well as cognitive factors such as prior knowledge and metacognition (Figure3.5 and 3.6). The importance of metacognition for conceptual change also is discussed by Gunstone (1992) and Baird and White (1996). Gunstone asserts that conceptual change in students' ideas and beliefs about learning is just as important as conceptual change in science content. He says that students' transmissive views about learning and the passive role they play in this process are substantial barriers to improved metacognition. Gunstone (1992) and Baird and White (1996) report on the Project to Enhance Effective Learning (PEEL) and the Teaching and Learning Science in Schools (TLSS) projects. The implications from both projects are that conceptual change "requires that learners be willing and able to recognize, evaluate, and, if necessary, reconstruct existing ideas and beliefs" (Gunstone, 1992, p. 138) and that "time, opportunity, guidance and support must be made available if students, and teachers are to ... develop appropriate metacognitive strategies" (Baird & White, 1996, p. 199).

1) Anomalies:	The character of the specific failures of a given idea are an important part of the ecology which selects its successor.
2) Analogies and metaphors:	These can serve to suggest new ideas and to make them intelligible.
3) Epistemological commitments:	a) Explanatory ideals: Most fields have some subject matter-specific views concerning what counts as a successful explanation in the field. b) General view about the character of knowledge: Some standards for successful knowledge such as elegance, economy, parsimony, and not being ad hoc seem subject matter neutral.
4) Metaphysical beliefs and concepts:	a) Metaphysical beliefs about science: Beliefs concerning the extent of orderliness, symmetry, or nonrandomness of the universe are often important in scientific work and can result in epistemological vies which in turn can select or reject particular kinds of explanations. Such beliefs played a large role in Einstein's thought. Beliefs about the relations between science and commonplace experience are also important here. b) Metaphysical concepts of science: Specific scientific concepts often have a metaphysical quality in that they are beliefs about the ultimate nature of the universe and are immune from direct empirical refutation. A belief in absolute space or time is an example.
5) Other knowledge:	a) Knowledge in other fields. b) Competing concepts: One condition for the selection of a new concept is that it should appear to have more promise than its competitors.

Figure 3.5: The conceptual ecology from Posner et al. (1982), pp. 214-215.

Classroom contextual factors	Motivational factors	Cognitive factors	Conditions for conceptual change
Task structures	Mastery goals	Selective attention	Dissatisfaction
Authentic			
Challenging	Epistemic beliefs		
Authority structures		Activation of prior knowledge	Intelligibility
Optimal choice			
Optimal challenge	Personal interest		
Evaluation structures	Utility value	Deeper processing Elaboration Organisation	Plausibility
Improvement-based			
Mistakes as positive	Importance		
Classroom management		Problem finding and solving	Fruitfulness
Use of time	Self-efficacy		
Norms for engagement			
Teacher modelling		Metacognitive evaluation and control	
Scientific thinking	Control beliefs		
Scientific dispositions			
Teacher scaffolding		Volitional control and regulation	
Cognition			
Motivation			

Figure 3.6: Factors related to the process of conceptual change (Taken directly from Pintrich et al. 1993, p. 175).

Note: The Pintrich et al. (1993) paper does not suggest an horizontal relationship between the items listed in the columns of this figure.

Even though Pintrich et al. (1993) are more explicit about motivational factors, as noted in the early part of this chapter, Posner et al. (1982) do not discount motivation in conceptual change.

> Our cental commitment in this study is that learning is a rational activity. That is, learning is fundamentally coming to comprehend and accept ideas because they are seen as intelligible and rational. ... It does not, of course, follow that motivational or affective variables are unimportant to the learning process. The claim that learning is a rational activity is meant to focus attention on what learning is, not what learning depends on. (p. 212)

The debate over the rationality of learning and the role of motivation and affective factors in conceptual change is one that continues in the research literature. This debate has directly influenced the development of the theoretical framework for conceptual change that is used in this thesis and therefore is discussed in more detail in Chapter 5.

Summary and Conclusions

In this chapter, nine key issues influencing the conceptual change research agenda have been discussed in order to synthesise the theory building and empirical collection of data that has occurred over the past decade and a half. So where does the researcher of this study stand with regard to these issues? What is conceptual change? In this study, weak revisions as well as strong revisions are included in the description of conceptual change; it seems that in some situations a revolutionary realisation is required for students to fruitfully apply a scientific theory to a problem; in other situations a gradual adjustment process results, in the end, in a significant conceptual change. These contrasting situations and all the combinations and permutations that may exist between them are considered in this study to be significant for a conceptual change research agenda. Conceptual change does not imply that initial conceptions are "extinguished". Initial conceptions, especially those that hold explanatory power in non-scientific contexts, may be held concurrently with new conceptions. Successful students learn to utilise different conceptions in appropriate contexts. That is, the status of one particular conception may change in differing contexts.

Conceptual changes can be relevant to only one specific content area or domain, or they may be relevant across all content areas, that is, they are domain-general. Researchers should be aware that domain-general changes, such as a change from dualism to multiplism in Perry's model of intellectual development (as reported in

Finster, 1989, 1991), may not necessarily be incorporated across all domains concurrently. For domain-specific research, the nature of the content is important when considering conceptual change as there are several properties of content that are important determinants of the kind of conceptual change that may take place. The age of an individual is relevant to a study of conceptual change if it is assumed that, in most cases, intellectual capacity increases with age. This occurs because the importance of metaphysical aspects of conceptual change increase with the development of an individual's intellectual capacity. Factors in the students' conceptual ecology as well as motivational and classroom contextual factors are likely to be important in influencing conceptual change. Teaching approaches to engender conceptual change can emphasise conceptual conflict and the resolution of the conflict by the learner or build on learners' existing knowledge structures.

To date, a surprisingly small amount of research has been conducted on conceptual change in the field of genetics, and that is a good rationale for investigating the genetics content in this thesis within a framework of conceptual change. There is a body of literature that discusses factors influencing learning in genetics, however, and these research papers are discussed in detail in the introduction to Chapter 8 where the factors influencing conceptual change about the concept of the gene are addressed.

A journey metaphor for conceptual change approaches to teaching is developed by Scott et al. (1992).

> A comparison of a student's existing conceptions with intended learning outcomes provides an overview of the desired conceptual change and gives some indication of the extent and nature of the intellectual journey which the learner must make. (p. 326)

Part of the purpose of this thesis is to make available information to teachers about the "intellectual journey" that the learner must make when learning about the concept of the gene. To provide a context for this journey, nine salient aspects of a conceptual change view of learning have been elaborated in this chapter.

This summary concludes the literature review of conceptual change and has provided background information for the Pilot Study and the larger investigation that constitutes the main part of this thesis. Chapter 4 presents the pilot study in which four different theoretical perspectives of conceptual change are utilised to analyse four teaching/learning situations in biology classrooms.

CHAPTER 4
THE ROLE OF ANALOGIES IN PROMOTING CONCEPTUAL CHANGE IN BIOLOGY

> The nature of the contribution of analogies to conceptual change is far from straight forward. (Dagher, 1994, p. 601)

Introduction

Conceptual change has been described from a multitude of perspectives. For example, from an epistemological perspective Posner et al. (1982) and Strike and Posner (1992) claimed that for conceptual change to occur, the status of the students' naive conceptions must be lowered and the status of the scientific conception must be raised. Chi et al. (1994) focus on the ontological category that the concept belongs to, and assert that many of the difficult concepts to learn in science require a change in the students' mind from a "thing" category to a "process" category. Pintrich et al. (1993) highlight the importance of motivation and the social aspects required for conceptual change to take place. It is easy to become overwhelmed by the literature in this field such that no matter how much you read, it is still difficult to answer the question, what is conceptual change? Few would argue that a radical change from a Newtonian to a relativistic view of mechanics or from a geocentric to a heliocentric view of the world as radical conceptual change. Recent literature, however, questions whether these wholesale, radical changes really do occur. For example, the idea that naive and scientific conceptions coexist and are used preferentially in different contexts has been suggested (Driver et al., 1994). The notion of conceptual change is blurred further when we look at Carey's (1985) work where she describes how children start with very little knowledge and slowly build up a theory of biology over a number of years. Can we call this slow, incremental construction of knowledge conceptual change? And what of the smaller changes that occur during this period? When does learning become conceptual change? The intention is not to answer these questions in this chapter. The point is, however, that when different classroom teaching and learning episodes including analogies are investigated for their contribution to conceptual change, one particular theoretical position of conceptual change best explains the learning taking place. This learning is dependent on the role of the analogy in the teaching-learning episode.

The purpose of this chapter which consists of the pilot study was to investigate the role that analogies play in conceptual change in biology. This investigation conformed with the initial purpose of this thesis which was to examine the role of analogies in conceptual change in genetics. As explained in Chapter 1, the purpose of the thesis changed to focus on conceptual change and the concept of the gene rather than the role of analogies in bringing about conceptual change. This pilot study was conducted in the early phases of the doctoral program, however, and the results, which are reported in Venville and Treagust (1996), have played an integral part in the development of the theoretical framework presented in the methodology section in Chapter 5. While this pilot study is an interesting and relevant piece of research in its own right, the most salient aspect for this thesis is the use of multiple perspectives of conceptual change to analyse classroom learning situations.

This pilot study was designed to examine the contribution that analogies can make to learning and to conceptual change in science, taking into account a range of theoretical positions about conceptual change. Dagher (1994) recommends such an examination "not only in relation to enhancing the development of specific concepts but also in promoting creative aesthetic appreciation, and positive attitudes" (p. 610). In this chapter the focus is on the role of analogies and their relationship with conceptual change in biology. Analogies can be seen as a process of identifying similarities and differences between two objects or processes for the purpose of explanation or extrapolation. Our research group's work on the use of analogies in science teaching has shown that they play various roles in the way they are used as a pedagogical tool. For example, it was observed that a wheels analogy was able to engender within some members of a class of Year 10 students a fruitful explanation of refraction of light (Treagust et al., 1995a). In another classroom, it was observed how a bookcase analogy helped Year 8 students to successfully visualise the abstract notion of energy levels of an atom (Venville et al., 1994). Other researchers have noted the different roles that analogies can play. For example, from a constructivist position, Duit (1991a) says that analogies can be useful pedagogical tools in that they are thought to help students construct new knowledge by linking it with knowledge structures they already have; analogies are valuable when trying to help students visualise abstract or unobservable phenomenon; and a sometimes overlooked advantage of teaching with analogies is their motivational role.

It is fascinating to marry the role that analogies play with interpretations of conceptual change from various theoretical perspectives. Indeed there appears to be more than a coincidental parallel between the different roles that analogies can play in the classroom and the differing theoretical perspectives of conceptual change. The purpose of this pilot study was to analyse four case studies involving teaching episodes in biology from four different theoretical perspectives of conceptual change and on the basis of this analysis to make assertions about the roles that analogies play in the promotion of conceptual change in biology.

Perspectives of Conceptual Change

In Chapter 3, several perspectives of conceptual change were shown to exist in the conceptual change literature. In this chapter, four perspectives used to analyse and interpret the data are those by Posner et al. (1982), Vosniadou (1994), Chi et al. (1994) and Pintrich et al. (1993).

One of the most influential theories of conceptual change in the field of science education has been the conceptual change theory (Posner et al., 1982; Strike & Posner, 1992) that classifies the status of conceptions as being intelligible, plausible and fruitful to the student. For conceptual change to occur, students first must be dissatisfied with old conceptions, and then the new ideas must meet the conditions of intelligibility, plausibility and fruitfulness to be successfully incorporated into their working conceptual framework. In this chapter, Posner et al.'s perspective of conceptual change is utilised to interpret the use of an analogy for developing intelligibility of a new concept.

Vosniadou's idea of mental models and their connection with the cognitive structures such as framework theories and specific theories is the aspect of her perspective of conceptual change utilised in this chapter. Vosniadou uses the term mental model to refer to a mental representation which is the focus during cognitive functioning (see Figure 3.3). Vosniadou claims that mental models are generated from the specific theories and framework theories an individual possesses. Analogies probably have a role to play in the generation of mental models and mental models "are the points at which new information is incorporated into the knowledge base" (p. 48). The issue explored later in this chapter is that of generating mental models or memory recall. Is it plausible that a person may prefer to use an analogy from a different, but more familiar context to generate a mental model in order to recall the desired concept?

A third theoretical perspective on conceptual change by Chi et al. (1994) argues that entities in the world belong to different ontological categories such as "matter", "process" and "mental states". For students to build the preferred scientific conception, according to Chi et al., they often need to shift the ontological status of the entity from one category to another. Chi et al. claimed that concepts which do not require the shift in ontological category are easy to learn and those which do are extremely difficult. In this pilot study, the role that analogies may have in precipitating the change of a scientific concept from one ontological category to another is explored.

Pintrich et al. (1993) suggest that students' motivational beliefs, related to goals, interests and values and their roles as individuals in a classroom learning community are instrumental in the promotion or hindrance of conceptual change. One aspect of a students' motivation which Pintrich et al. discuss is students' beliefs about their capability to accomplish the task. They called these beliefs "self-efficacy", and suggest that one aspect of teaching for conceptual change would be the promotion of self-efficacy or the promotion of the students' confidence in their own thinking and learning strategies. The role that analogies have in motivating students and more specifically their role with regard to students' self-efficacy is explored in this pilot study.

Method

Over a period of three years the researcher has been working with a cadre of nine teachers in a collaborative manner in order to study their use of and the efficacy of analogies for teaching high school science (Treagust et al., 1995b). All the teachers have been voluntary participants in what has been seen as a mutually beneficial program. The program has involved the researcher in observing, audio-taping and sometimes videotaping teachers using analogies in their classrooms (Merriam, 1988). The feedback and discussions with the teachers has developed their expertise in the use of analogies (Treagust et al., 1995b). Following three of the four lessons which form the case studies, the researcher conducted student interviews in order to further explore the efficacy of the analogy in the learning process. Students were selected for interviewing through a process of purposeful sampling (Patton, 1990) firstly on the basis of their participation in the classroom lesson, that is, those who demonstrated interest or perceptive understanding or had difficulty with the content in the lesson. This was done with the intention of collecting fruitful data from students who were more likely to be interested in and to be articulate about the topic. When the situation was such that none of the students had an opportunity to demonstrate their suitability for interviewing, they were randomly selected by the researcher from the class. Seven students from the first and second case study classes, and eight from the fourth case study class were interviewed. The student interview protocols generally explored the students' understanding of the science concept, then encouraged the students to relate that understanding to the analogy and describe if and how the analogy had been useful to them (Carr, 1996; Treagust et al. 1996; White & Gunstone, 1992). Teacher interviews followed each lesson and aimed to explore the teachers' reasons for using the analogy, the preparation they had made for the lesson, and their perceptions of the lesson they had taught (Fontana & Frey, 1994). All interviews were audio-taped and fully transcribed.

The initial analysis of the data corpus resulted in two researchers (the researcher writing this thesis and her supervisor) collaboratively deciding on the key, or most prominent, role that each of the analogies played in the conceptual change process in each classroom situation. Given that the researchers had a broad knowledge base in the field of conceptual change and had a thorough understanding of the data which had been collected at a first-hand level, the initial analysis was done on an intuitive, but an informed basis (Erickson, 1986). The data then were rescrutinised and evidence collected to describe and document the key roles the analogies seemed to play in each of the case studies. The conceptual change literature was then further examined and different theoretical perspectives of conceptual change were found to best explain the key role that each analogy played in each of the four case studies. Table 4.1 outlines the analog and target in each case study, the key role the analogy played, the theoretical perspective of conceptual change which was found to best explain the case study data and the associated authors of the theoretical perspectives.

Table 4.1: The four case studies showing the role of each analogy and the underlying theory of conceptual change

	Target science content	**Analog**	**Role of analogy**	**Theory of conceptual change**	**Authors**
Case 1	Classification of living things	Supermarket sorting and display	Sense maker	Conceptual change model	Posner, Strike, Hewson and Gertzog (1982)
Case 2	Human temperature homeostasis	Car cooling system	Memory aid	Framework theory and mental models	Vosniadou (1994)
Case 3	Cell membranes	Fluid mosaic	Transformer	Ontological categories	Chi, Slótta, and deLeeuw (1994)
Case 4	The heart	Buckets and pumps	Motivator	Motivational perspective	Pintrich, Marx and Boyle (1993)

Results and Discussion

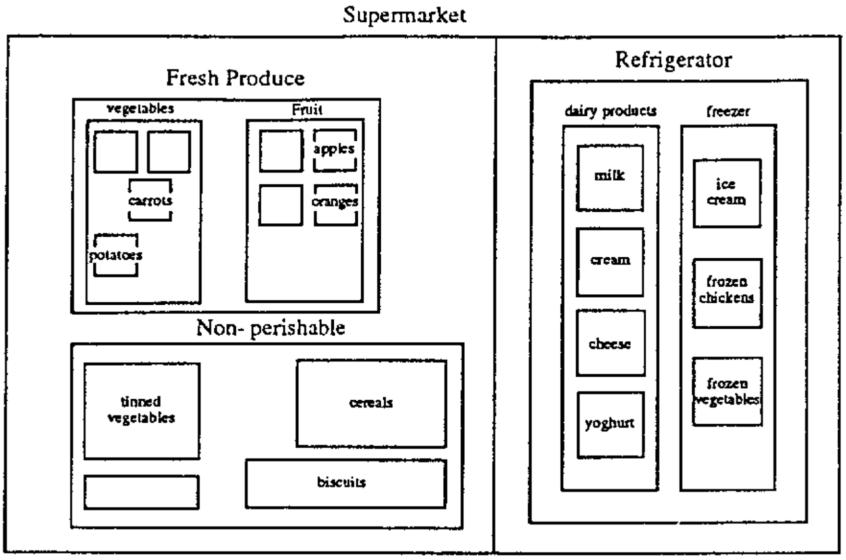
The following four case studies each describe an analogy which was part of a teaching episode in a secondary biology classroom. For each case, the role that the analogy played in the learning process was then explored through one of the "coloured glasses" of the four theoretical descriptions of conceptual change discussed above. Had the analogies been viewed from a different theoretical perspective than that chosen here, the role that they played in the learning process may have been perceived to be different. As will be seen in the conclusion of this chapter, the theoretical perspective used for analysis is a major issue of this research. The analogies chosen for discussion are interpreted from only one theoretical perspective of conceptual change which, we believe, is most consistent with the classroom practice and the learning outcomes.

Analogy as a Sense Maker: The Supermarket Analogy for Classification of Living Things

The utility of analogies and metaphors in being able to suggest new ideas or create an initial image of a concept has been well documented (Duit, 1991a; Gentner, 1988; Hesse, 1967). Posner et al. (1982) describe analogies and metaphors as a feature of the conceptual ecology which can serve to make concepts intelligible. In this sense, the analogy acts as a *sense maker* providing an initial, intelligible idea of the new concept for the learner. It is then up to the learner to modify the initial idea where necessary, to fill out and complete the new concept through prior and further experience. Here we discuss a supermarket analogy which was presented to a class of junior high school science students while they were learning about classification of living things (Venville & Treagust, 1996). The analogy played the role of a sense maker in that it helped students comprehend a concept which was initially unintelligible.

In this situation, Ms Myer found that her Year 8 students had difficulty understanding the hierarchical system of classification of living things. Particularly, they had difficulty understanding how one organism could belong to several different groups at the different levels of the hierarchy at the same time. The analogy involved comparing the classification system for living things with the way that goods are sorted and presented in a supermarket. For example, a supermarket can be subdivided into major groups such as refrigerated goods, fresh produce and non-perishables just as living things can be divided into major kingdoms, such as Plantae, Animalia and Monera. The major groups can be further subdivided, for example, refrigerated goods can be subdivided into meat, dairy and frozen goods just as the kingdom Plants can be subdivided into the division Tracheophytes and other major divisions of algae and mosses. Both systems are grouped in a hierarchical manner which was described to the students as a box-within-box method of classification. The analogy was taught using overhead projections shown in Figure 4.1.

The box-within-box classification for some of the items in a supermarket



The box-within-box classification for living things

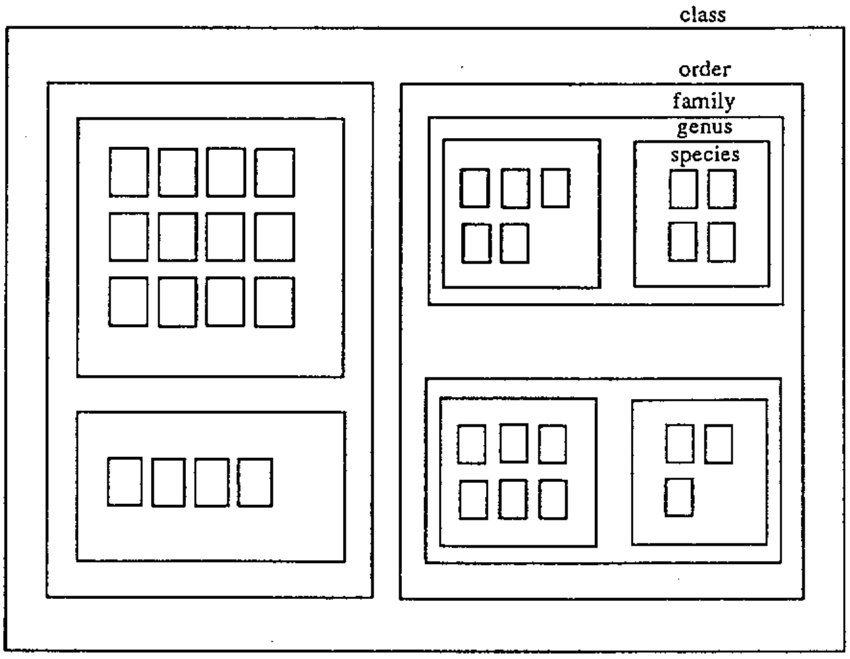


Figure 4.1: The overhead transparencies used by Ms Myer for the analogy between supermarket organisation and the classification of living things (Australian Academy of Science, 1991).

At the end of the lesson, Ms Myer asked the students if they could give a definition of classification. The students responded with comments like: "dividing things so it's easier to find them, or to notice them," "an organised way of grouping things," "putting things in groups so we can identify them" and "putting things in groups according to their similarities and differences." These comments suggest that by the end of the lesson the students understood that classification is an organised way of grouping things according to their similarities and differences. If we look at the individual, post-lesson student interviews, we can see that the supermarket analogy played an important role as a sense maker in establishing the initial picture of a hierarchical classification system and making the idea that one organism can be classified under several different groups at different levels of the hierarchy intelligible to them. Aaron, for example, demonstrates an understanding of the box-within-box, or hierarchical system of classification, by being able to answer that the big boxes contain the most variety. Later in the interview he says the analogy made it easier for him to understand how the classification system went from "the big groups down to the smaller groups." We argue that this is because the supermarket analogy acted as a sense maker of the information he was learning about living things; consequently, he was able to transfer the classification concept from the supermarket context to the living things context.

Interviewer: All right Aaron would you like to tell me what you know about classification?

Aaron: Well it's like when you classify things it's sort of like groups so you can make it easier to figure out what kind of animal it is and they classify things on their similarities and differences, and that's what a biologist does.

Interviewer: Do you remember box-within-box at all?

Aaron: Oh yeah, that's when they um, like they put one thing into a group and then it goes separate into another like group.

Interviewer: And which boxes, the big boxes or the small boxes have the most variety of animals and plants?

Aaron: The big boxes, because then they get separated into smaller groups, smaller boxes and then smaller boxes again.

Interviewer: Ok, do you remember Ms Myer comparing that to a supermarket?

Aaron: Yeah.

Interviewer: What do you know about that?

Aaron: Well it's like how they sorted the foods into their like boxes or groups or something like that.

Interviewer: Do you think is was like the classification [of living things] at all?

Aaron: Yeah, because it went from like the bigger boxes down to the smaller ones. Like you had your, all the ice-creams and that in the cold section and stuff that could stay by um.. they wouldn't go stale, they'd stay for a while in another group.

Interviewer: Right, the non-perishable stuff?

Aaron: Yeah.

Interviewer: *And did that help you to understand classification (of living things) at all do you think?*

Aaron: *Oh yeah, it like made it easier to understand how they went from like the big groups down to the smaller groups.*

The following student, Tamara, also found that the supermarket analogy helped her understand the hierarchical nature of the classification of living things, or as she puts it, how "things can be in a big group and they can be in a smaller group also."

Interviewer: And do you remember what box-within-box is?

Tamara: Yeah, like with the supermarket, there's the big supermarket, the actual supermarket and then it's broken up into sections and then in that section there might be another two sections in that section, and in the other two.

Interviewer: So which, do the big boxes or the little boxes have most variety?

Tamara: Um, the big boxes.

Interviewer: Right and so you remember Ms Myer talking about the supermarket, did that help you to understand classification at all?

Tamara: Yeah, a little bit.

Interviewer: Yeah, how did it help you?

Tamara: I don't know coz, like [it helped me to understand] you know that things can *be in a big group and they can be in a smaller group also.* Like they're not in just one big group or something like that.

Interviewer: Right, so it cleared up how they can be in different groups, the same thing?

Tamara: Yeah.

Other students in the class who were interviewed showed varying levels of understanding of the hierarchical or box-within-box classification system but most, like Aaron and Tamara, seemed to indicate that the supermarket analogy made sense of the classification concept for them, that is, it made the concept intelligible to them. This analogy's key role, therefore, was as a sense maker in that it transferred intelligibility of the new scientific concept from another, better known context.

Analogy as a Memory Aid: The Car Cooling System Analogy for Temperature Homeostasis in Human Beings

The teacher of this lesson, Mr Holden, was concerned that the analog which he planned to use may not have been familiar to some of his Year 12 Biology students. He therefore gave a brief description of the car cooling system in order to ensure student familiarity with the analog before teaching about temperature homeostasis in human beings. He justified this in the post lesson interview as follows:

Mr Holden: ... One thing in doing it (the analogy) I was concerned about the sort of gender side of things, just how familiar perhaps some of the girls would be with the function (of the car cooling system). That's why I did a very brief, well these are the four key elements the engine, the radiator, the thermostat and the water pump. They did surprise me, a lot of them, both boys and girls with their sort of basic knowledge. ...

Mr Holden then went ahead and clearly outlined the similarities and differences between a car cooling system and the temperature control system in human beings which were set out in his teaching notes and written on the white board and which can be seen in Figure 4.2.

The post-lesson interviews indicated that the students felt the analogy would help them remember the science content in the imminent examinations. For example, Bernard, in the following excerpt said if he had to write an essay about temperature homeostasis in the exam he would "start thinking about the car and think about what happens there and then compare that to ... the body".

Interviewer: Did that (the car analogy) help you at all?

Bernard: Oh, yeah I suppose when you're comparing it to a car engine it will probably help me in the TEE [tertiary entrance] exams.

Interviewer: Why?

Bernard: Oh it'll just give you something to compare it to and you can think , oh yeah, that's what happens there and that sort of thing.

Interviewer: So if you were writing an essay in the exam about body temperature control, you'd, what would you do?

Bernard: Well what do you mean, how would I go about it?

Interviewer: Yeah, how would you think about it?

Bernard: Oh I'd probably you know start from, if anything *I'd probably start thinking about the car and think about what happens there and then compare that to what happens to the body.*

Interviewer: Oh all right so it would help you remember things you think?

Bernard: Yeah.

CAR ENGINE (Analog)	HUMAN (Target)
SIMILARITIES	
1. energy conversion chemical (fuel) + O_2 -> kinetic + heat + others	1. energy conversion chemical (CHO) + O_2 -> kinetic + heat + others
2. inefficiency/friction -> excess heat	2. inefficiency/friction -> excess heat
3. excess heat lost through convection, conduction and radiation	3. excess heat lost through convection, conduction and radiation
4. coolant carries heat around motor (core -> surface)	4. blood carries heat around body (core -> surface)
5. water pump pumps coolant	5. heart pumps blood
6. increasing convection -fan -car moves -> air flow -coolant flow through motor	6. increasing convection -fan/breeze -move around -flowing water (swim, shower)
7. increasing radiation -radiator "honeycombed" -water channels through radiator/thin metal water flow does same as blood	7. increasing radiation -large skin surface area -blood vessel network near skin -blood flow brings warm blood constantly -> temperature gradient
8. increasing conduction -motor/radiator not covered -cool air flow (over heating more likely in summer) temperature goes up when idling	8. increasing conduction -remove clothing -exposure to cool air or water (flowing -> temperature gradient)
9. thermostat - controls coolant flow through motor/radiator	9. regulation -thermoregulator (hypothalamus) controls blood flow through skin (and sweating)
10. a cold car doesn't run well - needs choke. A hot one boils water and burns oil.	10. end result temperature maintained within close limits so chemical reactions can proceed at optimum
DIFFERENCES	
no evaporative cooling	evaporative cooling through sweat
fluid is water	fluid is blood
pump is mechanical pump	pump is biological heart etc.

Figure 4.2: Mr Holden's notes describing the car cooling system analogy for temperature homeostasis in human beings.

Leanne felt the analogy would help students remember the science content because "you should straight away think of the car". Additionally, she felt you would "automatically remember" the drawing the teacher did of the car.

Interviewer: Ok and why do you think he (the teacher) talked about that (the car)?

Leanne: Oh, I thought it was just to give examples, like to make comparisons also *so that we'd remember,* I mean when you give examples like that *you should straight away think of the car* and think what does it need? and so you relate that back to the human.

Interviewer: And do you think it helps you remember?

Leanne: Yeah, yes.

Interviewer: Why do you think it helps you remember?

Leanne: Because if you see a question like that *you'll automatically remember, like that stupid drawing he drew, well I thought it was anyway, of the car.* And so you just remember it because, I don't know you just laughed at it.

Heat is a topic which is most often studied in a physical science context. We propose, therefore, that these students found it easier to recall the concept of temperature homeostasis in a physical system like a car than a biological system like a human body. If we think of the role this analogy is playing here in terms of Vosniadou's view of cognitive structures, we can explore the reasons why it seems to be playing the role of a memory aid. Vosniadou claims that mental models or mental representations used during cognitive functioning are generated from an individual's specific theories and global framework theories (see Figure 3.3). Vosniadou (1994) also says that it is possible that mental models can be stored and "retrieved from long-term memory when needed" (p. 48). The initial mental model of temperature homeostasis was generated from a framework theory of physics through the car analogy. The mental model was then adapted to the human body context and transferred to a specific theory of homeostasis within a biology framework theory in the students' cognitive structures. Because the theory of temperature homeostasis within the biology framework is new and not well established, it was difficult for the students to recall. Therefore, the students found it easier to rely on the analogy to recall the mental model from the physics framework theory. In this sense the role of the analogy was a memory aid because the mental model was more easily recalled from the physical science framework theory where the car analogy is situated than from the biological framework theory where the science lesson was being studied.

Other students in the class also said they felt the analogy would help them remember the science content. Joe said the analogy would make the science content "easier to think about because it's something that you can learn" and "you might just forget it altogether if you're just thinking directly as to how humans can control their own (body temperature)." Sarah, quoted below, initially seems unconvinced that the car analogy would help her remember the content in an exam because she says she would "probably" think about the car. Contradictorily, she seems confident that the car analogy would be useful to "jog my memory" or "remind me" in an exam situation.

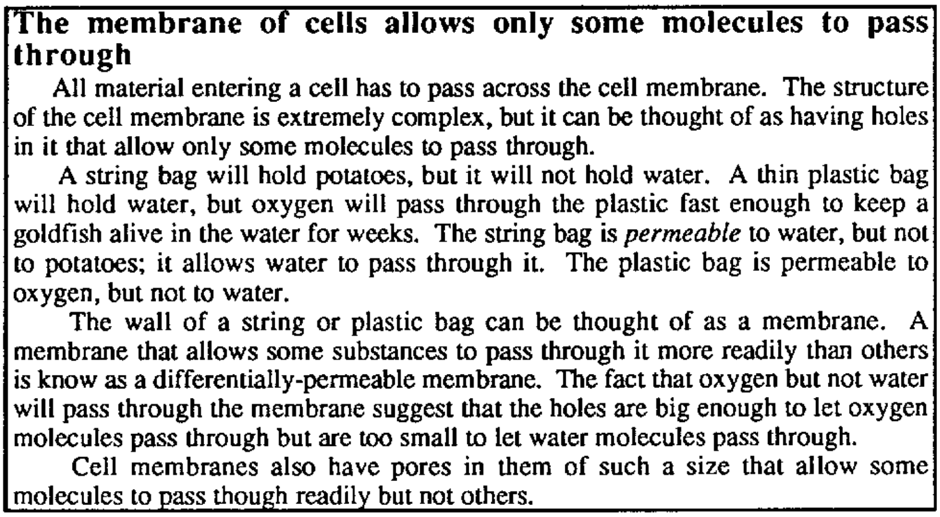
Interviewer: And do you think that helped you learn a little bit about the body?
Sarah: Yeah, well, you use comparisons. If you think about the car you can think back to the body and what it does with the body. By using, you just think about what's in the car and you think, oh yeah, that can relate to the body somehow.
Interviewer: And so if you were writing an essay in the exam do you think you'd think about the car?
Sarah: Yeah, I'd *probably.*
Interviewer: Why do you think you'd think about that?
Sarah: I'd just use that to *jog my memory.* I'd think about the car and what that has compared to the body and what that does with it. So it interrelates with each other. I don't think I'd mention the car in the essay though.
Interviewer: But you'd use it?
Sarah: Yeah, *it would remind me.*

Even though this analogy probably had an important initial role as a new mental model generator, the imminent examinations seemed to influence what was important for the students' in this case study. The role as a memory aid, to recall an established mental model, was the most prominent role which emerged from the data. We can conclude, therefore, that the key role of the car analogy for homeostasis in human beings was a memory aid.

Analogy as a Transformer: The Fluid Mosaic Analogy for Cell Membranes

Chi et al. (1994) are critical of a commonly used water flow analogy for teaching electric current. They say that electric current is a phenomenon which belongs in the process ontological category and that the water flow analogy sometimes generates alternative conceptions by perpetuating the idea that electricity is in the matter category and has inherent matter properties such as volume and space. We suggest that other, more appropriate analogies may have a similar but more positive effect compared with the water flow analogy for electric current. That is, an analogy may have the role of transforming the ontological category of a concept from the erroneous ontological category to the preferred category. In this sense the role of the analogy in the process of conceptual change could be described as a *transformer*.

Many explanations and analogies used to describe cell membranes emphasise their static, barrier properties. For example, Figure 4.3 shows how cell membranes are described as being like a string bag in the Australian biology textbook, *Biology: The Common Threads Part 1* (Australian Academy of Science, 1991). This model of cell membranes accounts for their semi-permeability and may be useful when explaining such concepts as osmosis, but it does not account for many other properties of cell membranes.



The membrane of cells allows only some molecules to pass through

All material entering a cell has to pass across the cell membrane. The structure of the cell membrane is extremely complex, but it can be thought of as having holes in it that allow only some molecules to pass through.

A string bag will hold potatoes, but it will not hold water. A thin plastic bag will hold water, but oxygen will pass through the plastic fast enough to keep a goldfish alive in the water for weeks. The string bag is *permeable* to water, but not to potatoes; it allows water to pass through it. The plastic bag is permeable to oxygen, but not to water.

The wall of a string or plastic bag can be thought of as a membrane. A membrane that allows some substances to pass through it more readily than others is know as a differentially-permeable membrane. The fact that oxygen but not water will pass through the membrane suggest that the holes are big enough to let oxygen molecules pass through but are too small to let water molecules pass through.

Cell membranes also have pores in them of such a size that allow some molecules to pass though readily but not others.

Figure 4.3: A section from *Biology: The Common Threads Part 1* (Australian Academy of Science, 1991, p.189) a biology textbook describing membranes as being like a string bag.

Cell membranes are not only semi-permeable but they can alter their permeability to some substances depending on the presence of chemical or electrical triggers, that is, they are differentially permeable. They can transport some substances across them actively and also enclose and discharge materials at their surfaces (Stevenson, 1992). Membranes are clearly very flexible, dynamic structures. The fluid mosaic model of cell membranes accounts for these properties. According to this hypothesis, a membrane consists of a double layer of lipids with proteins embedded in it like mosaic tiles. The bilipid layer accounts for the impermeability of cell membranes to some substances and the proteins provide specific channels for substances which can move across the membrane by processes such as diffusion and active transport. The proteins are not fixed in one place and move in order to facilitate the transport of materials, hence the "fluid" nature of the mosaic pattern.

A biology teacher was observed and video-taped developing and extending with her Year 11 class the fluid mosaic model of cell membrane permeability into an analogy which emphasised the dynamic nature of cell membranes. Mrs Tile approached the lesson by initially splitting the fluid mosaic model into the two analogies, that of the mosaic and that of the fluid. She brought in examples of mosaic art from the art department of the school to ensure student familiarity with the analog concept. After building up the idea of proteins embedded in the lipid layer like mosaic tiles, Mrs Tile then switched to the fluid analogy and used that to discuss the mobility of the proteins in the lipid bilayer and how that accounts for many properties of cell membranes. This can be seen from a brief part of the lesson transcript which follows below.

Mrs Tile	The model has tried to explain to us that there is this movement within cell membranes by putting this word (fluid) in at the start of the model. That it's like a mosaic, like this picture, but instead of being a picture which is stationary where once the pieces are stuck on they can't actually move, they believe that there is a certain amount of movement within the membrane...

Although not strictly a transition from a "thing" ontological category to a "process" category as described by Chi et al. (1994), the key role of this analogical model used by Mrs Tile was to de-emphasise the static, structural barrier perspective of cell membranes and to emphasise the process-related properties. In this sense, the analogy is acting as a *transformer* to change the students' view of cell membranes from a "thing" category to a "process" category. Further, student-based research is needed to determine whether or not this is indeed something which occurs in the students' minds.

Analogy as a Motivator: The Bucket and Pump Analogy for the Heart

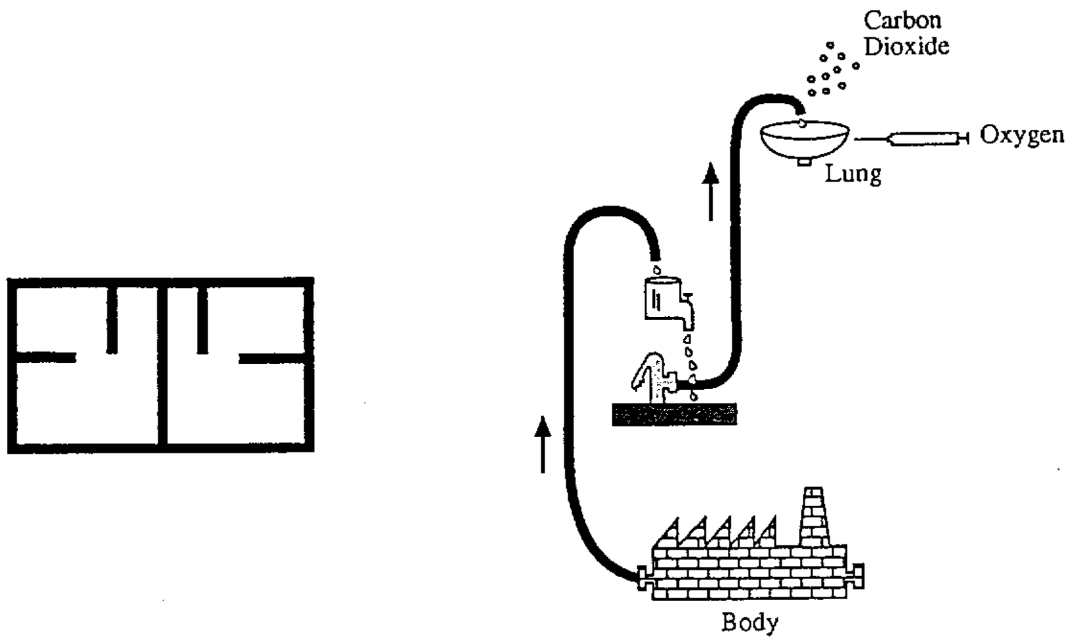
Viewing conceptual change from the motivational perspective of Pintrich et al. (1993), one can assume that the promotion of self-efficacy should be an integral part of the strategies that teachers use to promote conceptual change. Is this the case with analogies? We will discuss here a multiple analogy for the heart which suggests that analogies do have a role to play as motivators. In this case the analogy increased students' confidence that the learning task at hand was something achievable.

As a consequence of his empathy with students who had difficulty learning how the blood flowed through the heart and body, Mr Pail devised a simplified analogical model of the heart that could be displayed on an overhead projector (Wilkes, 1991; Venville & Treagust, 1993). The four overlays of the model related the functioning of the atria and ventricles of the heart to buckets and pumps respectively, the lungs to a needle injecting oxygen and the body to a factory with waste products (see Figure 4.4). During the observed lesson the teacher went through the overhead projected model and related the parts of the heart and body to the analogies and asked the students to copy down the diagrams into their workbooks. During the teaching process, Mr Pail involved his students by encouraging them to predict what would happen to the blood at the next stage of the diagram.

The teacher overtly used the analogy as a motivator and morale booster in the classroom. As soon as he put the first overhead projection sheet of the analogy up for the students to see he said, " it's easier already, isn't it." He then continued a little later in the lesson:

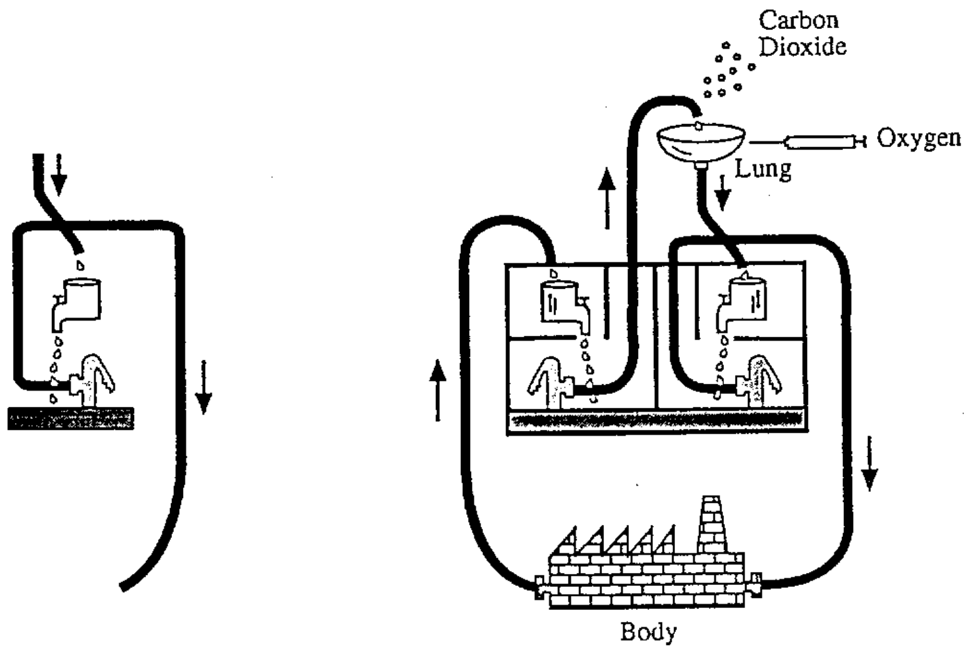
Mr Pail: ...Ok, so the top chamber's really just for storage. The blood goes into that top chamber and it flows down into that bottom one. Chris, if the blood 's in the top chamber and it's all pouring down into the bottom chamber, what's going to happen to the bottom chamber?
Chris: It'll fill up too.
Mr Pail: Right, good. The bottom chamber's going to fill up, so Bradley, what do we have to do to that bottom chamber to stop it filling up?
Bradley: Empty it.
Mr Pail: Perfect, can't go wrong on this, can we? ...

Mr Pail used the analogy to make the content seem easy for his students to learn, to raise their self-efficacy and motivation. By getting the students to predict what is going to happen to the blood next in the above excerpt, and then praising the students by saying, "Perfect, can't go wrong on this, can we?", he is establishing in the students' minds confidence in the analogy and their self-efficacy. In a post-lesson interview with the researchers, Mr Pail reiterated his belief that students' involvement in the lesson by working out difficult concepts or ideas seemingly by themselves, was seen as worthwhile.



Transparency 1

Transparency 2



Transparency 3

Transparency 4

Figure 4.4: The overhead transparency teaching sequence used for the analogical model to illustrate the heart.

Teacher: ... I really think part of the success is doing it (the analogy) just one little piece at a time. When they understand that piece you can actually ask them what is going to happen next. So they almost have an input into what's happening. And they always see worth in that too.

Interviewer: So they're generating it from what they know?

Teacher: Yeah. Like they think, oh yeah, I knew that was going to happen, like they're quite happy to draw it next. Whereas if they're all confused, you know their diagram won't even be accurate.

Student interviews also corroborated this idea that the analogy acted as a motivator by increasing their self-efficacy or making the content seem easier and more understandable compared with a more literal explanation or more realistic diagram. For example when asked if the analogy helped him Chris replied, "Yeah, because I didn't really understand it at first, I didn't know there was anything leading anywhere, and the box and all that (the analogy) ... it helped me a lot." Likewise the section of the transcript below shows that Craig found the model much easier to follow and understand compared with the more realistic diagram originally shown to the students.

Interviewer: Did you know much about the heart and how it works before Mr Pail did this the other day?

Craig: No, I didn't, I don't think at all. I just knew that it provided blood to the body and that's about all.

Interviewer: Well, how much do you think you know about the heart now?

Craig: A lot, a lot, he showed a diagram where it just had what it really looks like and it was just a heart and all these funny arrows and numbers and then he showed us this (the analogical model), and you can understand it straight away.

Interviewer: So this model was a lot easier to follow than the actual heart diagram itself?

Craig: Yes, way easier by far, I couldn't, I couldn't even start to understand the other one really.

Interviewer: Why?

Craig: Oh, it was just really complicated, but there was like no straightness to it at all, just kind of like a scribble and it was just a heart and little heart things around it and all over the place.

Interviewer: But you can see some sense in this diagram?

Craig: Yeah, a lot of sense.

Interviewer: And you really do think it's helped you understand it?
Craig: Yes, I do.

Technical language can be confusing and threatening for students (Sutton, 1992). When learning about the circulation of the heart, young students have to grapple with words like valves, ventricle and atrium. This analogy represented these parts of the heart with the familiar, analogical terms "taps", "buckets" and "pumps". The following extract from a post-lesson student interview indicates that one student, David, found the content easier to learn because the analogy eliminated the technical language barrier which he seemed to find a threat to his ability to assimilate new ideas.

Interviewer: All right, so did you think that these buckets and pumps were useful to help you understand how this flowed through the heart?
David: *Well, yes it was easier, I think, to learn because (before the analogy) all types of like technical names kept popping up. I don't think I would have remembered quite as much.* Like I might have remembered the name of the pump and how it squeezes something. Like it's easier to remember like this (with the analogy).

The post-lesson interview revealed that David had developed an accurate, scientific knowledge of the circulation of the blood through the heart and body and the processes involved in oxygenating the blood. The technical language of this concept, however, had previously presented a mental barrier to David in his attempt to learn the circulation of the blood. This can be seen by his comment that "all types of like technical names kept popping up. I don't think I would have remembered quite as much." For David and many other students in this class, the analogy took on the role of a motivator in that it eliminated the technical vocabulary, boosted confidence in their ability to learn the content and allowed the learning process to proceed. It therefore seems evident that the key role the analogy played in the learning of the heart concept in this lesson sequence was as a motivator.

Conclusions

The conclusions of this pilot study are discussed in the following paragraphs as four assertions about the role that analogies can play in conceptual change in biology and about conceptual change theory in general.

Assertion 1

Analogies have many and varied roles to play in the process of conceptual change in the classroom.

Here classroom evidence has been documented to suggest that in a given context a particular analogy can play one of several roles. These roles are:

- a *sense maker* to transfer the basic structure of a concept from the analog domain to the target domain in order to establish intelligibility of the new science material being taught,
- a *memory aid* to help students recall a concept which is difficult to remember within the newly learned content area,
- a *transformer* which facilitates the change in ontological category to which the concept belongs in the mind of the learner from "thing" to "process", and
- a *motivator* to enhance the self-efficacy of students and give them confidence in their ability to learn the science content.

The various roles that analogies have played in these case studies was illuminated by looking at the data from differing perspectives of conceptual change. We suggest that analogies play many more roles in the classroom and that this is an area for further study.

Assertion 2

One perspective of conceptual change can best explain situation-specific learning outcomes, though other perspectives can contribute to this explanation.

By using the four different perspectives of conceptual change to interpret each of the analogies presented in this paper, we have, as expected, come to different conclusions about the role that each of the analogies played in the learning process. The results seem to be complementary and cumulative, with each case study providing further information about the way that analogies are able to contribute to the conceptual change process. This illustrates the complexity of the nature of conceptual change and learning in general and perhaps demonstrates the futility of searching for the generic "perfect" or "best" description of conceptual change. According to the data in this pilot study and that of an earlier study (Treagust et al., 1995a), as well as that of others (Caravita & Halldén, 1994), conceptual change is extremely situation specific. Therefore, each learning situation must be explored and studied complete with the idiosyncratic features of the learner, the teacher, the content being learned and the learning environment and interpreted from a particular perspective of conceptual change that explains the situation specific learning outcomes.

Assertion 3

The key role that a single analogy will play for a particular student may be dependent on a combination of factors.

Several factors which influence the key role that an analogy will play for a particular student have become evident from the four teaching/learning episodes described in this pilot study and are listed below. Other factors may become evident through further research.

• *The nature of the difficulty of the science concept*

If the science concept is difficult because it is abstract or because it includes a lot of technical language then this may be the area where the analogy will be useful in helping the learner overcome the difficulty and thus determine the role that the analogy will have for a student. For example, the familiarity of the organisation of a supermarket helped students understand how living things were classified. Also, the bucket and pump analogy helped David overcome his difficulty with the technical language associated with the heart.

• *The teaching style of the teacher and the teachers' intention when using the analogy*

The teacher may perceive a lack of self-confidence among her or his students when it comes to learning a particular topic as did the teacher who used the buckets and pumps analogy for the heart. The teacher may then deliberately choose an analogy which is fun or morale boosting and encourage the students to use the analogy in a motivating way.

• *The previous science content knowledge of the student*

The student may already have memorised and understood small pieces of the content to be learned, but has failed to create an integrated, connected picture. The analogy may serve to provide the scaffolding for the integrated, connected concept and be a sensemaker as was the supermarket analogy for classification of living things.

• *The learning environment*

If examinations are emphasised as an important part of the student's learning environment, as with the students who learned about homeostasis through the car analogy, then the analogy is likely to be utilised by the student as a memory aid.

• *The student's stage of intellectual development*

If a student is unable to think in abstract terms, the analogy may be useful in providing concrete cognitive models for the student to think with. This could have been the case for many of the Year 8 students in Mrs Myer's class who were able to understand the classification of living things from the supermarket analogy.

Assertion 4

The perspectives of conceptual change used as interpretive frameworks in this chapter have been just as applicable to the interpretation of everyday, classroom learning as they are to interpret radical conceptual change.

Writers and researchers in the conceptual change arena tend to be explicit and exclusive when defining the limits of conceptual change. Posner et al. (1982), for example, developed their conceptual change model within the accommodation paradigm. More recent papers by Hewson and Hewson (1992, p. 62) and by Hewson and Thorley (1989, p. 543) are less rigid in the limitations of their definition of conceptual change and include assimilation (which they refer to as conceptual capture) as well as accommodation (conceptual exchange). Similarly, Dagher (1994, p. 609) claims that "restricting worthwhile conceptual change to the radical type is equivalent to restricting worthwhile science to revolutionary science".

Summary

In this pilot study, the data and interpretations support the claims of the authors cited in the last paragraph. The theories of conceptual change have much to tell us about the everyday learning that occurs in the classroom, and these everyday or "normal" shifts in conceptual understanding are just as important as "radical" conceptual change. Having described the roles that analogies have to play in the everyday learning process for students in biology, we can conclude that the learning taking place in each of the four situations could best be explained by taking into account a different perspective of conceptual change. The content and context are likely to influence the kind of conceptual changes that take place, and hence has implications for the investigation of student learning of the concept of the gene. For example, student learning about the concept of the gene and any associated conceptual change is likely to be different from conceptual change in other content areas. The findings of this pilot study with regard to the use of different perspectives of conceptual change have influenced the development of the theoretical framework for the larger part of this thesis. In Chapter 5, the methodology, the idea of using different perspectives of conceptual change is developed into a multidimensional theoretical framework. In addition, Chapter 5 presents the approach taken to other aspects of the research process such as the research paradigm, the theoretical orientation, the research design, data collection, trustworthiness and ethics.

CHAPTER 5
METHODOLOGY

> To prepare an interpretation is itself to construct a reading of these meanings; it is to offer the inquirer's construction of the constructions of the actors one studies. (Schwandt, 1994, p. 118)

Introduction

An interpretive research approach is appropriate for this study because it enables the researcher to provide details of the nature of teaching and learning in science classrooms (Erickson, 1986; Gallagher, 1991). A major component of the research questions in this study is to understand students' learning about the concept of the gene in natural classroom situations. Interpretive research methodology allows researchers to examine the teaching of science in natural classrooms and the ways that students make sense of classroom learning situations. The significance of interpretive approaches to research on teaching concern the nature of classrooms as socially and culturally organised environments for learning (Erickson, 1986).

This chapter presents the methodology of the thesis and outlines the specific approaches taken in each aspect of the research process. The methodology has been placed after the pilot study because the results of the pilot study contributed conceptually to the development of the multidimensional interpretive framework outlined in this chapter. An outline of the research approach is presented in Table 5.1, and the terms presented in Table 5.1 are used to structure this chapter. The approach embraces Patton's (1990) pragmatic approach to paradigm choices. That is, rather than having to align with one paradigm for methodological orthodoxy, appropriateness is the primary criterion for judging method. The main issue is that appropriate and sensible decisions are made to chose methods that will fit the purpose of the inquiry, the research questions and the resources available regardless of the paradigm the methods are most frequently aligned with. Having made a commitment to Patton's pragmatic approach to paradigm choices, it is evident that the majority of decisions that have been made in the development of the methodology for this thesis are consistent with the constructivist paradigm.

Table 5.1: An outline of the research approach taken in this study.

Aspects of the Research Process	Approach Taken in this Study
Research paradigm	Constructivism
Theoretical orientation	Grounded theory Orientational qualitative inquiry
Theoretical framework	Multidimensional framework for conceptual change
Research design	Multiple case study
Data collection	Participant observation Student interviews Teacher interviews Student work-sheets Classroom quizzes
Data Interpretation	Analysis of work-sheets Construction of case studies Classification of status of conceptions Search for disconfirming evidence
Trustworthiness	Truth value Triangulation Dependability Confirmability Transferability
Ethical issues	Informed consent Exchange of information Confidentiality Trustworthiness

Research Paradigm: Constructivism

As outlined in Chapter 1, constructivism is the theory of knowledge that is at the root of the conceptual change interpretive framework employed in this thesis. Accordingly, constructivism is the basic belief system or paradigm that informs and guides the choices of method for the inquiry. Interpretive research and the constructivist paradigm are closely related by several authorities in research methods (Denzin & Lincoln, 1994; Gallagher, 1991; Linn & Erickson, 1986; Schwandt, 1994). Gallagher (1991) places constructivist research with ethnographic, qualitative, participant observational, case study, phenomenological and symbolic interactionist research as a family of approaches that can be classified as interpretive research. Denzin and Lincoln (1994) describe one of the four major research paradigms as "constructivist-interpretive" (p. 13), without any distinction between the two terms. However, Guba and Lincoln (1994), in the same volume as Denzin and Lincoln, refer to one of the four paradigms they outline simply as "constructivism". Schwandt (1994) claims that the real meanings of the terms "constructivist, constructivism, interpretivist and interpretivism" (p. 118) can only be distinguished by the people who use them and the terms are only general descriptors of a family of methodological paradigms. Schwandt (1994) says that both "constructivist or interpretivist share the goal of understanding the complex world of lived experience from the point of view of those who live it" (p. 118). Yet despite this shared goal to understand the world as it is lived, Schwandt outlines the differences in constructivist and interpretive ways of thinking. The differences tend not to be about methodology but more about their understandings of the purpose of human inquiry and the ways that we can know the world of human action, that is, the differences are about matters of knowing and being, or epistemology and ontology.

The purpose of constructivist inquiry, as suggested in the quote at the beginning of this chapter, is "understanding and reconstruction of the constructions that people (including the inquirer) initially hold" (Guba & Lincoln, 1994, p. 113). This is in contrast to more traditional paradigms such as positivism that see the purpose of inquiry to be explanation, prediction and control of physical or human phenomena. The purpose of this thesis is the understanding of the process of learning that students undergo when they learn about genes, a purpose that is within this description of the constructivist paradigm.

On the question of knowledge or epistemology, constructivists believe that knowledge consists of constructions about which there is relative consensus among those qualified or competent to interpret the construction (Guba & Lincoln, 1994). This is consistent with Schwandt's (1994) description of the constructivist view of epistemology that "human beings do not find or discover knowledge so much as construct or make it. We invent concepts, models, and schemes to make sense of experience and, further we continually test and modify these constructions in the light of new experience" (p. 126). The purpose of this thesis is to make sense of students' experiences when they are learning about genes, by constructing models and schemes of how this learning experience occurs. The aim is that the researcher, through the research process, is to become informed and competent enough to interpret the student and classroom data in order to generate knowledge about the students' learning process. There also is an expectation that the constructions made as a result of this thesis will be continually tested and modified in the light of new experience. The epistemology of the researcher is, therefore, consistent with the constructivist paradigm.

According to Guba and Lincoln (1989), more traditional forms of inquiry include the belief that "there exists an objective reality, 'out there' which goes on about its business irrespective of the interest that an inquirer may have in it" (p. 85); this can be termed a realist ontology. In contrast, a constructivist view is that "there exist multiple, socially constructed realities ungoverned by natural laws, causal or otherwise" (Guba & Lincoln, 1989, p. 86); this can be termed a relativist ontology. Schwandt (1994) points out, however, that "one need not be an antirealist to be a constructivist. One can reasonably hold that concepts and ideas are invented (rather than discovered) yet maintain that these inventions correspond to something in the real world" (p. 126). Von Glasersfeld (1993) also does not deny an ontological reality but claims that we cannot in any sense know a real world. As discussed in Chapter 1, the researcher's views are consistent with those of Von Glasersfeld, that an ontological reality probably does exist; however, we can only ever know our own construction of that reality. With regard to the content of this thesis, the researcher believes that genes do exist ontologically, but we can only construct our own understanding of the reality of genes through our own experiences.

Theoretical Orientation: Grounded Theory

What is the approach to theory in this study? Generally, research can be described as being deductive or inductive with regard to theory. Deductive research is associated with more traditional forms of research such as positivism that include experimental research designs (Patton, 1990). This approach requires the statement of a specific theory or hypotheses before the research begins, and the data collection is designed to test the theory or hypothesis (Patton, 1990). Grounded theory is a kind of inductive approach to research in which the theory is grounded in or emerges from the data (Patton, 1990). The research occurs without the researcher imposing any preconceived theory on the data collection process, allowing the important patterns and theories to emerge from the data collected (Patton, 1990). "Grounded theory depends on methods that take the researcher into and close to the real world so that the results and findings are 'grounded' in the empirical world" (Patton, 1990, p. 67). There are several different kinds of grounded theory that take an inductive approach to generating theory. The kind of grounded theory that is utilised in this research is that which Patton (1990) describes as orientational qualitative inquiry. A general assumption of grounded theory approaches is that the researcher goes about the research process without any preconceived ideas about theory. The problem for the researcher is to maintain an open mind when collecting data. Hermeneutics takes the position that nothing can be interpreted free of some perspective, so researchers should be explicit about their own perspective (Patton, 1990). Orientational qualitative inquiry is similar to hermeneutics in the approach taken to theory, but it goes even further. Patton explains.

> Orientational qualitative inquiry begins with an explicit theoretical or ideological perspective that determines what variables and concepts are most important and how the findings will be interpreted. ... In these instances, the orientation or perspective of the researcher determines the focus of inquiry. ... Within each of these theoretical or ideological orientations one can gather qualitative data. But the focus of inquiry is determined by the framework within which one is operating, and the findings are interpreted and given meaning from the perspective of that preordinate theory. Such qualitative inquiry, therefore, aims to describe and explain *specific* manifestations of already presumed general patterns.
>
> *What is required is that the researcher be very clear about the theoretical framework being used and the implications of that perspective on study focus, data collection, fieldwork, and analysis* (author's italics) (Patton, 1990, pp. 86-87).

The framework within which this research is conducted is the multidimensional interpretive framework for conceptual change (Tyson, Venville, Harrison & Treagust, 1997). This framework is a general interpretive framework of conceptual change that guides the focus of inquiry, and the findings are interpreted and given meaning from multiple perspectives of conceptual change. The emergent theory that results from this study is a specific manifestation of the multidimensional framework focused on student learning about the concept of the gene. As Patton (1990) suggests, the researcher's intention is to be very clear about the framework being used, and hence presents the framework in the next section.

A Theoretical Framework for Exploring Conceptual Change in Genetics

The multidimensional interpretive framework for conceptual change was developed by a collaborative research group at the Science and Mathematics Education Centre at Curtin University of Technology (Tyson et al., 1997). This research study has played an integral part in the development of the multidimensional framework along with the research carried out by the other members of the group, David Treagust, Louise Tyson, and Allan Harrison. Chapter 3 provided an overview of themes and issues that emerge from the conceptual change literature published over the past 15 years. Here those themes and issues are drawn upon in order to argue the need for a multidimensional framework for interpreting conceptual change. The generalised multidimensional framework for conceptual change is then described with specific reference to its three major dimensions, ontology, epistemology and social/affective.

The Need for a Multidimensional Framework of Conceptual Change

The most influential research involving conceptual change has been the Conceptual Change Theory (Posner et al., 1982; Strike & Posner, 1992) which describes the conditions necessary for conceptual change. Until recently however, researchers working from alternative theoretical perspectives have been largely ignored. For example, a paper which considered the role of motivational beliefs and classroom contextual factors in the process of conceptual change (Pintrich et al., 1993) highlighted a social perspective of conceptual change which had not previously been considered in such detail. It warned of viewing "academic learning as cold and isolated cognition" (p.167), described research that has been carried out on classroom motivation and learning, and provided a focus of this research to the conceptual change arena. Until 1993, empirical research had focussed primarily on the cognitive aspects of conceptual change (Smith, Blakesbee & Anderson, 1993). In highlighting the "ways in which students' motivational beliefs about themselves as learners and the roles of individuals in a classroom learning community can facilitate or hinder conceptual change", (Pintrich et al., 1993, p. 167) opened a new perspective by discussing the potential mediating role of students' goals, values, self-efficacy, and control beliefs in the process of conceptual change. It should be acknowledged that the original paper by Posner et al. (1982) did not discount the role of these factors but chose to focus on more "rational aspects of learning."

The special issue of *Learning and Instruction* (Vosniadou, 1994) provided a selection of articles dealing with different perspectives of conceptual change in addition to the Posner et al. focus on status of conceptions and the Pintrich focus on social issues. The paper by Chi, Slótta and deLeeuw (1994) viewed conceptual change as a process from an ontological perspective where students with non-scientific conceptions must change the way they view a concept. The ontological category to which the concept belongs in the students' mind, according to Chi, et. al., must change from a non-scientific category to the scientifically correct category. In the case of science, this often involves students changing their view of concepts such as electricity and light from belonging to an ontological category of "matter" to a "process" category, or more specifically a constraint-based interaction category. Although there are deficiencies with this perspective of conceptual change as discussed by Duit (1995), Chi et al.'s theory has established a way of looking at conceptual change that is unique when compared with their contemporaries. The ontological perspective introduced by Chi et al. is one that should be considered when investigating or teaching concepts that traditionally seem to be resistant to conceptual change. This perspective is likely to illuminate ontological changes that are necessary for conceptual change to occur, an aspect that possibly hasn't been considered previously and which is likely to provide teachers and researchers more insight into the conceptual change process for particular concepts.

The research discussed so far has largely remained committed to one or another particular theoretical perspective of conceptual change as a framework for their data analysis and interpretation. In contrast to this approach, as described in Chapter 4, Venville and Treagust (1996) utilised four different perspectives of conceptual change to analyse different classroom teaching situations in which analogies were used to teach biology concepts. The four perspectives used are Posner et al.'s (1982) conceptual change model, Vosniadou's (1994) framework theory and mental model perspective, Chi et al.'s (1994) ontological category perspective, and Pintrich et al.'s (1993) motivational perspective. Venville and Treagust (1996) found that each of the perspectives of conceptual change had explanatory value and contributed a different theoretical perspective on interpreting the role that analogies played in each of the classroom situations. Could every learning situation be better explained if, like Venville and Treagust, multiple perspectives of conceptual change were used as an interpretive framework?

To construct a holistic picture, it is possible and beneficial to consider a learning situation from differing theoretical perspectives of conceptual change. For example, rather than only considering conceptual changes in knowledge that a student constructs in moving from, say a pre-scientific notion to a scientific view of a concept, a more complete and informative picture would be painted if these changes were viewed from a multidimensional perspective. The way the student views a concept in terms of it's status (Posner et al., 1982), or its ontological category (Chi et al., 1994), or the motivational and contextual factors (Pintrich et al., 1993) necessary to precipitate the conceptual change also should be considered. From this point, it becomes clear that a multidimensional framework utilising differing perspectives of conceptual change to view a learning situation has merit (Tyson, et. al., 1997). The purpose of the multidimensional framework is to bring different perspectives of conceptual change together in order to view conceptual change from different perspectives.

Consequently, this research has been conducted within a multidimensional framework by examining the changes in students' conceptions of the gene from several theoretical perspectives of conceptual change including, ontological, epistemological, and social/affective dimensions. The following paragraphs give a more detailed description of each of these perspectives.

An Ontological Perspective of Conceptual Change

According to the Macquarie Dictionary (1981), ontology is "the branch of metaphysics that investigates the nature of being and of the first principles, or categories, involved." From a broad philosophical perspective, ontology is related to the nature of everything in existence. There are several branches of thought along a continuum from idealists who view reality as a mental construct and physical objects as having no existence apart from the mind, to realists who accept that there exists an external reality (Guba & Lincoln, 1989; Schwandt, 1994). To be able to apply this broad notion of ontology to learning, and more specifically to conceptual change, it is useful to look at the ways that researchers in the conceptual change field use and describe ontology. Chinn and Brewer (1993) describe ontological beliefs as "beliefs about the fundamental categories and properties of the world" (p. 17). Chinn and Brewer go on to say that ontological beliefs are an important characteristic of students' prior beliefs that influence how an individual responds to anomalous information. They list examples of mistaken ontological beliefs that have been found to resist change, including beliefs that objects like electrons and photons move along a single discrete path (Brewer & Chinn, 1991), that time flows at a constant rate regardless of relative motion (Brewer & Chinn, 1991; Hewson, 1982), that heat is a substance (Wiser, 1988), and that force is something internal to a moving object (McCloskey, 1983).

Bliss (1995) describes children's ontological judgments about the world as "how children imagine the nature of objects and events" (p. 160). Bliss goes on to say that:

> ... ontological reasoning is unreflective and practical. It is about how we imagine the basic nature of objects and events, it tells us what things can obviously do, and what we can expect to happen in ordinary everyday situations. (p. 161)

In describing how children make these ontological judgements, Mariani and Ogborn (1990, 1991, 1995) suggest that objects and events can be placed along dimensions, for example, dynamic *vs* static, place-like *vs.* localised, cause *vs.* effect, discrete *vs.* continuous. For example, a student may make an ontological judgement about a solid salt in a solution as being a static system. A chemist would have a different ontological judgement and would see the system as being a dynamic system. For students to understand the salt solution in the same way that the chemist does, it would require a change in their ontological judgements about the system.

Empirical studies which report mistaken ontological beliefs that have been found to resist change are discussed by Bliss (1995). For example, Nicholls and Ogborn (1993) investigated students' ideas about energy. The students were asked simple questions about how objects can store energy, can have energy, need energy, use up its own energy, etc. The major findings were that students saw a clear source-user distinction - fuels and natural phenomena as sources and energy-using devices as users. Brosnan (1993; as reported in Bliss, 1995) examined physical and chemical change and formulated basic categories of thought or schemes that might fit students' ideas. In a similar manner, Venville and Treagust (1996) described a teaching sequence about the fluid mosaic model for cell membranes being taught by the teacher with the purpose of changing students' ontological view of cell membranes from a static, structural view to a more process-oriented view.

What is important here is that if students do think of concepts as being in different ontological categories to those in which scientists put them, then, in those cases, conceptual change must involve ontological changes in the students' cognitive structure. Chi et al. (1994) describe three experiments where students are presented with physics concept problems about light, heat and electrical current. The research uses a technique for assessing when conceptual change has taken place at the highest ontological level by the kind of predicates that students use. The authors claim that their experiment demonstrates that novices do not make use of the veridical process-predicates for light, heat and electrical current whereas experts do. That is, they claim that the students see these concepts belonging to an ontological category of matter and experts see them belonging to an ontological category of process. Chi et al. assert that this fundamental difference in the students' and experts' ontological view of light, heat and electrical current is of pivotal importance for conceptual change. This study concurs with Chi et al.'s conclusion that their definition of conceptual change "provides a lens to scrutinise and make sense of a great deal of data in the literature" (p. 42) and that their approach could lead "to a more rigorous way of operationalising and assessing what is meant by conceptual change, and when and under what conditions it can successfully be captured" (p. 41).

An Epistemological Perspective of Conceptual Change

Grosslight, Unger, Jay and Smith (1991) describe epistemology as "the nature of scientific knowledge and how it is acquired (p. 800). Similarly, Cohen and Manion (1989) describe epistemology as "the very bases of knowledge - its nature and forms, how it can be acquired, and how communicated to other human beings" (p. 6). Cohen and Manion discuss whether knowledge is "hard, real and capable of being transmitted in a tangible form, or whether knowledge is of a softer, more subjective, spiritual or even transcendental kind, based on experience and insight of a unique and essentially personal nature" (p. 7). As described above, ontology is the study of the nature of everything in existence; epistemology is essentially a subset of ontology because it is the study of one aspect of everything, that is, knowledge. Duschl and Gitomer (1991) claim that a central issue in the application of epistemology to science education "involves describing the mechanisms for change in the structure of theories or in the structure of conceptual schema as each relates to the growth of knowledge" (p. 847).

Duschl and Gitomer also discuss the learner's epistemological framework, that is, what learners consider to be evidence for or against an emerging scientific explanation. In this regard, Posner et al.'s (1982) conceptual change model, which describes students' conceptions as being intelligible, plausible and fruitful, is from an epistemological perspective because it describes the qualitative judgements and commitments about various theories and conceptions that a student might have. In a similar way, Perry's theory of intellectual development, which discusses students' ability to hold more than one theory and the ethics involved in becoming committed to a particular theory also is from an epistemological perspective (Finster, 1989). Hewson (1985) describes epistemological commitments as "the standards which a person holds which he or she uses to judge knowledge" (p. 164) and examines two epistemological commitments, internal consistency and generalisability. His conclusion to this paper is particularly relevant for a multidimensional approach to conceptual change:

> ...I have tried to make it clear that such commitments [epistemological] are not sufficient to explain student learning in science. To do that, it is certainly necessary to consider, at least, the specific content of the knowledge that students hold, the way in which that knowledge is structured, where and how they obtained it, and of course how each piece of knowledge is related to other knowledge that they possess. The point about each of these aspects is that they are all important in their own right, and need to be studied. But in doing so, it is remarkably easy to lose sight of epistemological commitments, to take them for granted, to assume that we need never worry about them. As far as instruction is concerned, I believe this is particularly true. Since I also believe that they play an essential role in learning, I hope that by making this role explicit, I shall encourage others, besides myself, to investigate ways of including them in our teaching (p. 171).

The conceptual change theory (Posner et al., 1982; Strike & Posner, 1992) advocates that competing conceptions gain or lose status in the students' mind. A students' conception can be considered to have no status or it can be intelligible, plausible or fruitful, in ascending order of status, to the student.

In the quote above, Hewson (1985) cautions that it is "remarkably easy to lose sight of epistemological commitments, to take them for granted, to assume that we need never worry about them" (p. 171). There is evidence of empirical research that assumed that a change in the status of students' conceptions has taken place where in actual fact it has not been measured by the researchers. Some researchers have attempted to consider conceptual change from an epistemological perspective by discussing the conceptual change model in their theoretical framework. Jensen and Finley (1995), for example, developed a teaching strategy for Darwinian evolution which utilised historical arguments and was based on the conditions of conceptual change. Even though the teaching strategy was designed to take into consideration the conditions of conceptual change or the status that a conception has for a particular student, researchers did not analyse their results in these terms. Instead they used pre/post tests and a conceptual trace analysis to document the general effectiveness of the intervention and specific changes in students' conceptions of evolution. They made no attempt to determine the effectiveness of the intervention strategy by considering changes in the status of Darwinian evolutionary theory in the minds of the students in terms of being intelligible, plausible or fruitful, even though this was what it was designed to do. This problem can be remediated by analysing interviews and classroom discourse for determining status (Hewson & Hewson, 1992). In this way, Treagust et al. (1996) used interview data to classify students' conceptions about refraction as being intelligible, plausible and fruitful.

A Social/Affective Perspective of Conceptual Change

The social/affective perspective of conceptual change encompasses the ideas of Pintrich et al. (1993) and is extended by Duit (1995) who suggested that dissatisfaction with an inappropriate conception is dependent on affective features. Even if we go back to the scientific analogy of conceptual change upon which Posner et al. based their first conceptual change model, the social/affective aspect is not completely ignored. West and Pines (1983), however, suggest that Posner et al. (1982) and others, such as Novak (1977), acknowledge the social and affective aspects of conceptual change but ignore them while the rational, cognitive aspects of conceptual change are asserted. West and Pines (1983) suggest that "nonrational components are intrinsic to conceptual change in the individual and that they should not be excluded in investigations of conceptual change" (p. 37). Nussbaum (1989) suggests that "Lakatos, Toulmin & Kuhn do not approach conceptual change as a necessary logical process, therefore we must rely on something in addition to logic" (p. 537). This is exactly the thesis of Pintrich, Marx and Boyle, who highlight

> the theoretical difficulties of a cold or overly rational model of conceptual change that focuses only on student cognition without considering the ways in which students' motivational beliefs about themselves as learners and the roles of individuals in a classroom learning community can facilitate or hinder conceptual change. (p. 167)

In a similar vein, Bliss (1995) claims that a major challenge to Piaget has been that his theory ignored the socio-cultural context of learning in that "context and cultural practices are seen as the fundamental units within which cognition has to be analysed" (p. 152). Yet, empirical studies which have viewed conceptual change from such a social or cultural perspective are rare even though a decade ago Solomon (1987) discussed the social influences on the construction of students' understanding of science. She examined the influences that social interaction, language, culture and the media can have on student learning and argued that such social influences can prevent student access to scientific thinking.

In examining whether analogies can contribute to conceptual change, Dagher (1994) suggested that the way in which analogies contribute to the students' level of comfort and security, raising the students' interest and enhancing their imaginative potential, should be examined. Subsequently, Venville and Treagust (1996) analysed a teaching situation where an analogical model was used to describe the function of the heart. The analysis of the student learning was carried out from Pintrich et al.'s motivational perspective and found that the simplicity of the heart model and that the way the teacher overtly used it to motivate the students raised their self-efficacy, convincing them that learning this difficult topic was something they could achieve. The authors concluded that the analogical model of the heart contributed to the process of conceptual change by acting as a "motivator".

Lee and Brophy (1996) drew on theories of student motivation and conceptual change in science to analyse 12 students' levels of task engagement and overall patterns of motivation. The study concluded that motivational and affective aspects of conceptual change approaches to curriculum development and teaching programs deserve attention. Similarly, Lee and Anderson (1993), who studied the same group of 12 students, concluded that overly cognitive approaches to conceptual change have resulted in researchers not accounting for many barriers to learning such as the motivational and affective issues observed in the students they studied. Lee and Anderson suggest that cognitively oriented researchers must "develop analytical tools and instructional programs that recognise the importance of students' agendas and commitments, as well as their conceptions and learning processes" (p. 604).

It can be seen from the presentation above that the three perspectives of the multidimensional framework for conceptual change - epistemological, ontological and social/affective - are supported by considerable bodies of research literature. The purpose of the multidimensional framework for conceptual change is not to separate these dimensions into distinct and unrelated categories, but rather to bring them together. This is consistent with the comments made a decade or more ago by Strike and Posner (1983) who warned that:

> Trying to group the factors involved in conceptual change into categories like rational and nonrational or (heaven forbid) cognitive and affective (as though motives and feelings were not highly conceptualised states) is on a par with doing brain surgery with a jackhammer - messy and lethal. (p. 43)

There is considerable overlap between the epistemological, ontological and social/affective perspectives, but ignoring one or two of these aspects is probably just as lethal as Strike and Posner's metaphorical surgery.

Research Design: Multiple Case Study

Research design serves to link the research paradigm to specific methods of collecting and analysing empirical materials (Denzin & Lincoln, 1994). The design comprises the skills, assumptions and practices that researchers utilise as they work on the empirical aspects of their research programs (Denzin & Lincoln, 1994). The research design employed to organise and manage the materials to be collected in this thesis is the multiple case study (Yin, 1994). Merriam (1988) describes the case study from the perspective of the qualitative or naturalistic research paradigm, which also is referred to as the constructivist paradigm (Guba & Lincoln, 1994). She says that the case study in education is useful to gain an in-depth understanding of a situation with the interest on "process rather than outcomes, in context rather that a specific variable, in discovery rather than confirmation" (p. xii).

Hitchcock and Hughes (1989) define a case study research method by saying it:

> evolves around the in-depth study of a single case, event or a series of linked cases or events over a period of time, the aim being to try and locate the 'story' of a certain aspect of social behaviour in a particular location and the factors influencing this situation so that themes, topics or key variables may be isolated or discussed. (p. 214)

In accordance with this definition, this research was an in-depth study of a series of linked cases, each case being the teaching and learning of genetics and specifically the concept of the gene in a particular class. Stake (1994) also describes a "collective case study" and Yin (1994) describes a multiple case design. All three descriptions are essentially the same thing, they describe a study containing more than a single case. The collective case study is chosen by the researcher because "it is believed that understanding them will lead to better understanding, perhaps better theorizing, about a still larger collection of cases" (Stake, 1994, p. 237).

Each of the cases in a multiple case study also can contain subunits or embedded units of analysis (Yin, 1994). In this study each of the classroom case studies of learning and teaching involving genetics contains students that can be considered to be embedded units of analysis. In Chapter 7, the learning of the students in one of the case study classes is examined in detail. Such a detailed examination of an individual student's learning will be referred to as a "student case study" in order that it can be differentiated from the multiple "classroom case studies".

The Multiple Cases in Western Australia

The multiple cases were made up of different science classes in Western Australia, the students, the teacher, and the learning situations that occurred in these classes. Eight teachers known to the researcher through personal contacts or through the Science Teachers Association of Western Australia (STAWA) were approached and asked to participate in the research. The teachers were selected with the express purpose of acquiring a sample of confident, competent teachers, willing to participate in the research. The cases were linked in that each class was being taught genetics or genetics-related concepts. Most of the classes were Year 10 and Year 12 (Table 5.2); however, one class was a Year 8 class studying cells, which included some lessons on the nucleus and its function in genetics.

As explained in Chapter 1, the purpose of this research study changed emphasis during the three years in which it was conducted. Similarly, the boundaries of the multiple case study changed. During the data collection phase, data were collected from eight classrooms (Table 5.2), but during the analysis phase, the focus of the analysis was narrowed to student learning about the concept of the gene rather than on the use of analogies in teaching and learning genetics. Three of the four Year 10 classes produced the most comprehensive data about the learning of the concept of the gene and these were chosen to make up the final series of case studies presented in Chapter 6 (Patton, 1990). The collective data from three classes were used to make generalisations about student learning and conceptual change (see Table 5.2 and especially note *). For an in-depth case study of individual student learning, the class with the broadest spectrum of student understanding of the concept of the gene was chosen as a focus in Chapter 7 (see Table 5.2 and especially note #). Chapter 8, which examines the factors influencing conceptual change, draws on the larger series of eight linked case studies to provide supporting evidence for the assertions presented.

Table 5.2: An outline of the multiple case studies conducted on genetics teaching and learning showing the class topic and the data collection procedures.

Teacher	Class/Topic	Number of Lessons Observed	Teacher Interview	Number of Students Interviewed	Student Work-sheet	Student Quiz
Mr Moore	Year 12/ Biology	15	yes	none	no	no
Ms Brown	Year 8/ Cells	5	yes	10	no	no
Ms Hardie	Year 12/ Biology	7	yes	6	no	no
Mr Hudson	Year 10/ Reproduction and Genetics	5	yes	12	no	no
Ms Prentice*	Year 10/ Reproduction and Genetics	10	yes	8	yes	no
Mr Yulang*	Year 10/ Reproduction and Genetics	17	yes	13	yes	no
Mr Counter*#	Year 10/ Reproduction and Genetics	17	yes	8	yes	yes
Ms Davies	Year 12/ Human Biology	no	yes	6	no	no

Note: Classes with an asterix (*) were included in the smaller series of thee case studies analysed in Chapter 7 and the class with a hash symbol (#) was the class used for an in-depth case study of individual student learning in Chapter 8.

Methods of Data Collection

Erickson (1986) argues that in searching for quantifiable data, researchers destroy or ignore the qualitative context that is the day-to-day lives of ordinary people in routine everyday situations. Through interpretive research and qualitative data collection techniques "each instance of a classroom is seen as its own unique system, which nonetheless displays universal properties of teaching" (Erickson, 1986, p. 130). The use of qualitative data collection techniques has been shown to be effective with regard to evaluating students' conceptual understanding of scientific phenomenon (Hewson & Hennessy, 1992; Treagust, et. al. 1996). In this study, qualitative methods of data collection, such as interviews and classroom observation were used to examine the classroom learning situations.

Classroom Observations

During classroom observations, the researcher assumed the role of an "observer as participant", where the researcher's activities were known to the group and her participation in the group was secondary to her role of information gatherer (Merriam, 1988, p. 93). Throughout the investigation, the researcher did not interfere in the classroom so that the locus of control remained with the teacher in the form of naturalistic observation (Adler & Adler, 1994). Field notes were recorded by the researcher and classroom activities specifically of interest to the research were audio-taped and the tapes fully transcribed. Some lessons in some classes were videotaped.

The classes were involved in data collection to different degrees depending on the amount of time that the teachers were prepared to have the researcher in their classrooms, the availability of students for interviews, and the availability of classroom time for other data collection such as student work-sheets and student quizzes. This meant that in some cases, a sample of lessons from the genetics course was observed by the researcher; in other cases, the entire genetics component of the course was observed. The data collected from each of the classes is outlined in Table 5.2.

Student Interviews

The content of the student interviews took the form of an "interview about concepts" (Carr, 1996; White & Gunstone, 1992) which aimed to probe the post-instruction understanding that each student had about genetics concepts from the lessons, particularly the gene concept. Consequently, the interviews were conducted close to the end of the genetics course in each class. The interviews were semi-structured

(Fontana & Frey, 1994; Hitchcock & Hughes, 1989) consisting of a prescribed interview protocol within which the interviewer probes and expands the interviewees' responses. An example of a student interview protocol is included in Appendix 2. The semi-structured interview was considered to be appropriate for the data collection in this research because a certain level of structure was desirable for the interviews in order to give direction to the data collection and facilitate data analysis (Fontana & Frey, 1994). Each teaching episode was different, however, and it was therefore considered appropriate that the interviewer had some flexibility during the interviews with the students so that aspects particular to each classroom could be pursued. Additionally, since each student possessed an individual knowledge base, flexibility to allow for these differences was desirable. Each interview, which took between 10 and 20 minutes to conduct, was tape recorded and fully transcribed. A total of 62 students were interviewed from the eight classes (Table 5.2).

Several criteria were used in a process of purposeful sampling to select students for the interviews (Patton, 1990). During the classroom observations and interactions with students, the researcher noted students who might be of interest to interview. This may have been because the student had asked pertinent questions in class, or demonstrated that he or she had a good understanding, or was having trouble with the concepts in question. Subsequently, the teacher was consulted about students who might be informative to interview, and finally the students themselves were asked if they would be prepared to participate in the interview.

Teacher Interviews

Five experienced biology teachers were interviewed at the beginning of the research with particular reference to the kind of analogies that they use to teach genetics, which, as explained in Chapter 1, was the original focus of this thesis. All interviews at this early stage were tape recorded and fully transcribed. Two of these teachers became further involved in the study as case study teachers and were interviewed, along with the other case study teachers, on a more informal basis. These informal interviews which consisted of discussions before, during and after class when time allowed, and centred around issues related to the teaching process, were recorded as field notes (Fontana & Frey, 1994). The teachers are introduced in more detail in the context of the case studies in Chapters 6 and 7.

Work-sheets

Student work-sheets, prepared by the researcher, were used by the teachers in the series of three case study classes analysed in Chapter 6 (Table 5.2). The work-sheets were given to the students before and after genetics instruction and were designed to elucidate information about the students' understanding of genes, chromosomes and DNA. Work-sheet information was used to help develop a generalised model of student learning of which more detail is supplied in Chapter 6. The work-sheets also were used to triangulate information from the student interviews and the class quiz in Chapter 7. A student work-sheet is shown in Appendix 3.

Class Quiz

A class quiz on protein synthesis, which required students to write down how proteins are made, was given in Mr Counter's class, the class that is analysed in detail in Chapter 7. The class quiz was prepared by Mr Counter and the students' answers were photocopied by the researcher and used to triangulate work-sheet and interview data in Chapter 7.

Data Interpretation

Methods of data interpretation are described in detail in Chapters 6, 7 and 8. Chapter 6 includes the interpretation of the work-sheet and interview data to collectively analyse the student learning about genes in three Year 10 classes selected from the total of eight classes in this study. Chapter 7 outlines the methods of interpretation used to describe students' pre and post-instruction conceptions as ontological models and to classify students' post-instruction conceptions as being intelligible, plausible or fruitful to the learner. Chapter 8 outlines how several theoretical perspectives are used to analyse the data to demonstrate the factors that influence conceptual change. A search for disconfirming evidence (Erickson, 1986) was a continuous process throughout the interpretation of data and disconfirming evidence is presented and discussed in Chapters 6, 7 and 8 alongside the supportive evidence.

Trustworthiness

Guba and Lincoln (1989) use the term "trustworthiness" to refer to the overall quality of a piece of research. They argue that the paradigm of naturalistic or constructivist inquiry demands that standards should be different from the traditional standards of rigour in positivistic styles of research. Guba and Lincoln (1989) propose that the traditional notions of internal and external validity, reliability and objectivity should be replaced by the notions of credibility, transferability, dependability and confirmability.

Credibility

Internal validity, or how the research findings match reality, is a strength of qualitative research if "reality" is not viewed in the traditional sense but as something constructed in people's minds (Merriam, 1988). This interpretation of "reality" is compatible with the constructivist perspective of this research project. Altheide and Johnson (1994) suggest that "qualitative research ... is commonly guided by the ethic to remain loyal or true to the phenomena under study" (p. 488). In this regard, the researcher of this study does not attempt to describe the absolute truth, but to describe in a systematic manner the patterns that appear to the researcher to be present in the data. These patterns are based on the researcher's analysis and interpretations of the data collected by her. It is expected that people will read these interpretations and judge them by their own understandings of the research and the world in general.

Guba and Lincoln (1989) argue that the major aim of naturalistic inquiry is to reconstruct the perspectives of those being studied. One standard of trustworthiness, which Guba and Lincoln suggest is parallel to internal validity, represents the level to which the researcher can demonstrate that the interpretations of data are credible. Techniques for enhancing the credibility of research suggested by Lincoln and Guba (1985) include systematically considering many sources of data and techniques for obtaining and analysing data so as to be able to consider them from different angles and perspectives. The credibility of the research findings in this study is enhanced by the use of triangulation so that many sources of data and data collection techniques are utilised and the analysis is carried out from different perspectives of conceptual change (Mathison, 1988). Merriam (1988) also suggests the use of triangulation to enhance the internal validity or credibility of qualitative research studies. The comprehensive approach to triangulation at data collection and interpretation levels for each of the research questions of this thesis is outlined in the next section and in Table 5.3.

In addition to triangulation, Merriam (1988) suggests that peer examination of findings can contribute to the credibility of the research. As part of a collaborative research team at the Science and Mathematics Education Centre at Curtin University of Technology, the researcher is indebted to her colleagues for their continued peer examination of the findings of this research study. Not only has there been peer review by colleagues at the same university, the researcher has presented at research and teacher-oriented conferences and published in research and teaching publications

(See Appendix 1). This activity has put the findings of this research open to scrutiny by fellow teachers and journal reviewers at several stages of the research process. Although this practice has extended the thesis process, the critical feedback has contributed to the credibility of the findings.

Table 5.3: The system of triangulation in the research design at the data collection and interpretation levels.

Kind of triangulation	**Research Question 1**	**Research Question 2**	**Research Question 3**	**Research Question 4**
Data source and collection level: triangulation of sources and methods (Patton, 1990)	•work-sheets •class observation •student interviews	•student interviews •work-sheets •class quiz •class observation •teacher interviews	•student interviews •class observation •teacher interviews	•student interviews •work-sheets •class quiz •class observation •teacher interviews
Data interpretation level: perspective triangulation (Patton, 1990)	•ontological perspective •epistemological perspective	•ontological perspective •epistemological perspective	•social/affective perspective •other interpretive perspectives	•ontological perspective •epistemological perspective •social/affective perspective •other interpretive perspectives

Researcher bias is said to contribute to the poor credibility of interpretive research (Merriam, 1988). One way to address this problem, according to Merriam, is to clarify the researcher's theoretical orientation at the outset of the study. Earlier sections of this chapter have clearly outlined the researcher's theoretical orientations with regard to methodology and to conceptual change.

Triangulation

This research used qualitative methods of data collection. A criticism of qualitative approaches to research is that they can be subjective and present a biased view of the real situation. Thus the credibility of the research might be difficult to establish. One way which has been suggested for enhancing the credibility of research findings is to triangulate (Mathison, 1988; Altheide & Johnson 1994; Stake, 1994). Cohen and Manion (1989) define triangulation as "the use of two or more methods of data collection in the study of some aspect of human behaviour (p. 269)." According to

Merriam (1988), triangulation is a basic strategy to ensure internal validity and Stake (1994) suggests that for case study research triangulation serves to clarify meaning and verify the repeatability of an observation or interpretation while at the same time acknowledging that no observations or interpretations are perfectly repeatable.

Table 5.3 outlines how this research incorporated triangulation at the data collection, and interpretation levels. An integrated and thorough system of triangulation for each of the research questions was designed to enhance the credibility, transferability and dependability of this research.

Dependability and Confirmability

This qualitative study seeks to describe and explain, in a series of case studies, student learning about the gene concept. It is therefore a highly contextual study, and reliability of research in its traditional sense, referring to the extent to which the findings can be replicated (Merriam, 1988), is inappropriate. Merriam makes a case for circumventing reliability in qualitative research based on the notion that human nature is never static and that "reliability in research design is based on the assumption that there is a single reality which if studied repeatedly will give the same results" (p. 170).

Guba and Lincoln (1989) also voice objections to the use of the conventional term reliability in establishing trustworthiness in qualitative research, suggesting the alternative term, "dependability" (p. 242). They believe that in order for the research to be dependable the inquiry process needs to be "both tracked and trackable (publicly inspectable), so that outside reviewers of such an evaluation can explore the process, judge the decisions that were made, and understand what salient factors in the context led the evaluator to the decisions and interpretations made" (p. 242). Hence, dependability in a case study can be established if the data can be tracked to the sources, and the assembly of the interpretations is clear. Guba and Lincoln also suggest that the criterion of objectivity be replaced with the term "confirmability" and that this also can be established by the reviewer being able to track the data and interpretations presented in the research.

In order to establish the dependability and confirmability of this doctoral research study, the researcher has presented methodology and case studies with a "thick description" (Geertz, 1973; Guba & Lincoln, 1989). This allows the reviewers to proceed on their own tracking and interpretation process, coming to their own conclusions.

Transferability

Merriam (1988) defines external validity as the "extent to which the findings of one study can be applied to other situations" (p. 173), that is, how generalisable the findings are. Guba and Lincoln (1989) once again suggest a parallel criteria for external validity or generalisability. They believe that "transferability" (p. 241) is a better criterion for judging the adequacy of research carried out from a constructivist perspective. While generalisability is based on randomisation, transferability is based on a process of checking the degree of similarity between the context under study and the context to which the judgments are to be transferred (Guba & Lincoln, 1989). This process must be carried out by the person who wishes to do the transferring. The transferability of the study can be demonstrated by the researcher by "providing as complete a data base as humanly possible in order to facilitate transferability judgements on the part of others who may wish to apply the study to their own situations" (Guba & Lincoln, 1989, p. 242).

In order to strengthen the transferability of this research, several procedures have been integrated into the methodology. The use of a series of cases to study the same phenomenon strengthens the generalisability of the findings (Merriam, 1988). It also was considered important that a "thick description" of the case studies is provided in order to establish the transferability of the findings.

Ethical Issues

> What is plain is that codes and consent are opposed to deception.
> (Punch, 1994, p. 90)

The data collected for this thesis have not been of a highly sensitive nature, politically, socially or physically. Regardless of this, it has been of utmost importance to the researcher to maintain an ethical approach to the research process. Because the research has been conducted using the case study strategy, the most important ethical issues are related to the participants of the case studies, namely the teachers, their students and the schools in which the research was conducted (Brickhouse, 1991). The researcher has highly valued the interactions she has had with the participants and the ethical approach that guided this thesis is outlined below as a set of codes (Punch, 1994).

A Code of Informed Consent

In some forms of research, deception has been justified in that the value of the results of the research outweigh the harm it may cause the participants (Guba & Lincoln, 1989; Punch, 1994). In this thesis, this has not been the case and a code of informed consent has guided the involvement of the teachers, students and schools in the research.

The teachers were invited to participate in the research by the researcher and were fully informed about the nature of the research. The direction that research will take is not always entirely predictable and this makes informing the participants about the exact nature of the research questions difficult (Brickhouse, 1991). The focus of this research has changed during the three years that it has been conducted; however, at each stage participants were informed as accurately as possible about the purpose of the data collection at that particular time. A friendly and collegial relationship existed between the researcher and the teachers, and this enabled communication about the research process.

In order to maintain a code of consent, it was important that the teacher was able to negotiate with the researcher the extent to which he or she became involved in the research. This negotiation was upheld throughout the research so that the teachers could maintain control of the research process within their classroom. It can be seen from the variability of data collected in Table 5.2 that some teachers had a high level of involvement including classroom observation, teacher interviews, student interviews and student work-sheets, while others did not wish to be included in data collection other than classroom observation and teacher interviews. Although this inconsistency between cases made data analysis difficult, the ethical issue of whether or not to use valuable classroom teaching time for research was considered important, particularly for Year 12 students studying for their university entrance examinations (Wong, 1995). In some cases, Year 12 students were interviewed in their own time; however, this was not possible in all cases.

Students and their parents and guardians in all classes were informed by letter about the presence of the researcher in the classroom, the purpose of the research and the possibility that students would be asked to participate in interviews (see Appendix 4 for a sample of a letter sent to parents and guardians). The letter also informed the parents that student involvement in the interview process was voluntary. Students were asked if they were willing to participate in the interviews; only one student from all the classes declined to be involved. Before all interviews, students also were asked if they objected to a tape recorder being used to record data.

Principals of participating schools also were informed about the nature of the research by letter. In line with the Education Department of Western Australia's guidelines, the Principals' permission to enter the school to conduct research was gained before the researcher visited the schools (an example of letters sent to Principals can be found in Appendix 4).

A Code of Exchange of Information

When sensitive information is collected through the research process, it can be very difficult for the researcher to give feedback to the participants on the findings (Brickhouse, 1991; Deyhle et al., 1992). In this study, a code of exchange of information was maintained, and the researcher gave feedback to the participants in several ways. Firstly, casual meetings with teachers before, after and during lessons, when time allowed, often resulted in the researcher and teacher discussing the things that had been happening in the classroom and the researcher's analysis of those situations (Fontana & Frey, 1994). The teachers had an opportunity to respond and qualify the actions that had been taken in the classroom. Secondly, all raw data such as classroom transcripts and interview transcripts were returned to the teacher for his or her scrutiny and comment. Thirdly, summaries of the analysis of the classroom situations were provided to the teachers. Finally, even though it has been one or two years since the researcher visited some of the teachers' classrooms, it is planned that a final, executive summary of the findings of the research will be sent to each of the teachers who participated in the study. It is hoped that the classroom teachers will benefit from the study by learning more about the way that their students learn about genes and about some of the things that influence that learning process (Brickhouse, 1991). Research papers from this study have been made available to the participant teachers and other biology teachers through state, national and international journal publications and conference presentations (Appendix 1).

In some cases, this ethic of exchange of information may have caused anxiety for some of the teachers because their teaching approach may not appear to be effective in the light of the research analysis (Brickhouse, 1991). For this reason it was considered important that a code of confidentiality also was adhered to throughout the report writing stage of the thesis.

A Code of Confidentiality

Confidentiality was considered important in this thesis because the participating teachers' professional status was at risk through the disclosure of information about the teaching and learning that was happening in their classrooms. Confidentiality is not something that can be ensured because the nature of case study and the descriptive reporting process means that if someone wanted to identify participants, it is highly possible (Deyhle, Hess & LeCompte, 1992; Punch, 1994). Regardless of this, the researcher embraced a code of confidentiality so that the teachers, students and schools participating in the research are not immediately identifiable to people who read documents that report the findings. Several strategies have been employed by the researcher to enhance the confidentiality of the findings.

All teachers, students and schools have been given pseudonyms throughout this written report and other publications resulting from the research. Information other than names that could identify participants also have been altered or removed to enhance confidentiality. Raw data are kept in a locked filing cabinet and only the researcher and her supervisor have access to it. These strategies will help to protect the privacy of the participants and prevent any bias on the part of the readers/reviewers should they know the teachers, students or participating schools.

In one situation it was appropriate for this code of confidentiality to be broken. One of the teachers involved in the study worked as a co-author with the researcher to write a case study story for a science education book about the teaching in her own classroom (Venville & Bryer, in press). In this situation the teacher wished to be acknowledged as the teacher in the story and the code of confidentiality was considered inappropriate.

A Code of Trustworthiness

Finally, the trustworthiness or rigour of the research methodology and findings is an important aspect of the ethical approach taken to this research (Deyhle, Hess & LeCompte, 1992). The section above on trustworthiness outlines the attitude taken to ensuring thoroughness of methodology and the section on the multidimensional interpretive framework explains the multiple perspectives approach to interpretation.

Conclusion

The interpretive approach taken in this study to aspects of the research process has been outlined in this chapter, and a summary is provided in Table 5.1 This study was conducted in the constructivist research paradigm with a grounded approach to theory development. A multidimensional framework for conceptual change was used to guide the focus of the inquiry. The research design of a multiple case study of eight classroom sites is examined at three levels in the following three chapters that embody the findings of this research. The next chapter, Chapter 6, analyses the data collected from three of the eight classes in a collective manner to address the first research question, what happens to Year 10 students' conceptions of the gene when they learn genetics? An ontological perspective of conceptual change is used to examine the data. Chapter 7 focuses on one of these three classes to make a detailed examination of individual students, their learning and conceptual change from ontological and epistemological perspectives. Chapter 8 draws on several perspectives of conceptual change and data from the whole series of eight classroom case sites to elaborate on the factors that influence conceptual change.

CHAPTER 6

THE DEVELOPMENT OF AN ONTOLOGICAL PATHWAY TO DESCRIBE STUDENTS' LEARNING ABOUT GENES

> [U]nderstanding of a concept is not a dichotomous state, but a continuum. ... Everyone understands to some degree anything they know something about. It also follows that understanding is never complete; for we can always add more knowledge, another episode, say, or refine an image, or see new links between things we know already. (White & Gunstone, 1992, p. 6)

Introduction

This Chapter is the first in a series of three chapters that comprise the results of this thesis. Chapter 6 largely addresses research question 1 and describes a broad examination of students' understanding about the concept of the gene from before to after a genetics course in three Year 10 classes.

The concept of the gene is often portrayed in the media as a powerful scientific phenomenon. Recent developments in genetics such as the human genome project and genetic engineering technologies contribute to the high-profile image of the gene in our society, and huge amounts of money are being contributed by the world's governments to biotechnological research (Cook-Deegan, 1994). Genes will obviously have a large role to play in the lives of future generations: a role beyond the biological one that genes have played in the lives of past generations. Understanding the concept of the gene is, therefore, an important issue for young people. What can teachers do to help high school students understand what a gene is and what a gene does? A critical first step in answering this question is to determine what students understand about the concept before they start a high school genetics course and then to investigate the process that students go through when they learn more about the concept.

The gene concept is one that has had little concentrated attention from researchers in science education. As outlined in Chapter 1, however, two studies in the 1980s indicated that students at the high school level have an understanding that genes determine features but few of these students have a good understanding of the gene as a unit of genetic information or the nature of gene function (Clough & Wood-Robinson, 1985; Hackling, 1982).

More recently, Martins and Ogborn (1997) focused on the concept of the gene and investigated primary school teachers' understandings of the gene and related concepts. Martins and Ogborn (1997) use Mariani and Ogborn's (1990, 1991, 1995) ontological dimensions as a framework for analysing primary school teachers' metaphorical reasoning about genetics. Martins and Ogborn relate ontological judgements and metaphorical reasoning by saying that "in metaphorical thinking, necessity derives not from logical relations but from the basic nature of things as they are imagined to be" (p. 60). In this sense, they found that by elucidating the metaphors that primary teachers use for genes, they could examine the teachers' ontological judgements about genes, that is, how the teachers imagined the basic nature of genes. Martins and Ogborn found that the metaphorical images of genes that primary school teachers used could be described as two metaphorical models as shown in Figure 6.1.

gene = entity + natural action

(a) The basic model

gene = sequence of instructions

(b) The supplementary model

Figure 6.1: Two metaphorical models of genes proposed by Martins and Ogborn (1997).

The basic model of Martins and Ogborn (1997) (see Figure 6.1a) is described as one where teachers see a gene as a particle that moves from parent to child unaltered. In this model, the gene is associated with one feature and the presence of the trait is associated with the presence of the gene-particle. Many of the primary teachers in the study found, however, that this basic model failed to explain how genes act. This resulted in an extension of the basic model in that some teachers saw the gene-particles as being active rather than passive. That is, genes have a natural behaviour which is seen to be transmitted along with the particle from generation to generation. A supplementary model described by Martins and Ogborn was used by some teachers to account for the action of a gene (Figure 6.1b). This supplementary model considers genes as a set of instructions rather than objects, and the transmission is of commands rather than a feature associated with a particle.

The purpose of this chapter was to investigate students' understanding about the concept of the gene at the beginning and conclusion of instruction in a 10-week genetics course and to scrutinise any changes which take place for evidence of conceptual change. In this chapter, one aspect of the conceptual change framework developed in Chapter 5, that is, an ontological perspective of conceptual change, was used to examine the data. The possibility was explored that changes which occur in the way students "see" genes, in an ontological sense, can be described as shifts between the metaphorical models of genes such as those proposed by Martins and Ogborn (1997). Although the models proposed by Martins and Ogborn's are not developmental, it was considered possible to extend and modify the models to develop a picture of the way that high school students learn about the concept of the gene.

The Multiple Case Study

This research was conducted with a multiple case design (Yin, 1994) of a series of eight linked case study classroom sites (Hitchcock & Hughes, 1989; Stake, 1994). Three sites (Merriam, 1988, p. 47) within this series of eight case studies were chosen for examination in this chapter because they focused on the concept of the "gene" as taught in Year 10 in Western Australian high schools. The sites were three classes in two metropolitan high schools in Perth. Two of the classes were in a government, co-educational high school, the third in a private, girls-only high school. The three classes consisted of mixed ability Year 10 students (ages 14-15 years) who had not studied genetics previously and were taught by experienced biology teachers (two male and one female) during a 10-week course on sexual reproduction and inheritance.

Triangulation of data sources	Triangulation of data collection techniques
School A: Class 1	videotape, audio-tape and observation of classes
School B: Class 2	student work-sheets
School B: Class 3	student interviews

Figure 6.2: An outline of levels of triangulation built into the method of this study.

In order to enhance the validity of this research, triangulation at the data sources and of the data collection methods were built into the methodology (Mathison, 1988; Patton, 1990) (see Figure 6.2). The data sources included students from three different classes from two different schools. The data collection techniques involved audio-tape, videotape and observation of classroom lessons, student work-sheets and student and teacher interviews. Details of these data collection techniques are outlined in Chapter 5.

All students' pre-instructional and post-instructional conceptions of "genes", "chromosomes" and "DNA" were determined by work-sheets given before and after the course (see Appendix 3). The terms "DNA" and "chromosomes" were considered to be closely connected with the concept "gene", and it was thought that information that students wrote about these additional terms could be used to help determine their understanding about genes. The students were considered to be heterogeneous because none of the schools had a special selection process of entry to the classes, hence these data are discussed together. Consequently, a total of 83 students completed pre-instructional work-sheets and 79 completed post-instructional work-sheets at the end of the 10 week course. The work-sheets simply asked the students to write down what they knew about the terms "genes", "chromosomes" and "DNA". It was assumed that students would write down the things that they considered most important about the concepts. The work-sheets were scrutinised for students' ideas about genes, chromosomes and DNA which were expressed in the students' writing. A list of these ideas was made up and the number of students with the same idea was recorded. In this way, the ideas that students had about genes emerged from the data. At the end of the course, interviews were conducted with a total of 29 purposely selected students, eight from each of two classes and 13 from the third (Patton, 1990).

The Classroom Contexts

A summary of the three classroom contexts including the unit objectives and the classroom strategies utilised by the teachers is presented in Table 6.1.

The two male teachers who taught in the government schools, Mr Counter and Mr Yulang (pseudonyms are used for anonymity), used the Western Australian State School Curriculum unit called *Biological Change 6.2*. The specific objective in this unit which relates to students' conceptions of genes is simply that students will be able to "describe the nature of a gene" (Education Department of Western Australia, 1987, p. 95, objective K2464). There are other objectives related to genes, for example about dominance and recessiveness, sex linkage, monohybrid crosses and Gregor Mendel's work, but nothing more specific about the structure or function of the gene. Due to the non-specific and generalised nature of the objective about genes in this unit, the detail of gene structure and function that is taught is very much determined by the teacher. The female teacher, Ms Prentice, used a different curriculum, specific to the private school in which she worked. The specific objectives related to this course state that students will be able to: distinguish between a gene and a chromosome in terms of their structure and their role in the inheritance process, and; describe the nature of DNA (Biological Science Course 10, Topic 2, page 2).

Table 6.1: A summary of the three classroom contexts included in the multiple case study.

	Class 1	**Class 2**	**Class 3**
teacher	Ms Prentice	Mr Yulang	Mr Counter
school	private girls' school	government co-ed	government co-ed
unit objectives	• distinguish between a gene and a chromosome in terms of their structure and their role in the inheritance process • describe the nature of DNA	• describe the nature of a gene	• describe the nature of a gene
classroom strategies	• detailed twisted ladder analogy (~20mins) • briefly mentioned that genetic code is like morse code with information used to produce things like saliva	• brief lookout tower analogy for DNA structure (<2 min) • brief blueprint of architect's plan analogy for genetic code (< 1min)	• DNA paper cut out model (1.5 lessons) • protein synthesis model (~30 mins)
No. students interviewed	8	13	8

The three teachers involved in this case study used different teaching strategies and also emphasised different aspects of genes. See Table 6.1 for a summary of the teaching approaches utilised in the three classes. Ms Prentice concentrated on the structure of DNA and used a detailed twisted ladder analogy which took at least 20 minutes of class time. The analogy clearly drew the similarities between the rungs of a ladder and the nucleotides of DNA and the uprights of a ladder and the sugar and phosphate chain of DNA. Ms Prentice also outlined differences between the DNA and the ladder analogy, such as size and the twisted nature of DNA. She commented to the researcher that she felt that it was important for her students to learn the structure of DNA because many of them would need to understand how the genetic code is stored when they studied genetics in more depth in Human Biology or Biology in Year 11 and Year 12. Ms Prentice didn't teach protein synthesis in a detailed fashion because she felt it was unnecessary and too difficult for students at this Year 10 level. Ms Prentice did mention to her class, however, that genes control protein synthesis by saying that the genetic code is "like morse code because the letters which represent the nucleotide bases of the DNA form a code to produce something, like saliva, for example."

Mr Yulang explained to his class that the nucleus of the cell is like a "brain or a "computer" because it "controls the cell's functions". He also said that the structure of DNA is like a lookout tower in one of Perth's parks (the lookout tower is a DNA inspired double staircase) before he showed the students a diagrammatic model of DNA structure on an over-head projector. Mr Yulang did not, however, go into a detailed description of any of these analogies, spending less than two minutes on the lookout tower analogy and the over-head projection of the DNA model combined. Mr Yulang then proceeded to use blackboard notes and written questions about genes and DNA. Mr Yulang did not describe the function of genes or DNA in detail, however he briefly described the genetic code as being like a "blueprint or an architects plan of what you are going to look like". The class textbook (Williams & George, 1988), which the students were directed to read in class, also compared the nucleus with a computer (Figure 6.3).

> We can compare the nucleus to a computer, it contains a blue print or pattern for what that cell is to be like and what it is to do. The nucleus contains the pattern for the organism as a whole and influences its development.
>
> Inside the nucleus are structures called chromosomes. On the chromosomes are genes which carry the genetic information of the cell.
>
> ....
>
> Chromosomes contain the hereditary material (genes). They are found in the nucleus of the cell. A gene is responsible for passing on heritable characteristics.
>
> Genes occur along the length of each chromosome. By their actions, genes determine all hereditary characteristics of an organism.

Figure 6.3: Extracts from the student textbook (Williams & George, 1988) which describe genes and chromosomes.

The third teacher, Mr Counter, specifically concentrated on the structure and function of genes and chromosomes (see Table 6.1). Mr Counter organised his students to work in groups so that they could construct paper cut out models of the structure of DNA. The DNA models were detailed enough to show how the nucleotides represented a code. The students used their model of DNA to determine the order of amino acids in a protein, which they also constructed from cut out paper shapes. The amino acid chains constructed by the students were displayed at the front of the class. Mr Counter used a second model which demonstrated how the genetic code is transferred from the nucleus to ribosomes for protein synthesis. Mr Counter spent a total of about two, 50 minute lessons on these models. A detailed description of Mr Counter's teaching strategies is presented in the next chapter where individual student's learning in Mr Counter's class is examined in more detail. Mr Counter commented to the researcher that he believed that by using the models, his students could understand the idea of protein synthesis without detailed knowledge of transcription and translation. He said that he felt that it is important for introductory level students to make the connection between genes and protein synthesis, so that they can see how genes have an affect on the make-up of living things.

An Ontological Pathway of Students' Changing Conceptions of Genes

Based on the work-sheet and interview data collected from the three classes there are perceptible ontological shifts in the way this group of students saw genes - from being passive to active, from being particle-like to like a sequence of instructions, and to being associated with the process of protein synthesis. There are consistencies between these findings and the metaphorical models that primary school teachers used for genes as described by Martins and Ogborn (1997) (Figure 6.1). Martins and Ogborn's metaphorical models in fact provided an excellent framework on which to build a pathway of the changes in students' conceptions of genes. The next few paragraphs describe these ontological shifts and a pathway of learning, based on the collective classroom data, is proposed.

Students in all three classes clearly learnt facts and information over the course of instruction. For example, the work-sheet data (Table 6.2) (see Appendix 3 for work-sheet) which displays students' pre- and post-instruction conceptions about genes, chromosomes and DNA show that there was an increase from four to 59 in the number of students who wrote that genes are located on chromosomes (Table 6.2, Item 3); an increase from eight to 20 in the number of students who said that DNA is the structure or chemical found in genes or chromosomes (Table 6.2, Item

Table 6.2: Analysis of pre- and post-instructional work-sheets showing numbers of students holding certain concepts about genes, chromosomes and DNA.

	Concept	pre-instruction n = 83 (%)	post-instruction n = 79 (%)
1.	genes (chromosomes) are passed (inherited) from parents to offspring	58 (70)	35 (44)
2.	genes (chromosomes) control (determine, decide etc.) characteristics	35 (42)	60 (76)
3.	genes are located on chromosomes (DNA)	4 (5)	59 (75)
4.	DNA/chromosomes/genes code/hold information for characteristics	9 (11)	37 (47)
5.	DNA is structure/chemical found in genes/chromosomes	8 (10)	20 (25)
6.	chromosomes/DNA/genes/ are found in nucleus/cell	12 (15)	48 (61)
7.	there are 46 chromosomes in normal cells and 23 in gametes	0 (0)	32 (40)
8.	DNA is different in every human being	15 (18)	2 (3)
9.	DNA is a helix (ladder) arrangement	1 (1)	15 (19)
10.	genes are dominant & recessive/ genes have 2 alleles	0 (0)	13 (16)
11.	chromosomes determine sex	8 (10)	3 (4)
12.	DNA/chromosomes are in the blood	12 (15)	0 (0)
13.	DNA is "building blocks" of our body / DNA is what people are made up of.	11 (13)	3 (4)
14.	chromosomes divide	6 (7)	2 (3)
15.	genes make us up	5 (6)	0 (0)
16.	DNA consists of sugar/phosphate/nitrogen base/nucleotides	0 (0)	5 (6)
17.	DNA has something to do with blood testing	4 (5)	2 (3)
18.	DNA determine species / make up variation in living things	4 (5)	0 (0)
19.	DNA is in Jurassic park and can be used to recreate	4 (5)	0 (0)
20.	chromosomes make up genes	3 (4)	2 (3)
21.	chromosomes are found in your brain	3 (4)	0 (0)
22.	genes make you resemble your parents	3 (4)	0 (0)
23.	too many chromosomes can cause problems eg. Downs Syndrome, brain damage	3 (4)	0 (0)
24.	chromosomes are part of plant cells for photosynthesis	3 (4)	0 (0)
25.	DNA is the scientific name for genes/chromosomes	2 (2)	1 (1)
26.	genes are passed through sexual intercourse	2 (2)	0 (0)

5); and an increase from 12 to 48 in the number of students who said that genes, chromosomes or DNA are found in the nucleus or cell (Table 6.2, Item 6). However, it is not the facts and information that these students learnt that is important to this investigation, rather it is the changes in students' conceptions of genes in an ontological sense that are interesting from a conceptual change point of view.

The most common way for students to describe genes prior to instruction was as something that can be passed from parents to offspring (Table 6.2, Item 1). Before instruction, 58 (70%) students initially described genes in this way. Examples of comments written by students on their pre-instruction work-sheets which reflect this description of genes are included below.

Jo:	[Genes are] what your parents pass to you so that you get your characteristics.
Peta:	Genes are things that you inherit from your parents, they affect things like your hair and eye colour etc.
Michelle:	[Genes are] something you inherit from your parents.
Mark:	They [genes] are characteristic cells that are passed from one generation to another.
Briohny:	[Genes are] inherited characteristics that are passed down generation to generation by your ancestors.
Michael:	[Genes are] the cells that make you different which you get from your parents.

Comments such as "genes are things", "they are characteristic cells" and "genes are something" suggest that students have an image of genes as some kind of particle. The most important thing about this gene-particle according to the majority of students (70%) is that they "are passed down generation to generation", or that they are "things that you inherit from your parents". This suggests that many of the students initially saw genes as being passive, that is, what happens to them is more important than what they do. Before instruction, only 35 (42%) students said on their work-sheets that genes control characteristics. In other words, the idea that genes get passed from parents to offspring is more prominent, in the majority of students' minds, than the idea that genes have an effect on characteristics. This initial, passive, particle-like view of genes is consistent with Martins and Ogborn's

(1997) basic model that primary school teachers used and will be referred to henceforth as the "passive particle gene" model. This ontological view that a gene is a particle rather than something else, such as an event, a characteristic or an instruction for example, is probably the most common way that students in these three classes saw genes prior to instruction. The "passive particle gene" model is, therefore, an appropriate starting point to consider the changes in many of these students' conceptions about the gene.

From a Passive Particle Gene to an Active Particle Gene

At the end of the genetics course, the number of students who wrote that genes are passed from parents to offspring (Table 6.2, Item 1) decreased to 35 (44%). Conversely, the number of students that wrote that genes control characteristics increased from 35 (42%) pre-instruction to 60 (76%) post-instruction (Table 6.2, Item 2). This result indicates that there has been a significant increase in the number of students in these classes who now saw genes as being active rather than passive, that is, they saw genes as having "control of" or an "effect on" characteristics. This can be interpreted as an ontological change in the way students see genes from being passive to being active. The interviews following the course reflected this analysis based on the work-sheets in that, after instruction, many of the students said they saw genes as controlling characteristics. Some of their responses are included below.

Pippa:	They kind of, oh, I can't say it, um, control the characteristics of a person - like eye colour or whatever.
Karen:	It [chromosomes] holds genes so to control characteristics, sort of like the body.
Heidi:	Um, to determine different characteristics of the offspring.
Liz:	And the genes control certain characteristics of your body, like for example, I don't know, the shape of your nose or whatever.

This post-instruction increase in the number of students, from 42% to 76%, who associated some action or control of characteristics (Table 6.2, Item 2) with the particle-like gene can be represented by a second, "active particle gene" model. The shift in some students' conceptions from a "passive particle gene" model to an "active particle gene" model is represented in Figure 6.4. The students with this new conception still considered genes as a particle of some kind. However, what is important is that the description of genes tended to change from the passive idea that they are passed from parents to offspring to the more active idea that genes are associated with some kind of action or control over characteristics. Although the shift observed in students' conceptions in these three classes was from the "passive particle gene" model to the "active particle gene" model, it is acknowledged that the reverse shift could occur at a later date, hence reverse arrows are included in Figure 6.4 and subsequent figures of a similar nature. Because reverse shifts in student learning were not directly observed in this study, the reverse arrows are reduced in size.

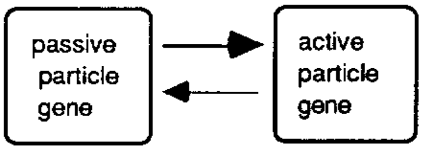


Figure 6.4: A diagram representing the shift in some students' conceptions from the initial "passive particle gene" model to an "active particle gene" model.

From a Particle-like Gene to a Sequence-of-Instructions Gene

A second ontological change in the way some of these students saw genes was from being particle-like to being like a sequence of instructions. There was an increase in the number of students who wrote that DNA or the chromosomes store the information or consist of a code for determining characteristics from nine (11%) pre-instruction to 37 (47%) post instruction (Table 6.2, Item 4). Examples of some students' comments on their post-instruction work-sheets follow.

April:	[Chromosomes are] things inside the nucleus that carry the information to decide what characteristics the organisms are going to have.
Paula:	Dioxoribonucleuic [sic] Acid contains genetic coding.
Peta:	Deoxyribonucleic acid. It is a double helix, a chemical & it looks like the ladder in King's Park. It is a code that controls functions of cells or the whole body.
Maria:	Genes are messages that tell the characteristics of an offspring ie: hair colour.

Samantha: Deoxyribonucleic Acid is what stores the information in a cell.

Allison: Genes are information stored on chromosomes. They decide things such as hair colour, eye colour. The are passed on from your parents. ... Deoxyribose Nucleic Acid carries the genetic information or the genes on the chromosomes.

Scott: Genes are situated on the chromosome like "bands" and store the information for the cells. Deoxyribosenucleic [sic] acid, this is a complex structure storing information.

Paul: [Chromosomes are] string like fibres which hold bands with genes of genetic information.

It is probable that students who wrote comments such as; DNA is "a complex structure storing information" and DNA "is a code which controls functions of cells" and "genes are messages" on the post-instruction work-sheet now saw genes more like a sequence of instructions rather than a particle. It is probable, therefore, that during the course of instruction, many students' conceptions of genes changed to something more like Martins and Ogborn's supplementary model (Figure 6.1b) which represents some primary school teachers' idea of a gene being like a sequence of instructions. The basic ontological nature of the gene has changed in some students' minds from being simply particle-like to being like a sequence of instructions. This change is represented by the third, "sequence of instructions gene" model as shown in Figure 6.5. It is not suggested that students discarded the idea that a gene is a particle. Rather, it is proposed that some students looked "within" the particle-like gene to see it as a sequence of instructions or a "code" or a store of "information".

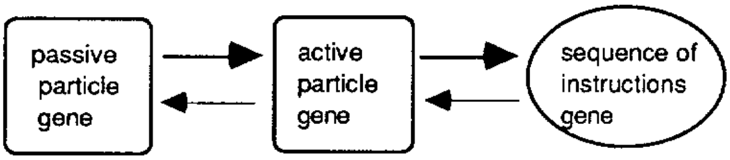


Figure 6.5: A diagram representing the development of some students' conceptions to a "sequence of instructions gene" model.

From a Sequence-of-Instructions Gene to a Sequence-of-Instructions-for-Protein-Synthesis Gene

Finally, a third shift in the way students understood the concept of the gene is reflected in the interview data. Two of the 29 students interviewed indicated that they understood the connection between genes and protein synthesis and protein synthesis and an organism's phenotype. Short excerpts from the interview with one student from Mr Counter's class, Douglas, demonstrates his understanding of this idea.

Douglas: Well, when the body wants to produce say hair or something like that, it'll send a messenger to the chromosome to get the coding for what they need and then the ribosome, that's the thing that will create the correct protein for it, which is what was on the chromosome.

Interview data such as the excerpt above suggest that when these students view genes as being in control of protein synthesis then there is additional growth in the students' conceptions of the gene. They see genes as being responsible to "make proteins" or that genes "will create the correct protein". This final ontological shift that emerged from some of the interview data is represented on the far right of the pathway in Figure 6.6 by the "productive sequence of instructions gene" model. This final ontological model is there to represent those students, like Douglas, who understood the idea that the production of proteins is the connection between the genetic code and the phenotype. They see a gene as a sequence of instructions and, in addition, they see the process of protein synthesis as an integral aspect of the functioning of genes.

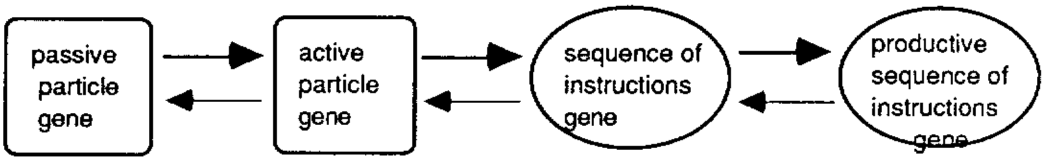


Figure 6.6: A pathway indicating the progress of Year 10 students through progressively more sophisticated ontological models of genes.

Figure 6.6 is a proposed pathway based on the ontological shifts in student thinking that emerged from the work-sheet data. There is no direct evidence that individual students move through each of these models, but the data suggest that the changes represented by this proposed pathway can be thought of as progressively more sophisticated ontological models of genes. It is important to note that the earlier models are consistent with the later models; however, the later models of genes have greater explanatory power from a scientific point of view. It is possible and probable that in one context students may use a "sequence of instructions gene" model, and in a second context find that a passive particle gene" model is adequate. In other words, some students may have within their cognitive structures all these models and utilise them in different situations. The pathway suggests, therefore, progressive and cumulative assimilation of models.

Describing the Different Ontological Models of Genes

The following paragraphs describe, in more detail, the models of genes presented in Figure 6.6. These descriptions are based on the work-sheet and interview data collected from the three classes involved in this case study.

Passive Particle Gene

Those students holding the "passive particle gene" conception imagine genes as being particles or entities which are transferred from parent to offspring. The student associates the presence of a gene with the presence of a characteristic. For example, a student with this conception may say that "Susan got her gene for blue eyes from her mother therefore she has blue eyes." Some students also may understand that the gene is a section of a chromosome much like a "bead on a necklace" with the bead representing a gene and the necklace representing a chromosome.

Active Particle Gene

Those students holding an "active particle gene" conception still visualise a gene as being a particle or entity which is transferred from the parent to the offspring. The main difference between this conception and the previous one is that the student attributes some kind of action to the gene which has an effect on the characteristic. For example, the student may say that the gene will "influence", "determine" or "control" a certain characteristic. With this conception of a gene, a student also may understand that more than one gene can influence a characteristic and the interaction of these genes determines the phenotype.

Sequence of Instructions Gene

Those students holding this conception of a gene perceive a gene as being a sequence of instructions. They understand that the sequence of instructions holds a code for a characteristic or the phenotype of an individual. With this conception of a gene, the student also may understand that a gene is made up of the chemical DNA, the structure of which enables the instructions for the characteristic to be stored in the cell's nucleus.

Productive Sequence of Instructions Gene

Those students with this conception see a gene as a sequence of instructions which is made up of a code and which determines the phenotype of an individual. The main difference between this conception and the previous conception is that students with this conception also understand that the genetic code is responsible for controlling the process of protein synthesis and that the proteins which are constructed from the code help to determine the phenotype. Students with this conception also may understand details of DNA structure, transcription, translation and the unitised nature of proteins. Students with this conception also would need to understand the importance of proteins in the structure and functioning of living things.

Progress of the Year 10 Students along the Ontological Pathway

Now that a pathway of learning about genes has been proposed (Figure 6.6), the obvious question is, how far did the majority of students in these classes progress? The pre- and post- instruction work-sheets were designed to obtain a broad view of the students' ideas about genes and did not specifically ask about the functional aspects of genes, DNA and chromosomes. Therefore, a detailed analysis of the work-sheets, classifying all students' conceptions along the ontological pathway, is not considered appropriate here. However, it is conspicuous that not one of the 79 students wrote on the post-instruction work-sheets that the code or information held in the genes or DNA is for the purpose of making proteins which in turn determine characteristics. This outcome is despite that this concept or idea was taught in all the classes observed and in great detail by Mr Counter (see Table 6.1).

The interview data, which did specifically probe the students' understanding of gene function, clearly demonstrates the poor understanding that they had of these important ideas. Of the 29 students interviewed, the majority (20, 69%) did not progress beyond the "active particle gene" model (Table 6.3). Only seven (5 + 2) of the 29 interviewed students were thought to have understood the idea that genes are a sequence of instructions (Table 6.3). Only three of these students were able to make appropriate connections between genes and protein synthesis and all of these students were from Mr Counter's class. The other students who were interviewed did not construct a complete picture of the process aspects of genes because they failed to make the connections between concepts such as DNA structure, the genetic code and the characteristics or phenotype of an organism. In other words, some of the students stated that genes are a code or contain information or a sequence of instructions; however, these students did not understand how the sequence of instructions had an effect on the body, and did not associate the sequence of instructions with the process of constructing traits.

Table 6.3: The number of interviewed students from each class and their positions on the ontological pathway of learning about the concept of the gene following instruction.

Model	Class 1 Ms Prentice n = 8	Class 2 Mr Yulang n = 13	Class 3 Mr Counter n = 8	Total n = 29
no definite conception	0	0	0	0
passive particle gene	0	2	0	2
active particle gene	6	11	3*	20
sequence of instructions gene	2	0	3*	5
productive sequence of instructions gene	0	0	2*	2

* Students selected from these groups for case studies in Chapter 6

For example, in the excerpt from her interview transcript that follows, Phillipa from Ms Prentice's class demonstrated her lack of understanding of the significance of the structure of DNA, that the double helix allows for a code to be stored in the genetic material. Phillipa was able to describe the structure of DNA as, "It's like a spiral ladder, kind of thing, it goes around and it's got little spokes across it"; however, she says "I'm not sure really", "No not really", "Not sure", when probed about the significance of the structure of DNA. When the interviewer finally introduces the notion of DNA being a code, Phillipa says she has heard of that idea; however, she indicates she is confused by saying the DNA is "mapped out somehow" and that it has "little numbers underneath and they number it and that's the code." When asked what she thinks the code is for, she again fails to make a connection with the characteristics of an organism and says "I'm not sure, for the DNA or something."

Interviewer: All right. If I asked you to describe what you think some DNA looks like, how would you go about it?

Phillipa: It's like a spiral ladder, kind of thing, it goes around and it's got little spokes across it.

Interviewer: Ok, so it's like, you say it's like a spiral ladder.

Phillipa: Yes.

Interviewer: Why is it like a ladder, any idea.

Phillipa: Not sure.

……

Interviewer: Where would you find it [DNA} do you reckon?

Phillipa: In the nucleus.

Interviewer: Why in the nucleus.

Phillipa: Because that's where all the functions like the brain and that tells the cell what to do and so that's in there.

Interviewer: So what role does DNA have in this?

Phillipa: Ah because it affects the like the characteristics and things like that.

Interviewer: Ah hum, have you heard any mention or have any ideas about DNA being a code?

Phillipa: Oh yes.

Interviewer: Tell me what you think.

Phillipa: Oh because it's like it gets mapped out somehow.

Interviewer: What gets mapped out?

Phillipa: The DNA, or the chromosomes or something like that and it they have little numbers underneath and they number it and that's the code, I think

Interviewer: The code, what for?

Phillipa: I'm not sure, for the DNA or something.

Phillipa, like many of the other students in the three classes, understood that genes control characteristics which is consistent with an "active particle gene" model (Figure 6.6). She seems to have learnt pieces of information about genes and DNA but has yet to put the pieces into an integrated whole so that she can fully appreciate the information and process nature of genes. That is, she needs to understand the relationships between the information she has learnt before she can utilise the "sequence of instructions gene" or the "productive sequence of instructions gene" models. She does not make the association between the genetic code and proteins and the importance of proteins in the structure and function of living things. Further detailed case studies of changes in student's understandings of the concept of the gene are presented in the next chapter.

Conclusion

The broad purpose of this chapter was to address research question 1: What happens to Year 10 students' conceptions of the gene when they learn genetics? An examination of the collective data from the three Year 10 classes revealed three distinct trends in the way that students described a gene from before to after instruction. Initially, many students described genes as having passive characteristics, more specifically, the idea that a gene is passed from parents to offspring was the most frequent way for students to describe a gene before instruction. After the genetics course, students were more inclined to describe a gene in an active manner, that is, they said that a gene "controls" or "influences" characteristics. The second trend observed in the data was that some students initially saw a gene as being particle-like and by the end of instruction the idea that a gene is more like a sequence of instructions became more prevalent. Finally, a third trend was observed in a few students' conceptions, that the sequence of instructions gene is associated with a process, that is, protein synthesis.

These trends observed in the data were synthesised and a pathway of four ontological models representing student learning of the gene concept was proposed. The models are considered to be ontological because they represent the ways that these students "imagine the basic nature of" genes (Bliss, 1995, p. 161). By the end of the course of instruction, the majority of students in these classes only progressed to the second of the four models in the pathway. Few students progressed beyond thinking about genes as a particle associated with some kind of action or effect on characteristics. Some students began to see genes as being a sequence of instructions but only a few students were able to articulate that the sequence of instructions was for the purpose of constructing proteins.

Words such as "bustling", "busy", "churn out", "cook up", and "created" are used by Schmidt (1994) in a kitchen scenario analogy for the functioning of genes in cells (see the final section of Chapter 2 for the full analogy). The words and phrases suggest movement, action and process, with the purpose of producing something. If indeed the analogy is a good one, as Schmidt suggests, was this the way the Year 10 students visualised genes after they had finished their course of genetics? It can only be concluded from the data presented in this analysis that the majority of students interviewed did not see genes as being like a recipe, and they certainly did not know what the recipe is for.

The data presented in this chapter indicate that these students had no clear preconceptions of the gene concept prior to instruction that had to be discarded in order that new conceptions could be introduced into the students' knowledge. Rather, the initial conceptions seem to be reconcilable with later conceptions. From these descriptions of the generalised nature of students' conceptions of genes, further questions arise. Do these changes that occur in students' ideas constitute conceptual change, and how can these changes be described? In order to answer these questions, the next chapter, which is the second in the series of three chapters that present the findings of this study, makes a detailed examination of Mr Counter's class and individual student's learning through a series of student case studies.

CHAPTER 7
CASE STUDIES OF YEAR 10 STUDENTS' LEARNING ABOUT GENES

Douglas: Genes are features that a child picks up from its parents. These include appearence [sic], hair colour, eye colour etc.

Introduction

Douglas is a student in Mr Counter's Year 10 genetics class. In this statement that Douglas made before the genetics course, there is no distinction between the idea of a "gene" and the idea of a "characteristic", they are one and the same. This chapter focuses on individual students, like Douglas, and their understanding about genes before and after a genetics course. Chapter 6 used data from three Year 10 classes collectively to propose trends in the way that the group of students' ideas about genes developed and changed. An ontological perspective of conceptual change was used to analyse the data and subsequently a pathway of student learning was developed (Figure 6.6). It was proposed that students' ideas about genes progress through the four models that constitute the learning pathway.

The purpose of this chapter is to address research question 2: When Year 10 students learn about genes, do the changes, if any, that occur in their conceptions constitute conceptual change, and if so, how can these conceptual changes be described? In order to address the research question, six detailed case studies of students, Alastair, Douglas, Beth, Jacinta, Tan, and John, have been prepared and presented in this chapter. The ontological learning pathway proposed in Chapter 6 is used to investigate these students' conceptions of genes, and an epistemological perspective of conceptual change is used to determine the status of the students' post-instructional conceptions (Hewson, 1981; Hewson & Hewson, 1992; Hewson & Thorley, 1989). In discussing the data, the nature of the content and the role of students' content knowledge is taken into consideration.

Method

Six students were selected from Mr Counter's class as described in Chapter 5 by a process of purposeful sampling (Patton, 1990). Of the three teachers described in Chapter 6, Mr Counter committed the most amount of classroom time to the concepts associated with gene structure and function on which this study focused. In addition, these students were thought to be the most interesting and revealing with regard to establishing a picture of the process of conceptual change (see Chapter 6 Table 6.3). A detailed description of the classroom procedure is included in this chapter to demonstrate that the related concepts of gene structure and function had been taught to the students in this Year 10 class. It is not unreasonable, therefore, to assume that the case study students had been exposed to the necessary language and could discuss the relevant ideas proposed in the interviews. The students' pre- and post-instruction conceptions of genes were analysed with regard to their positions along the ontological pathway proposed in Chapter 6 (Figure 6.6) and the epistemological status of that concept.

Qualitative methods of data collection, used to investigate this learning situation (Erickson, 1986), included classroom observations, student work-sheets and student interviews, as described in Chapter 6. One further form of data collection used with this particular class and not with the other classes was a class quiz administered by the teacher (see the "Describing Class Procedure" section later in this chapter) in which students were asked to write a paragraph about how proteins are made. Each student's answer to the quiz was photocopied and utilised with the interview and work-sheet data in the analysis.

The Status of Students' Conceptions

Hewson (1981) and Hewson and Thorley (1989) argue that for conceptual change to occur there are three conditions which a new conception has to satisfy before it can be integrated with existing knowledge. In addition to the new conception having a raised status, the preconception must have a lowered status to the point where the learner is dissatisfied with it (Hewson, 1996). The four conditions of dissatisfaction intelligibility, plausibility and fruitfulness have been described by various authors. An outline based on the Hewson and Hewson (1992) description of the conditions follows.

Intelligible: If the conception is intelligible to the learner, the learner knows what it means and can find a way of representing the conception, for example, in spoken, written or diagrammatic form. The sentence, "the cell drinks plant," is one that we do not find intelligible, that is, it makes no sense to us.

Plausible: If a conception is intelligible to the learner, and he or she believes that it is true, then the conception also is plausible to the learner. If the conception is believable then it must be consistent with and able to be reconciled with other conceptions accepted by the learner. The sentence, "bricks are made of living cells" is one that we find intelligible, but not plausible, that is, we understand its meaning but do not accept it as being the case.

Fruitful: A conception is fruitful to a learner if it is intelligible and plausible and it achieves something of value for her or him. Achieving something of value could mean that the conception can solve otherwise insoluble problems, or suggest new possibilities, directions or ideas. The sentence, "living things are made up of cells," is one we find intelligible. Its fruitfulness in biology is enormous. Many young students, however, have doubts about its plausibility (Dreyfus & Jungwirth, 1987).

Dissatisfaction. A central prediction of the conceptual change model is that conceptual changes do not occur without concomitant changes in the relative status of changing conceptions. If a new conception conflicts with an existing conception, then it cannot be accepted until the status of the existing conception is lowered. This happens, according to the conceptual change model, when the learner is dissatisfied with it.

In order that the status of a conception can be determined, Hewson and Hewson (1992) suggest that the analyst needs to take three steps. The first step is to identify statements that represent a conception, the second step is to identify metaconceptual statements, if any, that comment on the conception, and the final step is to interpret statements of representations and metaconceptual comments about statements using the conceptual change model and its technical language.

A case study by Hewson and Hennessey (1992) describes a situation where a 12 year-old student learned the technical language of the conceptual change model, ie., intelligible, plausible and fruitful, and was encouraged to discuss the status of her conception about forces. The study concluded that the student was able to determine the status of her own conception and that, even though she was able to articulate a scientific mechanism for force, her talk about status demonstrated her uncertainty with the mechanism. According to the researchers, her uncertainty was of significant importance to both the student and the teacher.

Rather than encouraging students themselves to make the status of their conceptions explicit, as did Hewson and Hennessey (1992), Treagust, Harrison, Venville and Dagher (1996) utilised non-technical interviews (Hewson & Hewson, 1992, p. 63) where the researchers established the status of the students' conceptions about refraction. Subsequently, comments by the students about their conception of refraction and the way the students utilised their conception to solve problems were used to determine the status.

The non-technical interview method (Hewson & Hewson, 1992) also was used in this case study to determine the status of each student's conception of the concept of the gene. The researcher examined interview data, especially with regard to metaconceptual statements, and ascertained whether the status of each student's conception was intelligible, plausible or fruitful, by using the criterion outlined above from Hewson and Hewson (1992). This process thus established each student's epistemology with regard to his or her conception of the gene (Treagust, Harrison, Venville & Dagher, 1996).

The Class Procedure

Mr Counter has more that 15 years experience teaching science and biology in Western Australian schools. This school is a suburban, government school with approximately 1200 students. The 10-week teaching unit which included sexual reproduction and inheritance is based on the Western Australian State School Curriculum unit called *Biological Change 6.2*. As described in Chapter 6, the specific objective in this unit which relates to students' conceptions of genes is simply that students will be able to "describe the nature of a gene" (Education Department of Western Australia, 1987, p. 95, objective K2464). There also are other objectives related to genes, for example about dominance and recessiveness, sex linkage, monohybrid crosses and Gregor Mendel's work, but nothing more specific about the structure or function of a gene. Due to the non-specific and generalised nature of the objective about genes in this unit, the detail that is taught about gene structure and function is largely determined by the teacher.

To teach about gene structure and function, Mr Counter concentrated on a paper model which involved students cutting out and pasting the components of DNA into a ladder structure. This paper cut-out model also was used to demonstrate to the students how the genetic code determined the order of amino acids in a protein. A second model was used by Mr Counter to demonstrate how the code is transferred from the nucleus to ribosomes for protein synthesis.

Tuesday 24 October: Cell Revision and Introduction to Chromosomes

Mr Counter revised cells by discussing plant and animal cells and the students were required to fill out a chart by describing the function of organelles of the cell. Mr Counter used an overhead projection of onion cells to open up a discussion of chromosomes. The students read from their textbook (Anderton, 1981, p. 22) about the nucleus of a cell, used microscopes to observe chromosomes from prepared slides of mitosis, and revised questions from their textbook.

Wednesday 26 October: Constructing DNA and Producing Proteins

Mr Counter handed out paper sheets (Appendix 5) and explained to his students that the shapes on the sheets represented components of the chromosome and that they could be cut out and put together to form a DNA molecule.

Mr Counter: ... they fit together and they will make the right shape which is the chromosome and you can see that there are substances called sugar, phosphate, adenine, thymine, cytosine and guanine. All these molecules go together to make a chromosome and the whole molecule is called DNA - Deoxyribonucleic acid.

Students worked in pairs to cut out the paper pieces and construct one section of a DNA molecule and the groups joined their work together to form two long chains of DNA. When the sections of DNA had been completed by the class, Mr Counter handed out a second work-sheet which included diagrams of protein made up of amino acids and a chart showing the mRNA codons for each amino acid (Appendix 5). Mr Counter proceeded to explain the way that proteins are synthesised in cells using the genetic code.

Mr Counter: You see all those shapes there - umbrellas, and triangles and circles and things - they are the components of the proteins that we eat. When we digest our food they all get broken up into bits, all those pieces and you see our bodies reconstitute them into the proteins that we want to build in our tissues, our muscles and the enzymes that we use in the body and whatever. ... How does our body know the order to rebuild them? And that is where the big chart on the right hand side [is important]. Now the big chart you will see the first one on the top left hand corner says UUU. That is a code for one amino acid and the amino acid is phenylalanine. ... So if the first one is A and the next one is G and the next one is A, so there are three of them, AGA, that will stand for one amino acid. So have a look through your chart and see what AGA stands for. Anyone found it?

Student: Yes. Argenine.

Mr Counter: Argenine, okay. So that particular little bit of a chromosome that this block here has built would be for argenine. And so the body knows that this is the particular amino acid which this stands for. So our whole body gets this code from the order of these things. All right, join some of them together and then make a starting point and see if you can see the pattern and find what some of the amino acids on your [chromosome] would be when you join them together.

After the students had constructed their DNA from paper cut-outs they were required to translate the genetic code. They did this by cutting out different coloured paper shapes to represent specific amino acids. The students used their DNA model to work out the order of amino acids before they stuck them together to make a model of a protein.

Friday 27 October: Continuing DNA Construction and Protein Production

The students continued to construct their DNA and protein. The DNA molecule and amino acid chain, when completed, were stuck up over the black board at the front of the room. At one stage during the lesson Mr Counter clarified some aspects of the model such as stop codons which he hadn't mentioned in the previous lesson.

Mr Counter: I didn't give you the black dot in our code but you might have seen that on our list there was one called 'stop'. 'Stop' is a reference to a particular [section of a] chromosome, that is the end of a run. Like it's like a code that we put in a computer program which says that's the end of the program, it goes no further. What it means in chromosome language is up till there is a protein for something, like to make hair in the body. And after that it's protein for another purpose, it might be for a protein to do with the skin.

The idea that different genes, or sections of chromosomes, work in different cells was introduced to the students, but this concept was not discussed in detail.

Mr Counter: In our body, somehow or other the skin cells know which bit of which chromosome to go and copy to manufacture that stuff we need for the skin. Somehow or other they, or the cells know which bit of the chromosome to copy. Now scientists work out which bit of which chromosome are for which part of the body and that's a very very hard job. It's very very difficult to say what bit of what chromosome is working in this part of the body.

Mr Counter asked the students if they had any questions. One student said that he didn't really understand where all this was happening in the body. The teacher responded by putting the protein synthesis activity which they had been doing into the context of a cell.

Mr Counter: This thing, this is in a nucleus of a cell, right, that chromosome. It's just one, that's the nucleus, Alastair, and that's the chromosome and we've only copied a little bit of that one. Okay. Now that magnified, that little bit there is that across here. Now out further in the cell there is a thing called the ribosome. You might remember we talked about ribosomes when we looked at the cells the other day. That's the spot on which proteins are made. So there is a molecule which goes into the nucleus, copies that data, makes a photocopy of it, comes back to the ribosome and acts as a template, these are all the codes which are in there.* ... And so on the ribosome it builds up all the different sorts of things. So that's how it makes a protein. Then the protein is out here it might be shipped outside the cell, it might be stored around here or whatever, but it will certainly be there to do its job.

Monday 30 October: Mitosis

Mr Counter did an activity on mitosis with the students. This activity was not directly associated with this part of the research and is therefore not described here.

Tuesday 31 October: Putting Protein Synthesis into the Cell Context

Mr Counter was concerned that the students had not clearly understood the relationship between the transfer of the genetic code from the chromosomes in the nucleus to the ribosomes and protein synthesis in the cytoplasm. In order to address the problem he had all the students draw a model of a cell on a large piece of paper. The model included a nucleus, two ladder shapes representing a pair of chromosomes in the nucleus, a ribosome in the cytoplasm and a star cut from red paper to represent

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* This transcript of Mr Counter's teaching suggests that messenger RNA is made outside the nucleus and moves within to copy the DNA information. However, it must be noted that messenger RNA is manufactured by the cell in the nucleus as a template of one strand of DNA (Strickberger, 1976).

the mRNA (Figure 7.1). The teacher called the mRNA star model simply a "messenger" and explained that a section of the chromosome is responsible for making a protein. A messenger goes to the section of DNA and copies information and brings it back to the ribosome.* The students then drew a dotted line from the ribosome to a section of the DNA and back again to represent the path of the "star" messenger (Figure 7.1). Mr Counter reminded the students that the chromosome had all the information for making all parts of a body. A substance called a messenger RNA can take a "photocopy" and come back and have the code for the ribosome so it can make a protein according to the genetic code.

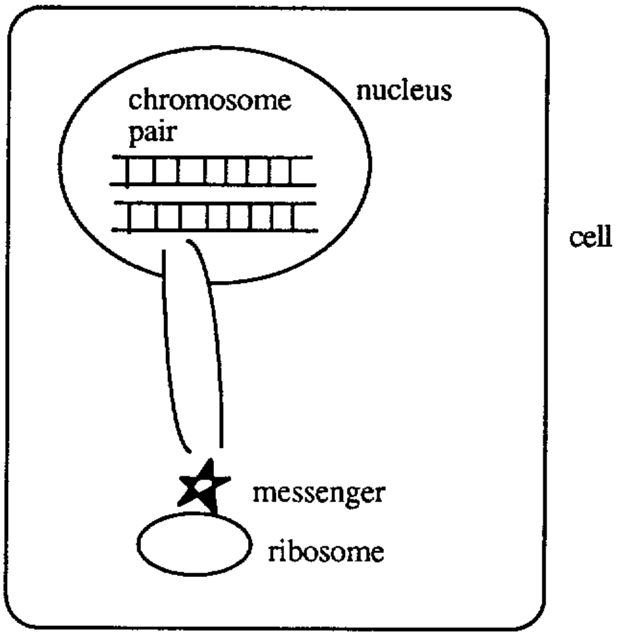

Figure 7.1: Mr Counter's whiteboard drawing of the transfer of the genetic code in the nucleus to the ribosome for protein synthesis that was copied by students.

Thursday 2 November: A Quiz on Protein Synthesis

The students completed the class quiz about how proteins are made. After they had completed the quiz, Mr Counter started discussing some of the terminology associated with Mendelian inheritance such as dominant, recessive, pure breed and hybrid. The teacher then concluded the lesson by discussing meiosis.

Students' Ontological Conceptions of Genes and their Epistemological Status

This section of the chapter describes the analysis from six student case studies.

Alastair

Alastair enjoys science more than other compulsory subjects and he enjoyed genetics more than the chemistry unit that the class did the previous term. His test score was a commendable 39 out of a possible 50 (mean: 34.5, range: 22-47). He has chosen biology to study next year in Year 11 and is interested to learn more about genetics.

Alastair's Pre-instruction Conception of a Gene

Before the Year 10 genetics course Alastair had a very simplistic understanding of genes and did not make any connections between genes, chromosomes and DNA on his pre-instruction work-sheet (Figure 7.2). He said that genes "create characteristics in an offspring" and "they come from parents". The word "create" could mean some kind of action by the gene on the characteristics; however, the limited responses on Alastair's pre-instruction work-sheet indicate that he really did not have a clear notion of action by the gene on characteristics. Rather, he probably used the word "create" in the sense that the presence of the gene brings into being the characteristic in question. The data suggest, therefore, that Alastair began the course of instruction with a "passive particle gene" model.

Genes:	*Certain things that create characteristics in an offspring. They come from the parents*
Chromosomes:	-
DNA:	*Says what your molecular structure is*

Figure 7.2: Alastair's written answers to the pre-instruction work-sheet.

(Note: All work-sheets and quizzes in figures in this chapter show students' written work in a *script* font. The spelling, grammar and punctuation are presented as the students wrote them.)

Alastair's Post-instruction Conception of a Gene

Alastair had learnt the relationship between genes and chromosomes by the end of instruction as on his post-instruction work-sheet (Figure 7.3) he wrote that genes "are contained in chromosomes."

Genes:	*Are contained in chromosomes and determine your genotype & partly your phenotype.*
Chromosomes:	*are contained in the nucleus and contain the genes. You get 23 from each parent, we have 46 in all cells except gametes.*
DNA:	*Deoxrybo nucleic acid. Is a sort of ladder like structure*

Figure 7.3: Alastair's written answers to the post-instruction work-sheet.

Alastair also said that genes "determine your genotype and partly your phenotype", but he did not make any connections between the genes or chromosomes and DNA or between genes or chromosomes and a code or a genetic message which determines characteristics. This suggests that, by the end of the course, Alastair had not begun to think of genes as a sequence of instructions. This also is supported by the interview data.

Interviewer: Okay so tell me what do you think genes do in the body?

Alastair: They what you look like, what you got. Half make up genotype and part your phenotype.

Interviewer: All right then and what's your phenotype?

Alastair: What it looks like on the outside, so it could be changed by the environment.

Interviewer: Okay so what's you genotype then?

Alastair: Well it's meant to be things that can't be changed by the environment. So how that's going to look, like your blue eyes or whatever.

Interviewer: Mm, and how do genes do that, how do they determine what you look like?

Alastair: They've got almost a blue print for what you're going to look like.

Interviewer: Mm.

Alastair: I'm not too sure from there.

Interviewer: Okay, lets' see what else [is on the work-sheet] "are contained in the nucleus, and containing the genes", all right, "deoxyribonucleic acid, a ladder like structure". Tell me about this ladder-like structure.

Alastair: I didn't know too much about that, it's just what you see on TV.

Interviewer: So you learnt that from the TV?

Alastair: Yeah, things like that.

Interviewer: Do you remember making the ladder-like structure in class?

Alastair: Yeah.

Interviewer: And what did you do with that?

Alastair: Other people stuck those shapes on it, I didn't really get that bit too much.

Interviewer: So do you know what those shapes were?

Alastair: Not really.

Interviewer: Not really sure?

Alastair: I think I was away that day. [Alastair was present during the activity.]

Interviewer: You were away. Oh that's not good. Okay so what's the difference between these [genes, chromosomes and DNA] or what's the same about these? What do you think?

Alastair: That [DNA] doesn't really determine what you look like, I don't think.

Interviewer: Ah hum, the DNA?

Alastair: The DNA, yeah. I'm not too sure what that is.

Interviewer: Ah hum, what about the genes and chromosomes, how are they related?

Alastair: I think chromosomes contain the genes and I'm not too sure what the chromosomes do but the genes determine the genotype, so.

Alastair had memorised that genes determine the genotype. However, when asked about what the genotype is, Alastair failed to provide a satisfactory answer. He said that the genotype is "meant to be things that can't be changed by the environment. So how that's going to look, like your blue eyes or whatever." It seemed that Alastair equated phenotype with characteristics that are influenced by the environment and genotype with characteristics that are not influenced by the environment. It is interesting that Alastair has learned that DNA is a ladder like structure but he had no idea about the significance of the structure or indeed of DNA's relationship with genes or chromosomes. When asked about the class activity where the students constructed a paper cut out of DNA and interpreted the genetic code Alastair said he "didn't get that bit too much" and when probed further tried to avoid giving answers by saying "I think I was away that day" when, in fact, Alastair was present in the class during the activity. Alastair did have the idea that the genes have a "blueprint for what you're going to look like", but in his words, he was "not too sure from there".

The classroom quiz (Figure 7.4) showed that Alastair had memorised the steps of how proteins are made. It is obvious, however, that Alastair had not made the connections between protein synthesis and his "program for the protein in the nucleus" with the genes, chromosomes and DNA. It is this lack of connection that has resulted in Alastair remaining with a particle model of a gene. He does associate some action by the gene on the characteristics with comments such as genes "determine your genotype and partly your phenotype" which he did not use prior to instruction. This indicates that he had moved to an "active particle gene" model by the end of instruction.

How proteins are made

1. In the nucleus, there is a program for the protein.

2. Something travels from the Rhybosome takes a copy of this program and travels back to the Rhybosome

3. The Rhybosome makes this protein according to the program.

Figure 7.4: Alastair's written answer to the class quiz about how proteins are made.

The Status of Alastair's Post-instruction Conception of a Gene

When Alastair was asked how he felt about his understanding of genes and chromosomes he replied:

Alastair: Oh, pretty good, I don't know, I suppose I understood it fairly well, but not all of it though.
Interviewer: Okay and does it help you explain a bit more about genetics?
Alastair: Yeah, like in the paper and things like that, you get what they're talking about more.
Interviewer: That's useful isn't it? Do you want to know more about genetics?
Alastair: Yeah, that's why I'm doing biology next year, and so I want to do something like that.
Interviewer: So you're quite looking forward to doing some more genetics?
Alastair: Yeah.

The idea that genes control or determine characteristics was intelligible to Alastair because he was able to articulate and explain the ideas in the interview and on his post-instruction work-sheet. In addition, phrases such as " I suppose I understood it fairly well" suggest that what he learnt made sense to him and it is believable to him. The "active particle gene" model is, therefore, plausible to Alastair. Alastair didn't have any notion of a mechanism by which genes could control characteristics, however, and comments such as, "They've got almost a blue-print for what you're going to look like, ... I'm not too sure from there", and "[I didn't understand] all of it though", suggest Alastair was quite aware of the limitations of his knowledge. He knew that there were questions that he couldn't answer and so the "active particle gene" model was not fruitful in Alastair's mind. This idea that Alastair is aware of the limitations of his knowledge is supported when he says that he understands articles in the newspaper about genetics more than he did before, but he wants to go on next year to do biology and learn more about genetics.

Summary

Alastair began the genetics course with a "passive particle gene" model. By the end of the course, Alastair continued to visualise genes as being a particle but associated this particle with an action on characteristics. Hence, his post-instruction conception of a gene was an "active particle gene". This notion was intelligible and plausible to Alastair but the model was not fruitful because he was aware of the limitations of his knowledge and of aspects of genetics which he could not explain with his "active particle gene" model (Figure 7.5).

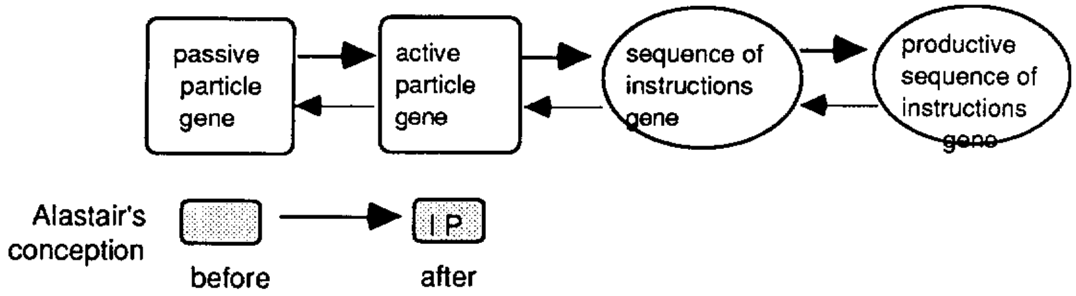

Figure 7.5: Alastair's progress on the pathway of ontological models of genes from before to after instruction in an introductory genetics course.

(Note: The letters in the "after" box indicate that the status of the students' post-instruction conception was classified as being; I - intelligible, IP - intelligible and plausible, or IPF - intelligible, plausible and fruitful to the learner.)

Douglas

Douglas enjoys science and is well known to his teacher. Mr Counter commented that he believes that Douglas often has a good understanding of scientific concepts but he does not score well in tests and exams. Douglas scored a below-average score of 33 in the test on genetics.

Douglas's Pre-instruction Conception of a Gene

Douglas began the course with a "passive particle gene" model because he simply said that "genes are features that a child picks up from its parents" (Figure 7.6). There was no mention of genes determining or coding for characteristics and hence there was no action associated with Douglas's gene model.

Genes:	*Genes are features that a child picks up from its parents. These include appearence, hair colour, eye colour etc.*
Chromosomes:	*Nothing, though I've heard the word before.*
DNA:	*DNA is the "building blocks" of the body. Each person's DNA is different to everyone elses. DNA tells everything about how you are made up.*

Figure 7.6: Douglas's written answers to the pre-instruction work-sheet.

Douglas's Post-instruction Conception of a Gene

During the course Douglas, like one of the other six students interviewed, Jacinta, learnt the Mendelian idea that characteristics are controlled by two alleles (Figure 7.7). Although this was the case in most of the characteristics studied in this Year 10 genetics class, there are many other forms of inheritance, and dominant/recessive inheritance is just one example of these.

Genes:	*Genes are characteristics that you inherit from your parents, Eg Blue Eyes, Brown hair etc.* *Each person has two genes for everything, one dominant and one recessive. The dominant wins out in you but you can pass either on if you have children.*
Chromosomes:	*Chromosomes are where your genes are stored. It is from here that your body gets the "recipe" to make new genes and body cells.*
DNA:	*DNA is the basic "building blocks" for all life. It is where all the important facts/characteristics about you are stored.*

Figure 7.7: Douglas's written answers to the post-instruction work-sheet.

Douglas also has learnt that "chromosomes are where your genes are stored" and that this is where "your body gets the 'recipe' to make new genes and body cells (Figure 7.7)." During the interview, Douglas was asked what sort of things he had learnt about genes during the course. His answer clearly demonstrated that prior to instruction he thought that "you had one gene for everything" and during the course the had learnt about two "genes" which can interact with each other to determine a characteristic. (The correct terminology for the alternative forms of a gene is "allele", but Douglas used the term "gene".) Douglas believed that these two "genes" must be dominant and recessive, which is possible but not the only combination of alleles that a gene can have.

Douglas: Well, I always thought you had one gene for everything, I didn't know you had two, you know one dominant, one recessive, that's basically the main thing I learnt.
Interviewer: Mm and what about chromosomes or DNA?
Douglas: Well, um chromosomes I sort of learnt more about exactly what they do and how they play a role in the body and that. I didn't know that before.
Interviewer: What sort of role do chromosomes play in the body. You know that genes are on the chromosomes, you've written that here.
Douglas: Well that's where all the information about you is stored and that sort of thing.
Interviewer: Do you know how it's stored, the information?
Douglas: I got the impression it was sort of, it was coded or something in there.

This section of the interview transcript also confirms Douglas's understanding that genes are on the chromosomes and that this is the place that all the genetic information is stored. Douglas saw this information as a code because he said, "it was coded or something in there". This suggests that Douglas's conception of a gene had, at this point changed to a "sequence of instructions gene" model. Douglas's written answer to a class quiz about how proteins are made (Figure 7.8) and further interview transcripts show that he clearly made connections between the chromosomes, the production of proteins and the characteristics of an individual.

How proteins are made

1. a "star thing" travels from the Rybisome in the cell membrane to the appropriate section of a cromosome in the nucleus and "copies" the appropriate formula for the protein needed e.g hair.

2. The "star thing" then returns to the rybisome and gives it the formula to make the appropriate protein.

Figure 7.8: Douglas's written answer to class quiz about how proteins are made.

Interviewer: Do you remember the activity you did with the cut outs?
Douglas: Oh the big long chromosome thing?

Interviewer: Yeah. Tell me about that.

Douglas: Well we started off. We'd done a previous lesson where we'd learnt about how chromosomes are made up and then we all sort of cut out pieces to represent the parts of a chromosome. And we divided the class in half and one side did one and the other side did one and using different colours we made up the bits of protein that go in with the chromosome.

Interviewer: And so what you think, you were making up the bits of protein, so tell me about what happens in the body that's the same as that process that you were representing with that activity.

Douglas: Well when the body wants to produce say hair or something like that it'll send a messenger to the chromosome to get the coding for what they need and then the ribosome, that's the thing that will create the correct protein for it, which is what was on the chromosome.

There are aspects of Douglas's content knowledge that are not very accurate from a scientific point of view. For example, he had difficulty distinguishing between DNA and chromosomes "I think DNA is probably more general, the whole body's sort of chromosomes, whereas chromosomes you're talking about one particular one." Another example is that Douglas was of the firm belief that all characteristics are controlled by two alleles, which is not the case. Regardless of these deficiencies in content knowledge, Douglas clearly made appropriate connections between genes on chromosomes, a code, protein synthesis and characteristics, like "hair". This suggests Douglas's conception has changed to a "productive sequence of instructions gene" model.

The Status of Douglas's Post-instruction Conception of a Gene

The "productive sequence of instructions gene" model was intelligible to Douglas and his explanations on the post-instruction work-sheet, the class quiz and the interview attest to this. The model appeared to be plausible to Douglas, the language he used suggested he believed this model to be an accurate model of reality. He spoke confidently and when asked how he felt about his understanding of genes and chromosomes and DNA, he agreed that he is quite confident.

Interviewer: All right then Douglas, so how do you feel about your understanding of genes and chromosomes and DNA and meiosis and stuff now?

Douglas: Well I know a lot more now that I did at the beginning of the topic.

Interviewer: And do you feel quite confident with your understanding?
Douglas: Yes.

This model of a gene was also a fruitful model for Douglas as he was able to use this model to explain how a gene controls a characteristic. He was able to explain how a gene is responsible for a characteristic like hair colour. In other words Douglas can answer questions about gene expression in a logical and fruitful way. From the three classes, he was the only one of 29 students interviewed who was able to do so. Whether the conception is fruitful to Douglas in other ways is not easy to determine because the interview did not probe the students with other problems.

Summary

Douglas started the course with a "passive particle gene" model. Even though there were some deficiencies in Douglas's content knowledge, by the end of the course his conception had changed to a "productive sequence of instructions gene" model. Not only had dramatic conceptual change occurred, evidence suggests that the "productive sequence of instructions gene" model had a high status of fruitfulness for Douglas because he was able to confidently answer questions about gene expression in a scientifically logical manner (Figure 7.9).

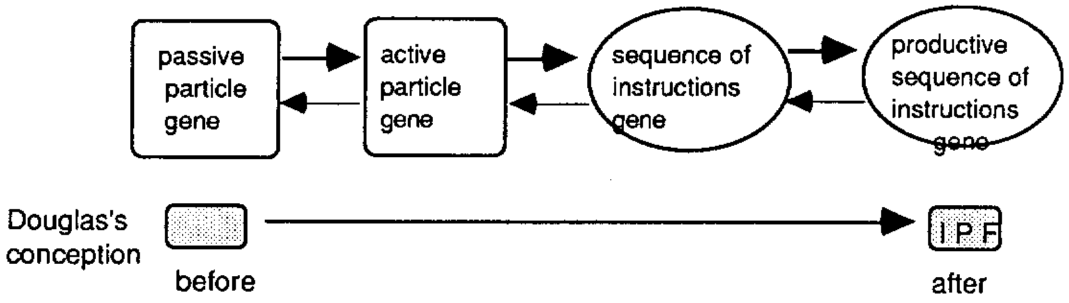

Figure 7.9: Douglas's progress on the pathway of ontological models of genes from before to after instruction in an introductory genetics course.

Beth

Beth is an average Year 10 science student, she scored 34 out of a possible 50 for the test on this science unit, Biological Change. Beth said that she thinks science is "okay", and genetics is "not one of my favourite topics". Beth usually understands in class but sometimes she can't remember afterwards - "Like it goes in and then it stays there and goes out". Beth intends to study Human Biology in Year 11 because she wants to work in the medical field; therefore she needs to understand genetics and "learn everything about it". Beth said that her mother doesn't think she can make it into the medical field, and Beth wonders about this also. Beth's brother is studying science at university, and she often asks him for help when she doesn't understand. She said he likes to help her with science.

Beth's Pre-instruction Conception of a Gene

Beth's pre-instruction work-sheet (Figure 7.10) indicated that before the genetics course she understood that genes are inherited down through generations in families. She also wrote that genes determine hair colour and other characteristics. At this stage, Beth had heard of chromosomes and DNA but didn't know what they were. In the post-instruction interview, Beth reflected and said that she didn't really know what genes were prior to instruction. When asked what she thought genes were before the course she replied:

> I just thought they were things that got passed on. But I didn't know that they like carried the characteristics and stuff like that. And with chromosomes I didn't even know what they were. And now I know they're like ladder-shaped kind of things in the nucleus of all cells. I'm not sure what DNA is still. But I'll have to study more to get it.

Genes:	*that is inherited down generations of families. Something that you or a member may have from other members etc. determines hair colour etc.*
Chromosomes:	*I don't know but herd of it.*
DNA:	*Herd of it but don't know what it stands for.*

Figure 7.10: Beth's written responses on a pre-instruction work-sheet.

Beth began the course with a "passive particle gene" model. She probably did not see the particle gene as being active because even though she said the gene "determines hair colour" on the pre-instruction work-sheet, she said in the interview she didn't know that genes "carried the characteristics" she thought they "just got passed on." It is probable that Beth simply associated the presence of a gene with the presence of a characteristic and did not connect the two with any notion of action by the gene on the characteristic.

Beth's Post-instruction Conception of a Gene

On the post-instruction work-sheet (Figure 7.11) Beth did not use any terms which connected gene with action or controlling or determining characteristics. Rather, she seemed to confuse the terms gene and phenotype because she said that an example of a gene is "brown eyes" and that genes "are the characteristics that will show on an organism". This seems to support the idea that Beth still saw genes as passive particles as she did before the course. In contrast, Beth attributed an information-carrying function to the chromosomes and, in addition, said that the genes are contained by the chromosomes. Beth described DNA as "the process of the genes given out or made". It is difficult to decipher exactly what she meant by this phrase, it would be pointless to postulate as it could have several meanings.

Genes:	*Genes are what are inherited from the parents to the offspring. They are the characteristics that will show on an organism. An example of a gene is brown eyes.*
Chromosomes:	*Things inside the nucleus and they [the chromosomes] hold the information of characteristics of what an organism is going to be. They contain the genes.*
DNA:	*is the process of the genes given out or made.*

Figure 7.11: Beth's written answers to the post-instruction work-sheet.

> *How Proteins are made*
>
> *The ribosime sends a special atom up to the nuclues to a chromosone and recieves messages about what protien is present (eg. hair) when the atom comes back to the ribosine. The atom knows what protien is present by going down the chromosane and seeing where a protien starts and finishes. (where a black mark is or a stop.).*

Figure 7.12: Beth's written answer to the classroom quiz about how proteins are made.

During the course, Beth completed a written quiz about how proteins are made (Figure 7.12). Although her spelling and scientific terms were not accurate she understood that a message from the chromosome is transferred to the ribosome. Beth referred to messenger RNA as an "atom" and it is not clear whether she understood that the "message" is used to produce a protein or not. She wrote the messages are about "what protien [sic] is present." This could refer to that protein for which the DNA of the chromosomes contains the code; however, this is not clear from her writing.

During the post-course interview Beth once again expressed herself in an idiosyncratic way which is difficult to interpret. When asked about what genes do in a cell she replied:

Beth: Like when we did that picture and it had that ribosome and all that and the molecule [mRNA] going up [to the chromosome], it just, genes is like, they're like, (pause) if you did a maths test, something like that, genes are like the notes that you take down to help and like, sort of, if you paste them together and they sort of create something, you know, an answer or something. Say with genes if you put them together they give you something and like give it to your baby or whatever and like your hair sort of.

Interviewer: And so they hold some sort of information?

Beth: Yeah.

Interviewer: And do you know how that information gets from the genes to make the baby?

Beth: Um, like when the cells produce like all those proteins and stuff like that so when they, I'm not really sure but what I think, when the cells produce the proteins they kind of go together and like produce something. And like if it's dominant it will take over the recessive and stuff like that.

Interviewer: Do you remember doing that activity where you had the ribosome, no, no, where you made up the ladder type thing and you stuck it out the front of the class. What do you think that was all about?

Beth: Um, to see like kind of where proteins you know, how do they have like those stop things and stuff like that. Like in-between there that would be one protein. So kind of like characteristics of the gene or something.

Interviewer: Okay, how do you feel about your understanding of genes now?

Beth: I don't think it's very good but I'll learn. Like I have some ideas but I don't think they're correct so I'll have to ask ... my brother.

During the interview, when asked what genes do in a cell, Beth initially tried to talk about the class activity where they modelled protein synthesis; however, she failed to fully explain herself. Beth then paused and, in order to answer the question, she resorted to her own analogy. She said that genes are like the notes you take down to help you in a maths test. Beth's analogy is not clearly described and is hence open to interpretation; however, from one point of view it is reasonable that the notes you take to help you with a maths test are like a blueprint for the correct answer that you need to write in the same way that genes are often described as blueprint for the protein that a cell needs to make. Beth continued "if you paste them together and they sort of create something, you know, an answer or something." This could be interpreted as being analogous to a whole lot of proteins being "pasted together" to create an organism. Later on in the transcript, it is clear that Beth understood that the cells produce proteins when she was asked if she knows how the information gets from the genes to make a baby. She replied, "Um, like when the cells produce all those proteins and stuff like that...". The data suggest therefore that Beth makes the connections between the characteristics of an organism and proteins, and between genes and protein synthesis. Therefore, it can be concluded that by the end of the course Beth could see genes as being a "productive sequence of instructions".

The Status of Beth's Post-instruction Conception of a Gene

By the end of the course Beth was linking together the concepts of gene, chromosome, genetic code, protein synthesis and phenotype. For this reason, it seems that a "productive sequence of instructions gene" conception was intelligible to Beth. Beth's inarticulate use of the appropriate scientific terms and her lack of confidence in her own conceptions about genes was demonstrated when she said "I'm not really sure, but I think...", and "I don't think it's very good but I'll learn". It is difficult to conclude that the "productive sequence of instructions gene" model is plausible to Beth because she makes comments such as "Like I have some ideas but I don't think they're correct", which indicates that she does not yet believe her ideas to be true. Even though Beth was obviously uncomfortable about her cumbersome explanations and lack of vocabulary she continued to answer the interviewer's questions in her own words. She also was able to answer questions such as, how does the information get from a gene to make a baby?, in a way that was consistent with the "productive sequence of instructions gene" model. It is possible that until this interview, Beth has had little opportunity to clarify her own conception of a gene and extend herself to answer problems that would require use of the more sophisticated model of a gene. Further consolidation and challenging problem-solving exercises would be necessary for the ideas to become fruitful for Beth.

Summary

Beth's conception of a gene changed over the period of the genetics course from a "passive particle gene" model to an "active sequence of instructions gene" model. The new concept of the gene is intelligible to Beth, but not plausible or fruitful for her, however, possibly because she has had little opportunity to utilise the new conception and increase its status in her mind (Figure 7.13).

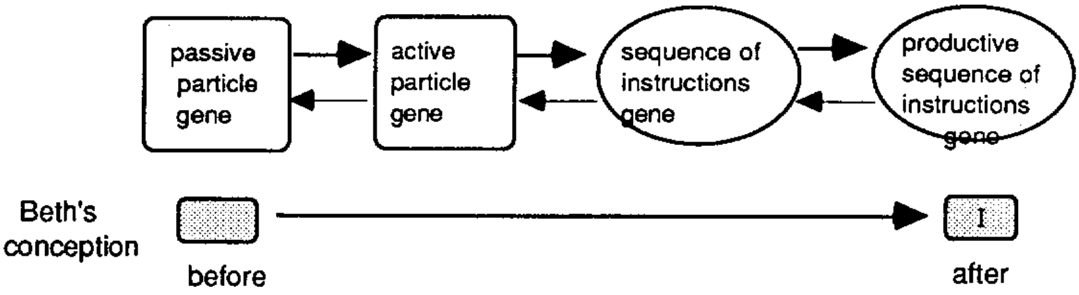

Figure 7.13: Beth's progress on the pathway of ontological models of genes from before to after instruction in an introductory genetics course.

Jacinta

Jacinta is an enthusiastic student who likes science "because I get As". She scored 38 out of 50 for this biological change unit. Jacinta also likes science more than some other subjects because "you have probably more direct answers" and she's "pretty interested in it." Jacinta says she has always been interested in genetics because "you hear it on the news and .. they've discovered all this stuff and ... you can make your baby have blond hair or blue eyes or whatever you wanted to do".

Jacinta's Pre-instruction Conception of a Gene

Jacinta's pre-instruction work-sheet (Figure 7.14) indicated that she used an "active particle gene" model because she wrote that genes were "something that you inherit from your parents" and they "determine your looks, intelligence, diseases etc." She also wrote that "DNA is a building block to determine the rest of your body." Whether this means Jacinta imagined DNA to be like a "blueprint" or "recipe" for building the body or a "building block" itself is not clear. In the post-instruction interview when asked about what she thought about chromosomes before the course Jacinta replied, "... I didn't know they were a part of the DNA and all that stuff um about combining them with your genes, like how genes are like along them." Before the course, therefore, Jacinta did not understand the relationship between genes, chromosomes and DNA. Jacinta's pre-instruction work-sheet (Figure 7.14) shows that she did make some connection between genes and chromosomes; however, she had the relationship reversed because she wrote that chromosomes are "something in your genes" rather than genes being in or along the chromosomes.

Genes:	*Something that you inherit from your parents to determine your looks, intelligence, diseases etc.*
Chromosomes:	*Something in your genes?*
DNA:	*Everybodies is different and it is like a building block to determine the rest of your body* *-DNA strands.*

Figure 7.14: Jacinta's written answers to the pre-instruction work-sheet.

Jacinta's Post-instruction Conception of a Gene

During the course of instruction, Jacinta clarified the relationship among genes, chromosomes and DNA. This is demonstrated by her writing that "genes make up chromosomes", and that DNA is the "chemical that makes up chromosomes", on her post-instruction work-sheet (Figure 7.15).

Genes:	*The things that make up chromosomes and determine individual characteristics depending on alleles.* *They are inherited from your parents.*
Chromosomes:	*Found in the nucleus and control the cells functioning. they contain genes and split etc in mitosis and meiosis* *-have 46*
DNA:	*Deoxribunucleic Acid* *The chemical that makes up chromosomes*

Figure 7.15: Jacinta's written answers to the post-instruction work-sheet.

During the post-instruction interview, Jacinta explicitly discussed how her previous idea that each characteristic is controlled by one gene inherited from one parent had been changed during the course of instruction. Jacinta's post-instruction idea is that each characteristic is controlled by two genes. It is possible that she believes also that the alleles are always dominant and recessive. It is interesting that Jacinta's idea that each characteristic is controlled by two alleles is still naive in terms of current scientific knowledge (see Chapter 2, "What do Genes do?"). If she goes on to do more genetics in school this conception is likely to be challenged with concepts such as polygenes.

Interviewer: Okay and what do you think the most important things are that you've learnt?

Jacinta: Um meiosis and mitosis and probably dominant and recessive things. I just thought it was pick of the draw, you know what I mean. Not just, you know, one overpowers the other one.
Interviewer: So you thought you only had one gene for each characteristic?
Jacinta: Yeah, Yeah, you either got it from your mum or your dad, there wasn't two like put there.

By the end of the course, both the interview and the class quiz (Figures 7.15 & 7.16) demonstrated that Jacinta understood that the chromosome has a code and the code is copied and sent to the ribosome for the purpose of protein synthesis.

Interviewer: Tell me about the proteins.
Jacinta: Um, I know they go to the ribosomes, the ribosome sends out a little thing and it comes back.
Interviewer: Where does it send the little thing to?
Jacinta: Part of the chromosomes part. And then the messenger goes back and tells, comes back with like a code and the ribosomes makes the protein for the chromosomes.
Interviewer: It makes the protein for the chromosome?
Jacinta: Yeah.
Interviewer: For the chromosomes, or from the chromosome, where does the protein go, what does the protein do, do you know?
Jacinta: Not really, I think it's probably helping in mitosis when it [the chromosome] needs to separate. I don't know if that's right or not.
Interviewer: And so what do you think the body, tell me again what you think the body might need proteins for?
Jacinta: Um its functioning, to maintain probably the characteristics that you have. Growth and repair.

While Jacinta explicitly connected the chromosome and its code with protein synthesis, she had difficulty connecting protein synthesis with phenotypic expression. Jacinta claimed that the ribosome made the "protein for the chromosomes". She didn't associate the production of proteins with phenotypic characteristics until probed twice by the interviewer. Finally, she said that proteins are "to maintain probably characteristics". This important connection between protein synthesis and characteristics also was not made by Jacinta in the class quiz; there again, she said that the proteins went "back to the chromosomes" (Figure 7.16).

It is possible that Jacinta had not previously made the connection between protein synthesis and the way that genes and chromosomes control characteristics. If this was the case, then it was only in the interview when Jacinta was probed about the issue of what the proteins do that she finally made the important connection. Although the interview did not probe the "code" idea very well, Jacinta had mentioned that the chromosomes are a code on the quiz and in the interview. It is probable that Jacinta's conception had progressed to a "sequence of instructions gene" model. Jacinta had learnt information about protein synthesis and understood the relationship between genes, chromosomes and DNA. However, because she had not made connections between gene expression and protein synthesis, it is unlikely that Jacinta had moved to a "productive sequence of instructions gene" model. It is important for students to learn about the relationships between genes, chromosomes and DNA, about alleles and about protein synthesis, as Jacinta did, but it is not until they start to put these concepts together in coherent relationships that conceptual change from a "sequence of instructions gene" model to a "productive sequence of instructions gene" model takes place.

How proteins are made.

- *The ribosomes in the cytoplasm contain nutrients to make proteins*
- *The ribosomes send out a structure to a part of a chromosome, a structure 'photocopies' it and sends the code back to the ribosome.*
- *The ribosome makes the protein and sends it back to the chromosomes.*

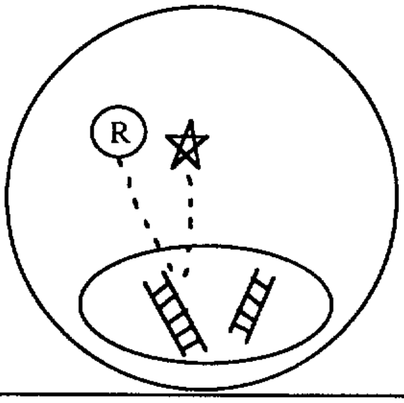

Figure 7.16: Jacinta's written answer and diagram on the class quiz about how proteins are made.

The Status of Jacinta's Post-instruction Conception of a Gene

Jacinta thought her understanding of genes was "all right, I suppose," and felt it helped her to understand some things that she had recently seen on television.

Interviewer:	How do you feel about your understanding of genes and chromosomes and DNA now?
Jacinta:	All right, I suppose, better than that one, better than the first one [pre-instruction work-sheet] but yeah.
Interviewer:	Does it help you understand some things? Like some things that you might hear on *The X Files* and stuff like that? [Jacinta had already mentioned the television program *The X Files* earlier in the interview]
Jacinta:	Yeah, definitely. You know you listen to all these science fiction movies and you know you kind of know what they're talking about, but you don't really know. And so even when I was, I watched recently Outbreak, and it had like a cow, the virus overtook the cells and how it reproduced and everything and I understood it so much better than if I didn't do [the genetics course].

The knowledge that Jacinta had constructed over the genetics course was useful to her and helped her understand the television program about virus reproduction. It seems, therefore, to be a fruitful conception because it has explanatory power for her. On the other hand, comments such as, "you listen to these science fiction movies and you know, you kind of know what they're talking about, but you don't really know", suggest that she also has had experiences where her genetics knowledge is not fruitful enough to give her a full understanding. As explained above, the "sequence of instructions gene" model is intelligible to Jacinta, but it is probably not plausible to Jacinta because she makes comments like "I don't know if that's right or not". Jacinta's situation raises interesting questions about the status of fruitfulness. In Jacinta's life the "sequence of instructions gene" model is fruitful to her in some instances, because, for example it helps her to understand television programs on virus reproduction. Jacinta's conception is probably also fruitful in helping her to solve Mendelian type genetics problems that are frequently used in Year 10 genetics classes in Western Australia. When Jacinta is challenged with questions like those in the interview requiring her to explain gene structure and function and make connections to characteristics, her explanation is inadequate. Jacinta, like Beth, is disadvantaged because it seems that she has not had an opportunity to create links between the isolated content knowledge that she has in genetics in order to develop a truly fruitful conception of a gene.

Summary

Jacinta started the genetics course with an "active particle gene" model. She learnt important content knowledge, such as that chromosomes entail a code and an understanding of protein synthesis, but there was evidence that she had not made vital connections between protein synthesis and characteristics. Consequently, Jacinta had moved to a "sequence of instructions gene" model and not a "productive sequence of instructions gene" model by the end of the course. Interview data suggest that although this model is fruitful to Jacinta in some instances, she is not entirely confident about her understanding and is not able to answer questions about how genes control characteristics. Therefore, the conception only can be classified as being intelligible to Jacinta (Figure 7.17).

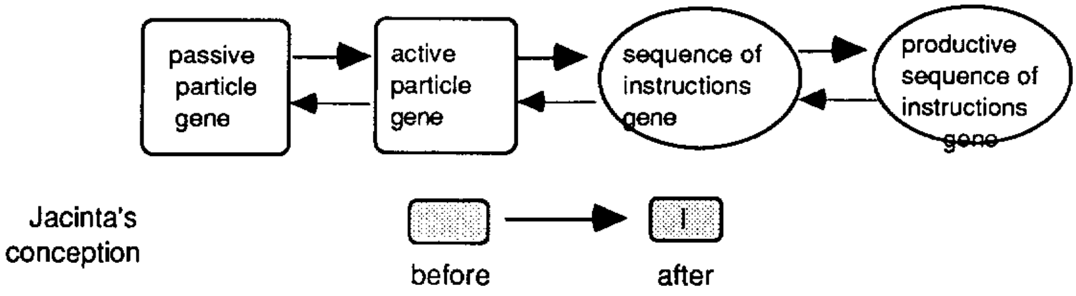

Figure 7.17: Jacinta's progress on the pathway of ontological models of genes from before to after instruction in an introductory genetics course.

Tan

Tan has enjoyed doing science since Year 8, and he feels he does well in science because he gets As and Bs. He enjoyed the genetics course but said he found it quite hard, especially the probability aspects. Tan scored an above average 36 out of a possible 50 for his end of topic test. Tan is an English-as-a-second-language student and his sentences tend to be short and to the point.

Tan's Pre-instruction Conception of a Gene

Tan's pre-instructional work-sheet (Figure 7.18) indicated that he had very little idea about genes, chromosomes and DNA before the genetics course. He simply wrote that "genes are what makes us up." This could mean that Tan thought genes are the building blocks of our body in which case he was perhaps confusing them with proteins, or it could mean that genes are the things that actually build our body. His statement that "chromosomes help plants photosynthesise" is quite extraordinary. If, however, we take into consideration Tan's poor English language skills and the similarity between the words chromosome and chlorophyll it is perhaps not so surprising. Because Tan made no logical connection between genes, chromosomes and DNA and did not even make any clear reference to characteristics or inheritance it is difficult to conclude he even utilised a "passive particle gene" model before instruction. The pre-instruction data are too limited to make a reliable judgement about Tan's pre-instruction conception of a gene. It is possible that it is Tan's poor English language skills that caused this impression rather than lack of knowledge. The evidence suggests, however, that Tan's conception is closest to the "passive particle gene" model on the pathway.

Genes:	*Genes are what makes us up.*
Chromosomes:	*Chromosomes help plants photosynthesis. It is also present in humans.*
DNA:	*DNA is different in every human being.*

Figure 7.18: Tan's written answers to the pre-instruction work-sheet.

When Tan was asked about his pre-instruction ideas in the post-instruction interview he laughed and replied:

Tan: Oh, first of all that [chromosomes help plants photosynthesise] was totally wrong.

Interviewer: All right, so what you've written about chromosomes. You've written "chromosomes help plants photosynthesise, it is also present in humans". So what's wrong about that?

Tan: Well, I understood more after genetics in science than I did before so it's quite helpful.

Interviewer: What, were you getting chromosomes mixed up with something else do you think?

Tan: Um, probably I think I mixed it up with chromophyll [sic] or something.

Interviewer: Chlorophyll, so what do you think chromosomes are now?

Tan: These worm like, I guess, things.

Interviewer: Molecules?

Tan: Molecules in the nucleus that they have information for provides them to copy or something to make proteins for the body.

Interviewer: I see, and what do you think the body uses the proteins for?

Tan: Anything, just stores it and then when it needed it'll get transported back to the body.

Interviewer: Okay, and what do you know about genes now?

Tan: Ah, it contains um, information for different parts of the body, like eye colour and skin colour and all that stuff.

Tan's Post-instruction Conception of a Gene

Tan's post instruction work-sheet (Figure 7.19) is consistent with the interview transcript in that he explained that genes are on the chromosomes. He did, however, say that the genes are "on each allele" and what this means is difficult to understand. It is possible that Tan confused the terms allele and locus. It would make sense if he was trying to say that chromosomes contain the genes on each locus. Tan repeated his idiosyncratic description of chromosomes being "worm like" on the work-sheet and in the interview and in contrast to his pre-instruction work-sheet he makes reference to characteristics such as "eye colour" and "hair colour". Tan described DNA as being "ladder like" and makes connections between chromosomes or genes. However, statements such as "[DNA] contains all the proteins like thymine for the body" may indicate some errors in Tan's content knowledge.

Genes:	*Contains information for different aspects of the body like eye colour and skin colour.*
Chromosomes:	*Are worm-like organisms that contains genes on each allele.*
DNA:	*DNA means Deoxribose Nucleic Acid. It is a ladder like structure that contains all the proteins like thymine for the body.*

Figure 7.19: Tan's written answers to the post-instruction work-sheet.

How proteins are made

2) How cells make proteins-cells make proteins by reading off the chromosomes and bringing it back to the ribosome for duplicating. The ribosome makes the protein and is carried around the cell until it is needed.

Figure 7.20: Tan's written answer to class quiz about how proteins are made.

Tan's class quiz (Figure 7.20) showed that he was able to write an acceptable, although brief, description of protein synthesis. From the interview transcript, the post-instruction work-sheet and the class quiz, it is possible to see that Tan made appropriate connections between genes and characteristics, between genes and chromosomes, between chromosomes and the code for producing proteins on the ribosome. There were, however, no explicit connections made by Tan between the proteins and characteristics. When asked what he thought the proteins were for, Tan replied, "Anything, just stores it and then when it needed it'll get transported back to the body". The idea that the body stores proteins is acceptable, but there was not indication that Tan understood that the proteins are important for determining characteristics. On the other hand, it is possible that Tan understood the importance of proteins, but this connection was not adequately probed during the interview. The interview did not follow the usual pattern of questioning because the student wanted to talk about his prior conception that chromosomes were related to photosynthesis. From all the data presented it seems that Tan constructed a "sequence of instructions gene" model by the end of the course because he understood that genes contain information about the characteristics of the body. It is possible that Tan's conception was like a "productive sequence of instructions gene" model but the interview data were not adequate to make this conclusion.

The Status of Tan's Post-instruction Conception of a Gene

It is very difficult to establish the status of Tan's concept of the gene is his own mind. The reason for this is that the interview with Tan is limited because he did not answer in a very detailed or expressive manner. For example, when asked how he felt about his understanding of genes and chromosomes after the course he did not really make any reflective or critical comments.

Interviewer: So how do you feel about you're understanding of genes and chromosomes and DNA?
Tan: [No answer]
Interviewer: [Pause] Are you happy with it?
Tan: Yeah.
Interviewer: Do you want to know more about something?
Tan: Yeah.
Interviewer: What do you want to know more about?
Tan: Um like different aspects of the body and like what they do or something.

From this section of the interview transcript it is possible to see how difficult it was to solicit the kind of information necessary to make judgements about the status of Tan's concept of the gene from him. This is probably attributable to Tan's uncertainty of spoken English and possibly to cultural differences between the student and the interviewer.

Summary

It is difficult to ascertain the changes in Tan's understanding of the concept of the gene and the status of Tan's concept because of his uncertainty of English and his lack of use of reflective and critical language. The data suggest, however, that Tan began the course with a very undeveloped concept of the gene and ended the course with a "sequence of instructions gene" model (Figure 7.21).

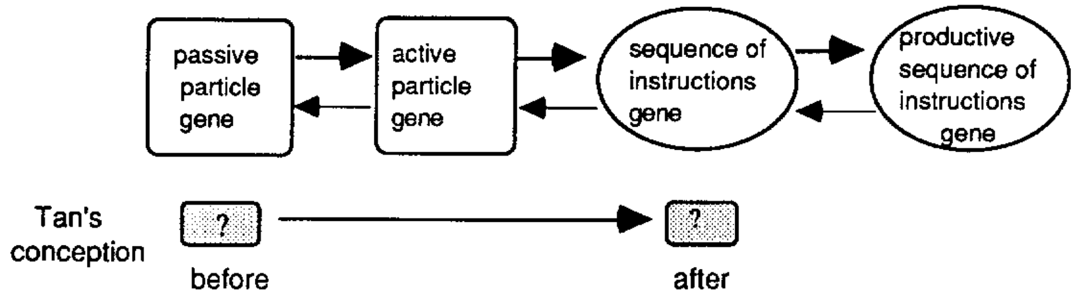

Figure 7.21: Tan's progress on the pathway of ontological models of genes from before to after instruction in an introductory genetics course.

(**Note:** The first question mark indicates that Tan's pre-instruction conception was difficult to place on the pathway. The second question mark indicates that the status of Tan's post-instruction conception was difficult to determine. See previous sections on Tan's pre- and post-instruction conceptions of a gene for more detail.)

John

John enjoys science and genetics and intends to study biology in Year 11 next year. He achieved the second top mark of 45 out of a possible 50 on the end-of-topic test.

John's Pre-instruction Conception of a Gene

Genes:	*they decide what your physical appearence will be. Inheretted from your parents.*
Chromosomes:	*strands of DNA, containing genes*
DNA:	*your conplete chromosome structure*

Figure 7.22: John's written answers to the pre-instruction work-sheet.

John's pre-instruction work-sheet (Figure 7.22) indicated that he already knew a lot about genes, chromosomes and DNA before the genetics course. He understood that genes are on the chromosomes and that DNA is the chromosomal structure. He also said that genes "decide what your physical appearance will be" and that they are inherited from parents.

John's Post-instruction Conception of a Gene

It is interesting that the information written on John's post-instruction work-sheet (Figure 7.23) changed very little in comparison with the pre-instruction work-sheet (Figure 7.22).

Genes: *parts of a chromosome which carry information about everything you look like, inheretted off parents.*
Chromosomes: *strands of genes*
DNA: *all of your heredity information.*

Figure 7.23: John's written answers to the post-instruction work-sheet.

The only significant difference is that post-instructionally he said that genes "carry information about everything you look like" whereas pre-instructionally he had said that genes "decide what your physical appearance will be". The change in phrase from "decide" to "carry information" suggests that there is a change in John's thinking about genes from an active particle to a set of instructions; however, we need to look at interview data to get a better understanding of John's post-instruction conception of a gene.

Interviewer: Yes, and what do you think chromosomes are?
John: They're, they've got genes and stuff in them and they've got information for what we look like and stuff.
Interviewer: Ah hum, you said it stores the information, so how does that stored information decide how you look like, do you know?
John: Well there are, ribosomes send out messengers and stuff to pick up the information from the genes in the nucleus and the ribosomes I don't know what they do with it, probably (inaudible) or something, I don't know.
Interviewer: Okay so the ribosomes, they pick up that message and then they do something.
John: Yeah.

The interview transcript shows that John understands that the ribosomes are involved in interpreting the information stored in the genes for helping to decide what individuals look like. However, he doesn't say what the ribosomes do with the information and he doesn't mention protein synthesis. If we look at the class quiz (Figure 7.24) where the students were asked to describe how proteins are made, John does make the connection between the ribosomes, the information in the nucleus and the production of proteins.

> *How proteins are made*
> *Proteins are made in the ribosomes. They send a small messenger into the nucleus, and collects the information on how to form a protein and takes it back to the ribosomes, where the information is stored, and the protein is built.*

Figure 7.24: John's written answer to the class quiz about how proteins are made.

The data suggest that post-instructionally John had started to think about genes as a productive set of instructions; however, the evidence is not entirely convincing because the connection between characteristics and proteins is not made explicit by him in the interview. It is quite difficult to understand John's conception of a gene because it is obvious that he understood all the content necessary for having a "productive sequence of instructions gene" model. For example, he understood the relationship between genes, chromosomes and DNA, he knew that genes contain information which determines characteristics, and he knew that ribosomes collect information from the genes to produce proteins. Yet, it is the connections between this content, particularly between the proteins and the characteristics, that seem to have been holding him back from making the transition from one model to another. This lack of connectedness between separate ideas seems to be an important aspect of conceptual change in genetics and is further discussed in the "Creating Links" section of this chapter and in Chapter 8. We conclude that John completed the course with a conception similar to the "sequence of instructions gene" model.

The Status of John's Post-instruction Conception of a Gene

John's conception was probably intelligible and plausible to him because he seemed to be convinced that his understanding was a true reflection of the world with his confident replies to the interviewers questions. He did, however, clearly say "I don't know" when he failed to make connections between ribosomes and protein synthesis. He was aware of the limitations of his knowledge about genes and acknowledged he understood "a bit more about them", rather than understanding them completely. For these reasons, John's conception of a gene was not fruitful for him. He had questions that he could not answer with his sequence of instruction conception of a gene.

Summary

John started the course with an "active particle gene" model. By the end of the course his content knowledge was good enough for him to have a "productive sequence of instructions gene" model. However, because of the lack of connectedness in John's mind between separate genetics concepts such as protein synthesis, ribosomes and character expression, he completed the course with a "sequence of instructions gene" model which was intelligible and plausible to him (Figure 7.25).

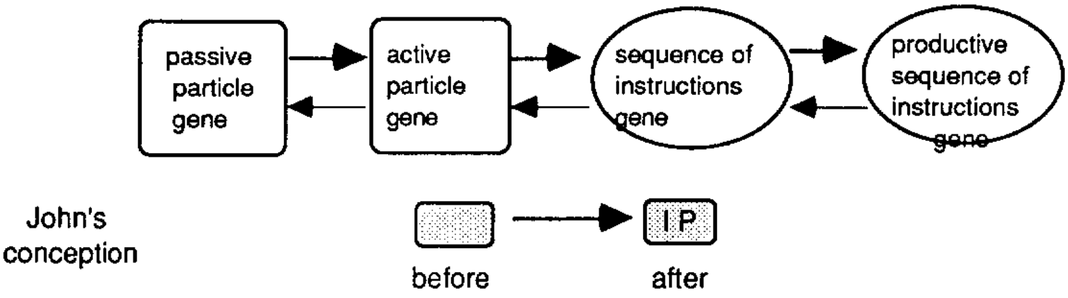

Figure 7.25: John's progress on the pathway of ontological models of genes from before to after instruction in an introductory genetics course.

Describing the Changes in Students' Conceptions about Genes

Douglas and Beth were the only students of the 29 interviewed from the three classes whose conception of a gene by the end of the genetics course was judged to be similar to a "productive sequence of instructions gene" model (Figure 7.26). Both of these students also were seen to start the course with a conception similar to a "passive particle gene" model. There was quite a considerable change in their ontological conception of a gene. The nature of the gene changed in their minds from being particle-like to being like a sequence of instructions and from being passive to being productive. The changes in Alastair, Tan, Jacinta and John's conceptions (Figure 7.26) were not as dramatic as the other two students. Alastair, Jacinta and John's conceptions were judged only to move from one model on the pathway to the next. Can these changes that occurred in the students' conceptions be described as conceptual change? The researcher proposes that the evidence presented in these case studies is evidence of conceptual changes. The following discussion supports this assertion and explores how the conceptual change that occurred for these students can be described.

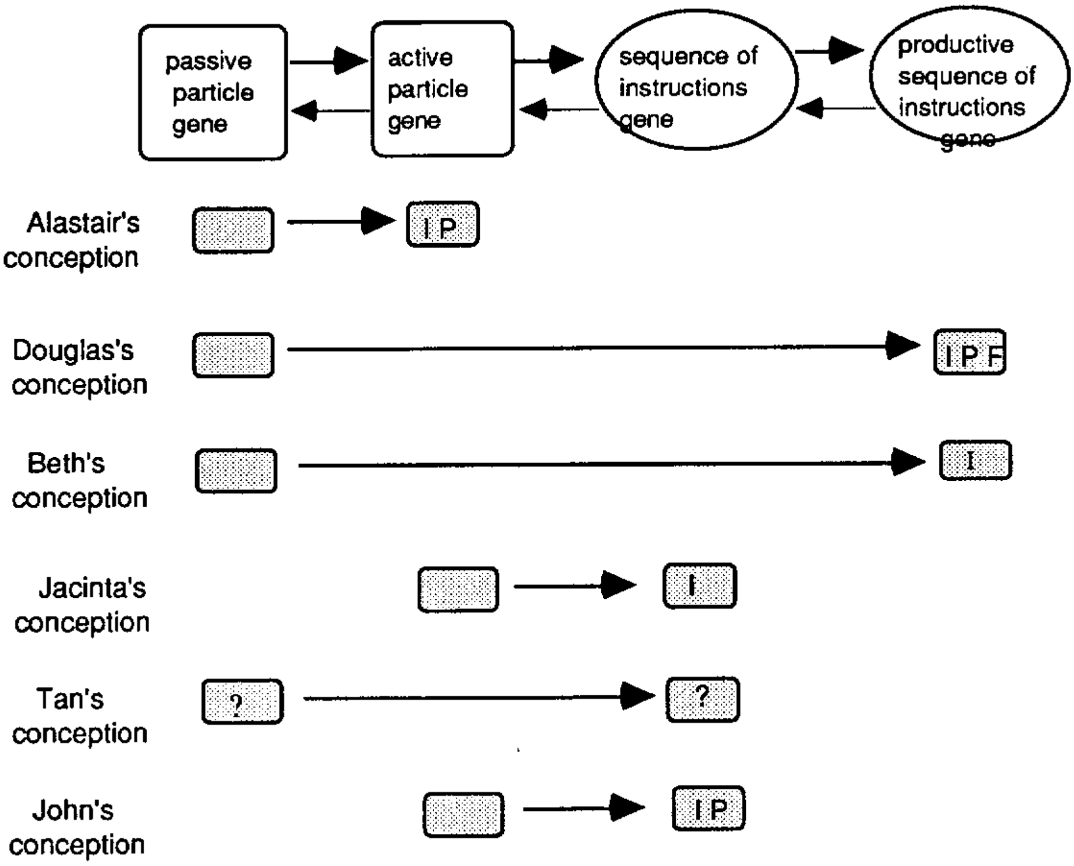

Figure 7.26: A composite figure representing the six case study students and their progress on the pathway of ontological models of genes from before to after instruction

Creating Links

Creating links is an important feature of conceptual change theory, and establishes the difference between conceptual change and simple rote learning or the process of addition. Rather than rote learning content knowledge, it is the "connectedness" (White, 1994b, p. 261) between ideas about genes that seems to be the most important factor in giving the students in these case studies the ability to visualise genes as a "productive sequence of instructions". If we compare Beth and John's post-instruction conceptions, this notion of the "connectedness" of ideas and conceptual change becomes evident. John understood that genes contain information which determines characteristics, and he knew that ribosomes collect information from the genes to produce proteins and yet he did not articulate the idea that it is the proteins that are responsible for the phenotype of the characteristics. Even though this seems obvious, and John understood the necessary content knowledge, he did not make the connection, and hence his post-instruction conception was like a "sequence of instructions gene" model rather than like a "productive sequence of instructions gene" model. Beth, on the other hand, was explicit in identifying the proteins as the main element in determining characteristics and building the body of an organism. When Beth was asked how the information gets from the genes to make a baby she replied, "when cells produce the proteins they kind of go together and like produce something". Beth, unlike John, had made the necessary connections between the ideas of protein synthesis and the phenotype of the characteristics. Her post-instruction conception, unlike John's, was considered to be like a "productive sequence of instructions gene" model.

According to the conceptual change model (Posner et. al., 1982), learning can be thought of as a change in a student's conceptions. "In this view, learning is not simply the addition of new bits of information, but involves the interaction of new knowledge with existing knowledge" (Hewson & Hewson, 1983, p. 732). In the same way that the pathway is about creating links between concepts, as described above, it also acknowledges the interaction of new knowledge with existing knowledge. In this regard, it is clear that if students are to progress along the pathway of models of genes, learning is not simply a case of addition, it does indeed require a process of reconciliation to link old with new conceptions. For example, Beth began the course of instruction with a conception of a gene that was described as being like the "passive particle gene" model (Figure 7.26). In the post-instruction interview she said that she didn't know that the genes "carried the characteristics" she thought they "just got passed on". Beth had to revise her original idea that the genes were simply passed on from one generation to another. After the course, Beth still believed the genes were passed from parents to offspring, but her new knowledge that genes on chromosomes "hold the information of characteristics of what an organism is going to be" is something she had to integrate with the old knowledge.

Not only was there evidence of reconciliation (Hewson & Hewson, 1983), there was other evidence to suggest that learning about the gene concept required a process of conceptual change rather than mere addition of knowledge. White (1994a) distinguishes between addition and conceptual change by stating that conceptual change "typically involves detailed explanations of phenomena" (p. 118) and has "far reaching effect on the total meaning we place on a term" (p. 118). The case studies of Beth and Douglas demonstrate a much more "detailed explanation" of the gene concept with the "productive sequence of instructions gene" than they did prior to instruction with the "passive particle gene" model. In addition, new ontological distinctions came into being in that these students' conceptions of a gene changed from passive to active, from being particle-like to being like a sequence of instructions, and to include the idea that genes are productive. These ontological distinctions had "far reaching effects on the total meaning" that these students had for the concept of the gene, and therefore suggest that the learning involved was of the conceptual change kind.

Strong Revisions or Weak Revisions?

Weak revisions as well as strong revisions (Figure 7.27) were included in the description of conceptual change in Chapter 3. Are the changes that occur for the students in these case studies of the weak kind or of the strong kind? There are many descriptions of strong and weak kinds of conceptual change discussed in Chapter 3 and two different descriptions of weak and strong revisions are utilised to analyse these case study data. The first, epistemological, perspective is based on the conceptual change model (Posner et al., 1982; Strike & Posner, 1985, 1992) and particularly on the line of this theory, promulgated by Hewson, that describes strong and weak forms of conceptual change as conceptual exchange and conceptual capture respectively (Hewson, 1981, 1982, 1985, 1996; Hewson & Hewson, 1984, 1992; Hewson & Thorley, 1989). The second, ontological, perspective is based on the theory of Chi (Chi, 1992; Chi et al., 1994) who describes strong and weak conceptual changes as changes across ontological categories and changes within ontological categories.

The result of interaction between old and new conceptions can be one of two things according to Hewson (1981, p. 386), it can be rejected either outright or until further investigation or it can be incorporated into the existing conceptions. This incorporation process, says Hewson, can occur in three ways, it can be memorised by rote, it can replace the old conception by the process of *conceptual exchange* (strong revision in Figure 7.27), or it can be reconciled with existing conceptions by the process of *conceptual capture* (weak revision in Figure 7.27). The interview data from the six students from this Year 10 class show that the changes in the students' ideas about genes could be described as progress through the pathway of models of genes (Figure 7.26). It has already been demonstrated that these changes are not simply rote learning because they require the interaction of new knowledge with existing knowledge and that links need to be formed between ideas for this process to occur. Are these changes, therefore, something that can be described as conceptual exchange or conceptual capture (Hewson, 1981)? Conceptual capture is a process where previous conceptions are reconciled with new conceptions and conceptual exchange is a process where previously held conceptions are discarded. The evidence suggests that students learn about genes through the process of conceptual capture, where previous conceptions are reconciled with new conceptions, rather than conceptual exchange, where previously held conceptions are discarded.

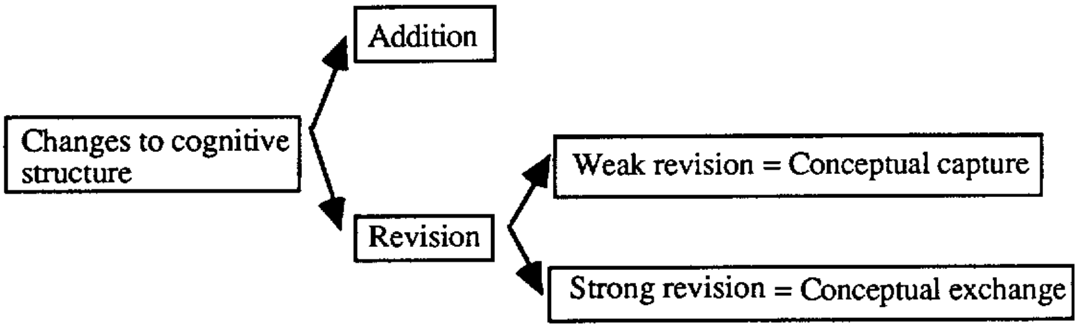

Figure 7.27: A model of the dichotomy of levels or kinds of conceptual change.

From an ontological perspective, Chi (1992) describes weak and strong forms of conceptual change as being changes within an ontological category (tree) or changes between ontological categories (trees) respectively. Chi (1992) states that conceptual changes within a tree do not result in changes to the basic meaning of the concepts themselves. Rather, Chi claims that the original tree evolves, "the concepts having acquired more attributes, or certain attributes may become more or less salient" (p. 134). For radical conceptual change, Chi, like Hewson (1982), uses the word "incommensurability" to describe the relationship between the original and the new conception. In other words, the two concepts are on distinct trees and are probably better developed independently. From this perspective, the changes that have been observed in the case studies seem to be of the weak kind of conceptual change, that is, within an ontological tree that Chi (1992) describes. There are many examples from the case studies where the original conceptions have acquired attributes or certain attributes have become more or less salient. For example, Tan's original particle-like gene acquired the attribute that it has information to make proteins for the body. Jacinta's original idea that genes are inherited from parents is still there post-instruction, however, it is less salient because other attributes of genes, such as the idea that they determine individual characteristics, is more prominent in her descriptions.

The Status of the Students' Conceptions

Douglas is the only student who was considered to have a fruitful conception of a gene. The idea of a "productive sequence of instructions" only had the status of intelligible and not plausible or fruitful to Beth and the status of Tan's conception remained undetermined (Figure 7.26). It is notable that there was only one interviewed student, and possibly the only student in this class and in all three classes, who progressed to having a fruitful conception that genes are a "productive sequence of instructions". The reasons why this is the case will be explored in the next chapter on the factors influencing conceptual change.

Determining the status of each students' conception was important because it was possible to establish a great deal more information about the process of conceptual change in each students' mind. For example, the low status of intelligible suggested that Beth required further opportunity to put her "productive sequence of instructions" conception to work, problem solving and explaining real genetics situations in order that the status of her conception could be raised and the conceptual change process enhanced. Even though the ideas were intelligible to her, they cannot be consolidated in her cognitive structures until the status of the conception is raised. Likewise, Alastair's and John's post-instruction conceptions were intelligible and they believed them to be true, but it seems they didn't have the opportunity to apply their knowledge and articulate the usefulness of the ideas to themselves. This kind of information is very useful when analysing the learning situation. Clearly, the idea of a "productive sequence of instructions gene" was presented to the students in this classroom by Mr Counter, and some of the students understood this idea, but for most of the interviewed students, the concept did not become part of their cognitive structure because it was not a fruitful conception for them. It is possible that if Beth's conception is not consolidated in her mind as a fruitful conception, she will revert to her pre-instruction notions of a gene.

Difficulty in Determining the Status of Conceptions

There is some evidence in these case studies that determining the status of students' conceptions was a difficult thing to do. Tan is the most obvious example of this because, as a non-native speaker of English, his answers were brief and he didn't use reflective or critical comments about his own conceptions. These "metaconceptual statements" are the kind of statements necessary to determine the status of a student's conception (Hewson & Hewson, 1992) and without them, determining the status is impossible.

The notion of fruitfulness, particularly, was difficult to determine and questions can be raised as to the validity of this status. Douglas's "productive sequence of instructions gene" conception was considered to have the high status of fruitful because he was able to confidently answer questions about gene expression in a scientifically logical manner. This is in accordance with Hewson and Hewson's (1992) description that a conception is fruitful if it can "achieve something of value for" the student. It also fits the criteria that it "solves otherwise insoluble problems" (Hewson & Hewson, 1992), in that without this conception Douglas would not be able to solve the problem of how genes express themselves as characteristics. But what about other problems? There are many problems and questions in genetics, some of which Douglas would not be able to answer with his post-instruction conception of a gene.

Before the interview, it is possible that John's "sequence of instructions" conception of a gene was fruitful to him. John did very well on his topic test, and it was possible for him to solve Mendelian genetics problems with the "sequence of instructions conception". However, it wasn't until the interview that he was faced with problems and questions that he could not solve. So was the conception still fruitful to him, or were the interviewer generated problems significant enough to lower the status of John's conception? As expected at the end of the interview, John had questions that could not be answered by his conception but those questions had only been introduced to him as a result of the interview process. This situation demonstrates the difficulty in determining the status of a student's conception because it is necessary for an interviewer to challenge a student with questions at the edge of his or her understanding to determine the limits of his or her knowledge. At the same time, this process is likely to result in students being asked questions to which they do not know the answers, which, in turn could possibly lead to a lowering of the status of their conception (Treagust et al., 1996).

Evolutionary or Revolutionary Conceptual Change?

A further point clarified in Chapter 3 was that revolutionary conceptual change or a gradual adjustment process and all the combinations that may exist between these two extremes are significant for a conceptual change research agenda (Duit, 1995). This means that conceptual change does not necessarily imply that initial conceptions are "extinguished". Initial conceptions, especially those that hold explanatory power in non-scientific contexts, may be held concurrently with new conceptions. Successful students learn to utilise different conceptions in appropriate contexts. Nussbaum

(1992) reflects on his own research and states that "[t]he records of each study's conceptual change suggest that it forms an evolutionary pattern in which the student maintains substantial elements of the old conception while gradually incorporating individual elements from the new one" (p. 288). *Evolutionary* seems to be an apt word to describe these Year-10 students' learning about genes. Initial conceptions do not appear to be extinguished. For example, the initial conception that genes are something that are inherited from an individual's parents is a conception that Jacinta continued to hold after instruction. This original idea is consistent with the new knowledge that she learned about genes. Jacinta incorporated the idea that "genes make up chromosomes" into her initial conception. Douglas also had the initial conception that genes are inherited from parents. He continued to have this idea at the end of the course; however, Douglas had modified the initial conception and incorporated such ideas such as "genes are stored on chromosomes" and "that's where all the information about you is stored".

Tan's case study shows disconfirming evidence that learning about genes is an evolutionary process. By the end of the course Tan completely discards his initial conception that chromosomes "help plants photosynthesis [sic]". This initial conception, however, was not a typical response of the students on the pre-instruction work-sheets (three students wrote this idea on their pre-instruction work-sheet and no students on the post-instruction work-sheet, see Chapter 6, Table 6.2) and the rest of the data from Tan's case study suggests that his learning about genes was a evolutionary rather than a revolutionary process. It is important to remember, however, that these observations were greatly confounded by Tan's less sophisticated ability to express himself in English.

Content Knowledge and Conceptual Change

It is suggested in Chapter 6 that an increase in some content knowledge is necessary for students to progress to more sophisticated models of genes. The case studies support the idea that as students' content knowledge increased they could construct a more sophisticated conception of the gene. An interesting phenomenon that was evident in the case studies, on the other hand, was that students could have a "productive sequence of instructions gene" conception or a "sequence of instructions gene" conception but still have some errors in their content knowledge. It is not appropriate to call these errors "alternative conceptions" as this would imply that the student had an alternative conception of the entire concept of the gene, which is not the case. The errors were on a smaller scale.

For example, Douglas's post-instruction conception of a gene was thought to be like the "productive sequence of instructions gene" model (Figure 7.26). Douglas seemed to hold firm beliefs that all characteristics are controlled by two alleles, which he referred to as genes. Douglas understood that one allele is dominant and the other is recessive. It is possible for a characteristic to be controlled by two allleles, one dominant and one recessive, and this is a common example used by genetics teachers. This, according to most genetics textbooks, is only one example of the many different combinations of alleles that are responsible for the control of most characteristics. Although Douglas seemed to have a fairly sophisticated conception of a gene compared with other students in the Year 10 group, his experiences in the classroom did not expose him to a wide scope of the alternative modes of inheritance, and his content knowledge was limited.

The case study of Tan also raises the issue of content knowledge. Some of the data suggested that Tan possibly confused the terms "locus" and "allele" and that he thought that the nitrogen base, thymine, is a protein. These errors in content knowledge, although important, do not seem to have limited Tan's capacity to visualise a gene as a "sequence of instructions", similar to the third model in the pathway. Beth also confused the terms "gene" and "allele" because she stated on her post instruction work-sheet that an example of a gene is "brown eyes" and that genes "are the characteristics that will show on an organism". This, however, did not seem to interfere with her notion of a gene as a "productive sequence of instructions".

Data Collection Methods and Determining Conceptual Change

The work-sheet data were particularly useful in Chapter 6 when they were used collectively to ascertain the general changes that occurred in the students' ideas about genes before instruction and after instruction. It was an appropriate data collection method for this purpose because the data could be analysed easily and were presented in a way that could be reduced to develop the generalised pathway of gene models. In the student case studies, however, the work-sheet data alone were not as useful in determining individual students' conceptions of genes prior to instruction. For example, Alastair used the phrase "certain things that create characteristics in an offspring" to describe a gene. With this information, it was difficult to determine if Alastair used the word "create" to mean that the presence of the gene simply brings into being the characteristic in question or whether he meant that a gene actually builds the characteristic. Neither of these ideas is strictly in agreement with the idea that a gene is a sequence of instructions. The point is that without further information from Alastair it was impossible to determine exactly with he meant.

During the post-instruction interviews it was possible to clarify what students meant when they used certain terms. For example, during the interview, Alastair said "[h]alf make up genotype and part your phenotype". The interviewer was able to respond with the question, "All right then and what's your phenotype?" in order to clarify Alastair's understanding of the term. Alastair's explanation of the term "phenotype" in the interview demonstrated that he did not have a clear understanding of the term. The work-sheet data collection method, on the other hand, does not allow this opportunity of clarification and deeper probing and hence is not a very appropriate method, on its own, to determine individual student's conceptions about genes. In contrast, the combination of pre-instruction and post-instruction work-sheets, class quiz and interview data were particularly useful for determining post-instruction conceptions because cross checks could be made between the different data sources. (See discussion of triangulation in the "Trustworthiness" section of Chapter 5 for more detail.)

The role of the interview in influencing students' ideas about genes and the possibility that they might contribute to promoting conceptual change should be considered. Jacinta, for example, was asked three times by the interviewer about what proteins do in the body before she finally said "to maintain probably the characteristics that you have". It is clear that this idea was not something that was primary in Jacinta's conception of a gene, or she would have suggested the link between proteins and characteristics earlier in the interview. There is a possibility that, in actual fact, Jacinta had not made the connection prior to the interview. The interviewer's insistent questions about the role of the protein is likely to have precipitated the idea that proteins are important in determining characteristics in Jacinta's mind. Beth also was clearly hesitant about her explanations, and it is probable that before the interview she had little opportunity to articulate and clarify her own conception of gene structure and function. It seems that the interview process itself enables the students to reflect on the content knowledge they have assimilated during the course of instruction and draw connections between concepts that have previously been unconnected in their minds. This is a phenomenon that has been commented on in a study of conceptual change in refraction where the interview process was seen to influence the conceptual change process (Treagust et al., 1996).

The other aspect of data collection that deserves comment is that these case studies only represent two snapshots of the students' conceptions, before and after instruction. This method of data collection has given the impression of a linear process of conceptual change. It is possible that further data collection at several stages during the learning process may give a very different image of students' learning about genes. It is possible that the conceptual change process may not be linear, there may be no progress, reversals in direction or leaps in understanding. The status of conceptions also may fluctuate and change throughout the course of instruction (Mortimer, 1995). A study by Tyson (1996) on conceptual change in chemical equilibrium shows examples of this lack of linearity in the learning process.

Conclusion

The evidence presented in this chapter in response to Research Question 2 indicates that when students learn about genes, the changes in their conceptions do constitute conceptual change. Douglas is possibly the only student who had experienced conceptual change from the "passive particle gene" to a fruitful "productive sequence of instructions gene". However, the students analysed in these case studies, and represented in Figure 7.26, can be thought of as being at different stages in an evolutionary process of conceptual change. Douglas and Beth progressed furthest in this evolutionary process compared to Alastair, Jacinta, Tan and John. Determining the status of the students' conceptions was not always a straight-forward process, but the status revealed information such as the need for students to further articulate and consolidate post-instruction conceptions.

Analysis of the case studies suggested that the observed conceptual changes fit descriptions of conceptual capture (Hewson, 1982) and conceptual change within an ontological tree (Chi, 1992). In conclusion, learning about genes observed in this study involved conceptual change of the weaker kind, not radical conceptual change. Creating links between ideas about genes was a crucial aspect of conceptual change for these students. Improvement in content knowledge also was important, however, certain deficiencies in content knowledge, such as misunderstanding the term "locus" or having limited knowledge of less traditional forms of inheritance, did not always inhibit the progress of a student along the pathway of ontological models of genes.

Factors such as creating links between ideas in genetics and students' content knowledge influenced the progress of students' conceptions along the pathway of student learning. A more detailed examination of such factors that influence the process of conceptual change is made in the next chapter, the third of three chapters in which the findings of this thesis are presented.

CHAPTER 8

FACTORS INFLUENCING CONCEPTUAL CHANGE WHEN STUDENTS ARE LEARNING ABOUT GENES

> There are two essential unifying concepts. The first is that genes emphatically are *not* passive bystanders in the life of the cell. ... *Gene expression* is the second important concept, one that serves to unify great swathes of biology. (Tudge, 1993, pp. 77-78)

Introduction

In the biological sciences, genetics is regarded as one of the most difficult subjects to teach and learn (Johnstone & Mahmoud, 1980; Longden, 1982). Research has shown that, even after instruction, students often have basic ideas about genetics which differ from the current scientific model of heredity (Brown, 1990; Clough & Wood-Robinson, 1985; Hildebrand, 1985; Hackling & Treagust, 1984). And yet many students enjoy learning genetics (Venville, 1996) and most probably many teachers enjoy teaching it. So why is the subject matter considered to be so difficult? The general purpose of this chapter is to address Research Question 3 by examining factors that influence the process of conceptual change in genetics. In addition, the ways that these factors influence conceptual change will be explored.

Several factors that influence the process of conceptual change were discussed in the literature review in Chapter 3 and included the nature of the content (White, 1994b), teaching approaches (Scott, Asoko & Driver, 1992), students' conceptual ecology (Posner et al., 1982), and contextual, motivational and cognitive factors (Pintrich et al., 1993). It also was noted in Chapter 3 that, to date, surprisingly little research has been conducted on conceptual change in genetics. There is, however, a considerable amount of research that reports factors influencing student learning in genetics. Longden (1982), for example, discussed teacher- and student-attributable factors which may individually or collectively influence the learning process for students in genetics. Problems identified by Longden that related to pedagogy included the separation in teaching time between the presentation of meiosis and the introduction of genetics and the type and extent of practical experience available to the student. Longden also found that some students' alternative conceptions were related to the nature of the concepts used in genetics such as the frequent representation of meiosis by fixed inanimate stage diagrams. Other sources of student alternative conceptions, identified in a study of high school biology textbooks by Cho, Kahle and Nordland (1985), included the interchangeable use of terms such as gene and allele, and the use of the Punnett square which may lead students to expect fixed ratios of offspring phenotypes or genotypes.

There is a significant body of literature that examines problem solving, and reveals some factors that influence student learning in genetics. An extensive review of the literature on problem solving in genetics can be found in Stewart and Hafner (1994). A series of studies (Stewart, 1983, Stewart & Dale, 1981; Stewart, Hafner & Dale, 1990) on students' ability to justify their solutions to textbook problems found that a large percentage of students were able to obtain correct answers. However, the answers, both correct and incorrect, did not distinguish those students who applied algorithms with an understanding of the underlying genetics concepts and those who did not. Hackling and Lawrence (1988) investigated high school students', teachers', university students' and teachers', and genetics counsellors' ability to solve genetics pedigree problems. Factors identified by Hackling and Lawrence to enhance the problem-solving abilities of the subjects were the use of cues in the pedigree to strengthen or weaken the solver's hypotheses about the mode of inheritance and the assigning of genotypes to individuals in the problem. Similarly, Smith (1988) reported a set of behavioural tendencies of successful and unsuccessful problem solvers. In reviewing Smith's work, Stewart and Hafner (1994) claim that the most significant of these tendencies was the perception by successful solvers that the task is not simply to arrive at an answer but to develop a valid solution with regard to their understanding of genetics.

Further information about factors that influence student learning in genetics is revealed by Kindfield's (1991b, 1993/4, 1994) detailed description of the relationship between problem solving and students' understanding of meiosis. Several alternative conceptions about chromosomes and about the process of meiosis were documented in Kindfield's work including the confusion of chromosome structure with ploidy (chromosome number). Expert and novice problem-solving characteristics were documented by Kindfield (1994) who suggested that understanding meiosis and its relationship to problem solving requires well developed pictorial skills that are rarely taught in classroom situations.

In the same way that Kindfield points to teaching practice, Wandersee (1994) suggested that the learning of microstructure-based content in biology, a significant part of genetics content, is impeded by the current pedagogical practice of using high-tech microscopic images (produced by the scanning and transmission electron microscopes and the computer-enhanced light microscope) because this practice requires a specialised pedagogy that most teachers do not follow.

Other studies in genetics education examine the meaningful learning orientation of students and improved understanding of genetics concepts and processes. The acquisition of interrelated, meaningful understanding of meiosis and the Punnett square was found by Cavallo and Schafer (1994) and Cavallo (1996) to be influenced more by the student's predisposed, generalised tendency to learn meaningfully than their aptitude and achievement motivation.

This thesis differs from other studies reported in the literature in that it focuses on student learning of the fundamental concept in genetics, the gene. If students do not have an adequate understanding of the concept of the gene, then understanding of concepts such as meiosis, Punnet squares, DNA fingerprinting and genetic engineering is not likely to be achieved. Chapter 6 presented a multiple case study of three Year 10 genetics classes and examined how students' understanding of the concept of the gene changed from before to after their genetics course. The collective data were examined from an ontological perspective of conceptual change which suggested that the students' understanding progressed through four models of genes which are presented in Figure 6.6 and are presented again here for the readers' convenience in Figure 8.1. Progress along the models can be considered a process of conceptual capture (Hewson, 1981) where more sophisticated models of genes assimilated by students are reconcilable with their previous, less adept models.

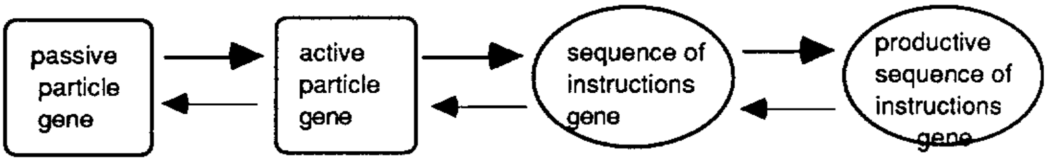

Figure 8.1: A pathway indicating the progress of Year 10 students through progressively more sophisticated models of genes.

Further examination of the data presented in Chapter 6 and the student case study data in Chapter 7 suggested that few students in the three classes progressed to the "sequence of instructions gene" model or to the "productive sequence of instructions gene" model.

Factors Influencing Conceptual Change

An examination of the historical development of the concept of the gene in Chapter 2, explored the question of whether the gene was a discovery or an invention, and concluded that the role of external pressures, such as social and political, have influenced scientific endeavour through the history of genetics. In a similar way, Carr et al. (1994) examined the fundamental basis of science content by comparing a constructivist view and a traditional view of science and the implications for pedagogy. These authors claimed that many teachers hold the view that science knowledge is unproblematic and provides the right answers and that truths in science are discovered by observing and experimenting. Carr et al. suggest that teaching based on this traditional view of science attempts to transmit to learners concepts which are precise and unambiguous. Carr et al. present an alternative constructivist paradigm which considers the history and philosophy of science and the psychology of learning. Within this paradigm, science is regarded as a "human and social construct, and [constructivists] view learning as the personal construction of new knowledge" (p. 149).

If we embrace this idea that learning is the personal construction of new knowledge, then a logical progression is that factors in the students' learning environment are going to influence that personal construction process. In addition, there are features about the science content itself that make it best taught and learned in different ways. White (1994b) argued that a theory of content is needed to help depict "the properties of content that matter, and that predicts the teaching and learning procedures that are most effective for each sort" (p. 255). White suggested that there was a lack of concern with content evident through the 1950s until well into the 1970s when content was merely a vehicle of the research. In discussing the alternative conceptions revolution that occurred in the mid-1970s with the appreciation of the role of content in learning, White suggests, however, that although this research has directed some interest towards the importance of content, there has been no research or clear advice about how to teach different content topics. This chapter addresses this issue by providing information from classroom research about the factors influencing conceptual change in genetics so that teachers can approach the teaching of the topic in an informed manner.

Over the past three years, the researcher has visited the genetics classes of eight teachers (see Chapter 5, Table 5.2) and interviewed more than 60 high school students about their understanding of genetics concepts such as the gene, DNA and meiosis. Data from a subset of three Year 10 classes were utilised in Chapters 6 and 7. In this chapter, data from these same three Year 10 classes as well as other Year 8, Year 10 and Year 12 classes are drawn upon to illustrate learning situations in genetics. Interviews with biology teachers also are used as data. Details about the classroom data collection and student and teacher interviews from the broader series of eight case study classes were described in the methodology section in Chapter 5.

During the data collection period, it become clear that there are several major factors that influence the process of conceptual change in genetics. Five of these factors - the teaching approach; student interest; the process aspects of genetics; linkage between ideas; and levels of representation - are discussed in this chapter. However, this does not suggest a finite list of factors that influence conceptual change, rather, these five factors are the most salient and were most easily demonstrated by the data collected. It should also be pointed out that these five factors are not mutually exclusive, the ideas presented under each heading often overlap with the ideas presented under other headings.

Epistemological and ontological perspectives of conceptual change were used in Chapters 6 and 7 to analyse the data. In this chapter, a social/affective perspective of conceptual change, as described in the multidimensional framework in Chapter 5, provided the theoretical groundwork for the exploration of factors influencing conceptual change. However, the influence that the teaching approach and student interest had on conceptual change are the only two of these five factors that are discussed from this perspective. While the other three factors did influence conceptual change, as is shown in this chapter, they did not fit precisely within the social/affective perspective.

A perspective about the nature of the content (White, 1994b), on the other hand, provided more satisfactory explanations for factors such as the process aspects of genetics content, the level of linkage and the different levels of representation in genetics content that influence conceptual change. These three factors are, therefore, discussed from a nature-of-the-content perspective. Furthermore, these content aspects have underlying epistemological and ontological implications and are not easily compartmentalised. It is important to note that while the five factors discussed in this chapter generally pertain to either a social/affective or a nature-of-the-content perspective of conceptual change, the discussion of the factors draws on literature from an array of areas in science education including teachers' use of analogies (Glynn, 1991; Treagust, 1995; Venville & Treagust, 1996), students' modelling ability (Grosslight, Unger, Jay & Smith, 1991; Harrison & Treagust, 1996), content (White, 1994b), motivation and interest (Hidi, 1990; Pintrich et al., 1993), instrumental and relational understanding (Skemp, 1976, 1987) and linkage across concepts (Fensham et al., 1994; White, 1994b).

Three Teaching Approaches for Genetics

From a social/affective perspective, Pintrich et al. (1993) discuss how "classroom tasks" (p. 168) influence conceptual change. Classroom tasks include the use of analogies and models, and White (1994b) outlines how some topics, more often than others, lend themselves to the use of analogies for explanations by teachers. He says that topics not open to common experience and those that are more abstract than concrete are the kinds of topics in which analogies are utilised. The use of those analogies is one part of the teacher's content-specific pedagogical knowledge (Shulman, 1986). However, analogies are not used by science teachers as often as might be expected (Dagher & Cossman, 1992; Treagust, Duit, Joslin & Lindauer, 1992; Venville & Treagust, 1995) in spite of the existence of useful analogies in the textbooks used in science classrooms (Thiele & Treagust, 1995; Thiele, Venville & Treagust, 1995).

In addition to analogies not often being used in science classes, research suggests that when analogies are used they are frequently not presented in a manner which enhances their effectiveness (Treagust et al., 1995a). Recent research has shown that teachers can substantially help students in their understanding of concepts if analogies are presented in lessons in a systematic manner that is meaningful to the students (Glynn, 1991; Treagust, 1995; Venville & Treagust, 1996). It seems most likely that the vast majority of science teachers have no formal training in the use of analogies, and hence it is not surprising that analogies are not used in providing explanations as much as they could be.

Genetics is made up of a mixture of content which is open to common experience and that which is not. Comments and experiences such as "I've got grandma's big nose" and "my fair skin comes from my mother's side" are common indeed. Genes, DNA and chromosomes, on the other hand, are concrete, but certainly not open to common experience. White (1994b) suggests that with content that is not open to common experience, students rarely hold misconceptions. The problem for students, therefore, is not one of conflict between competing conceptions but one of making sense of the new information. Analogies can be used for the teaching of this kind of content which is not open to common experience. However, as White points out, the problem with analogical explanations is that students, and teachers for that matter, often fail to appreciate that the representation is merely an analogy, with limitations.

In accordance with White's comments, the three teachers discussed in Chapter 6 utilised different analogies and analogical models in their approach to teaching the concept of the gene. It is interesting to look at the progress of the interviewed students in each of these classes along the pathway of models (Table 8.1). There is no intention that these three teachers are being ranked in teaching competency, rather, an analysis of the teaching approach used in each class and the progress of the students along the pathway is made. Hence, the influence that the teaching approach has on the process of conceptual change is examined in the following paragraphs.

Table 8.1: The number of interviewed students from each class and their position on the ontological pathway of learning about the gene concept following instruction.

Model	Class 1 Ms Prentice n = 8	Class 2 Mr Yulang n = 13	Class 3 Mr Counter n = 8	Total n = 29
no definite conception	0	0	0	0
passive particle gene	0	2	0	2
active particle gene	6	11	3	20
sequence of instructions gene	2	0	3	5
productive sequence of instructions gene	0	0	2	2

(Note: Table 8.1 is the same as Table 6.3. It is repeated here for the readers' convenience)

Ms Prentice's Teaching Approach and its Influence on Conceptual Change

Ms Prentice concentrated on the structure of DNA and used a detailed twisted ladder analogy which took at least 20 minutes of class time. The analogy clearly drew the similarities between the rungs of a ladder and the nucleotides of DNA and the uprights of a ladder and the sugar and phosphate chain of DNA. Ms Prentice also outlined differences between the DNA and the ladder analogy, such as size and the twisted nature of DNA. She commented to the researcher that she felt that it was important for her students to learn the structure of DNA because many of them would need to understand how the genetic code is stored when they study genetics in more depth in human biology or biology in Year 11 and Year 12. Ms Prentice didn't teach protein synthesis in a detailed fashion because she felt it was unnecessary and too difficult for students at this Year 10 level. Ms Prentice did mention to her class, however, that genes control protein synthesis by saying that the genetic code is "like morse code because the letters which represent the nucleotide bases of the DNA form a code to produce something, like saliva, for example."

The interviews with the eight students from Ms Prentice's class included a question about the differences between the twisted ladder and the structure of DNA. The question was included to determine if the students could define the limitations of the analogy.

Interviewer: Can you describe to me what DNA looks like?

Peta: It's like a ladder but it's a spiral. It looks like the King's Park spiral lookout (in Perth's botanical gardens) and it's got phosphate there and they've got sugar molecules and I've forgotten, and they join together to make bases which determine what the characteristics are...

Interviewer: Ok and what about differences between the ladder and the real DNA?

Peta: Definitely because I mean a real ladder is hard and DNA is I don't think is hard. A ladder is mainly just an example of the basic shape, but probably real DNA is lots smaller, softer, more complex than the actual example of a ladder...

Peta seemed to understand that a twisted ladder is simply used to explain one aspect of DNA, that is, its structure, and that there are many limitations to the analogy. Being able to understand the utility and recognise the limitations of analogies and models is an important aspect of a student's modelling ability (Grosslight et al., 1991) and something which teachers should promote. Through interviews with 7th-Grade students, 11th-Grade students and experts, Grosslight et al. identified three levels of thinking about models. In the general level 1 understanding, models are thought of as either toys or simple copies of reality. In the level 2 understanding, the student realises there is a specific explicit purpose that mediates the way the model is constructed and the model no longer must exactly correspond with the real-world object. In the third, expert, level, the purpose of the model is seen to be for developing and testing ideas rather than as a copy of reality. Peta is at least at level 2 in this scheme from Grosslight et al. because she understood that the model was used to explain the basic shape of DNA and that it does not correspond with the real-world object.

In the following excerpt from the classroom transcript, it can be seen that Ms Prentice explained to her students that the reason for talking about the ladder analogy was to help them understand the basic structure of DNA. Ms Prentice used models and analogies frequently when observed by the researcher and discussed the nature of modelling and the reasons for modelling with the students in this Year 10 class on at least one previous occasion. Ms Prentice used an overhead transparency sheet showing a diagrammatic representation of a DNA molecule during the following discussion.

Ms Prentice: Now if you could imagine that particular structure untwisted, what might it resemble? Put your hands up. Think about it carefully, there seems to be horizontal rungs. If we were to untwist that, what might it resemble, Pippa?

Student: A ladder.

Ms Prentice: A ladder, good. Can you imagine a simple ladder, that just has two sides to it and a whole lot of horizontal rungs joining the two sides. Well that's a very commonly used example to help you understand what the basic structure of the DNA molecule is like. It's like a ladder, a simple ladder with horizontal rungs, but what does the ladder do?

Students: Twists.

Ms Prentice: It twists, that's right. ... Let's now have a look at the structures which make up this molecule. And to do this I'd like you to have a look at the second work-sheet. ... Now the sides are made up of particular molecules, chemical molecules and so are the rungs, or these horizontal parts in the middle. And even though we form a long side it is made up of small units. Let's have a look at one of those units. Can we look at this molecule here to start with, this five sided molecule and I've labelled it a sugar molecule...

Ms Prentice continued to identify the similarities between the ladder analogy and DNA structure by explaining that the sides of the ladder also are made up of phosphate molecules in addition to the sugar molecules and that the rungs are made up of pairs of bases- guanine, adenine, cytosine and thymine - which can be represented by the letters G, A, C, and T respectively. Ms Prentice pointed out the limitations of the analogy by explaining that DNA is different from a real ladder in that it twists and early in the lesson she emphasised the difference in size between real DNA and the representations that they were going to use. Interviews following the lesson indicated that many of the students were able to discuss the limitations of the analogy in a similar way to Peta.

Amy: [I don't really know what DNA looks like] maybe because we've just been shown on the board how a model looks, not what the actual thing looks like. Like a model is not, it's stiff and phosphates are complete in, you know square stuff. Maybe it doesn't look like that really. Because it's gooey and circle and it's not, it's just a model when we look at it in our books and stuff. ...

Interviewer: Ok, and why do you think Ms Prentice described the structure of DNA as being like a twisted ladder?

Amy: It's a really good example of what a DNA molecule looks like. She also used the Kings Park [Tower] and it's just a really good [model]. They look the same but of course they are going to look different because they are not the same, it's a good example.

Not only could many of the students discuss the limitations of the analogy, most, like Amy, were able to discuss the twisted ladder as a model and articulate why they felt their teacher used the analogical model to explain the structure of DNA. Ms Prentice confronted the problem of concepts such as DNA structure not being open to common experience by using analogies and models; however, she did not neglect the problems associated with these strategies. She fostered in her students a clear understanding of why models are used and established a habit of pointing out at least some of the limitations of the analogies and models she used with her students.

Ms Prentice's teaching strategies with regard to the use of analogies and models in her teaching were exemplary. The question can be asked then, why did only two of the eight students interviewed from Ms Prentice's class have a conception of a gene that was like a "gene is a sequence of instructions" model. The transcripts of the interviews revealed that the students were able to give a fairly good description of the structure of DNA, which is to be expected considering the classroom time that Ms Prentice devoted to the concept of the double helix. Indeed, students, like Alison who describes DNA to the interviewer in the interview excerpt below, understood quite well the structure of DNA. The problem was that the majority of the interviewed students could not articulate the significance of the double helix structure. They did not know that this was a code, or a message, or a sequence of instructions, for determining the characteristics of an organism.

Alison: Um, it's like a ladder kind of thing and it goes um, it's got all the like rungs for the ladder and it goes up and it's twisted, it twists and.

The interviewer then probed Alison about the significance of the double helix structure.

Interviewer: Is there anything important about that structure, being like that?

Alison: As a, that's cell division. Oh, oh, (pause).

Later on, the interviewer revisits the idea about the function of the DNA.

Interviewer: Okay, well lets come back to the twisted ladder that you were talking about. Do you know any functional reason, any purpose behind it being like a ladder, twisted like a ladder?

Alison: Um (no answer).

Interviewer: Okay, is there any reason for it being ladder like, does that bear any relationship to its function that you know of?

Alison: Yes, so it can, oh what's the word, oh (long pause with no further answer).

Alison seemed to make a connection between the double helix and cell division in the first part of the interview transcript presented above. It is possible that she was trying to think of the word "mitosis" when she says "what's that word" to the interviewer's later questioning about the significance of the ladder shape of DNA. The connection between the double helix and the ability of chromosomes to replicate in cell division is a good connection for Alison to have made; however, the significant connection for understanding the concept of the gene is between the DNA structure and the idea of a code, which Alison was not able to make.

The important information gained from examining the influence of Ms Prentice's teaching approach on conceptual change is that the twisted ladder analogy was useful for the students to create an image of DNA structure. More significantly, however, this image does not enhance the conceptual change process unless the students are able to make connections between the structure and the function of DNA. That is, if the conceptual change process is to be enhanced, teachers need to encourage students to make clear connections between the double helix structure and the idea that the bases, or rungs of the ladder, contain information in the form of a code that determines characteristics.

The code idea was mentioned by Ms Prentice in the class and the ideas also were presented in the students' textbook (Biological Science Course 10, Topic 2), but there was no emphasis on the idea that the structure of DNA is a sequence of instructions for making proteins, which determine the phenotype. The emphasis, rather, was on the structure of DNA. Ms Prentice did not teach protein synthesis to these students because she thought that transcription and translation were too difficult for this age group; these concepts were taught in senior biology. Ms Prentice suggested that she was establishing in her students a sound base on which to move to senior biology where they could start to learn more about the functioning of genes. The alternative argument presented here is that if students only memorise ideas about the structure of DNA but do not know why it is significant and make no connections to other ideas, then it is not likely to remain in their cognitive structures for very long. In addition, if gene expression "serves to unify great swathes of biology" as Tudge (1993, p. 78) suggests, then it is possibly inappropriate for a teacher to ignore it until a later date. Surely the details of transcription and translation do not have to be imposed on 15 year-old students for them to understand the basic function of genes. By trying to protect her students from concepts that she sees as being too difficult, Ms Prentice has limited her students' conceptions about genes.

Mr Yulang's Teaching Approach and its Influence on Conceptual Change

Mr Yulang explained to his class that the nucleus of the cell is like a "brain" or a "computer" because it "controls the cell's functions". He also said that the structure of DNA is like a lookout tower in one of Perth's parks (the lookout tower is a DNA inspired double staircase) before he showed the students a diagrammatic model of DNA structure on an over-head projector. Mr Yulang did not go into a detailed description of any of these analogies, spending less than two minutes on the lookout tower analogy and the over-head projection of the DNA model combined. Mr Yulang proceeded to use blackboard notes and written questions about genes and DNA. Mr Yulang did not describe the function of genes or DNA in detail; however he briefly described the genetic code as being like a "blueprint or an architect's plan of what you are going to look like". The class textbook (Williams & George, 1988) which the students were directed to read in class, also compared the nucleus with a computer (Figure 6.3).

Thirteen students were interviewed from Mr Yulang's class and of those students, two ended the course with a conception of the gene similar to a "passive particle gene" model and the remaining 11 had an "active particle gene" model (Table 8.1). No students progressed to having a conception like a "sequence of instructions gene" model or a "productive sequence of instructions" gene model. Mr Yulang did not emphasise the structure of DNA or the idea of a code of information, nor did he discuss protein synthesis. It is not surprising then, that the students in this class did not progress very far along the pathway of models. Sandra, for example, understood that the genes have information about what you look like, but had no idea about how the information is stored or how the genes act to cause characteristics like blond hair.

Interviewer: What do you know about genes, tell me again?
Sandra: That it's got information about what you look like.
Interviewer: And how does it decide what you look like?

Sandra: Um there are different genes for different things so you might have a gene which says that it will be blond hair, and ones that are something else.

Interviewer: Alright, so how does it make you have blond hair, do you know?

Sandra: I don't know, you've just got the gene for blond hair.

Interviewer: Okay, and do you know how it stores the information at all about that?

Sandra: Not sure.

There has been criticism of the "blueprint" analogy, one of the analogies that Mr Yulang used.

> Richard Dawkins (1989) has pointed out that our modern knowledge of the way in which genes are expressed has rendered the concept of a genetic blueprint obsolete. He suggests that it would be better to visualize the genetic information as a recipe or series of instructions for creating an organism. In a blueprint there is a one-to-one correspondence between each element of the plan and its manifestation in the real world. But genes do not really encode for characters: they produce sequences of proteins which, interacting under suitable conditions, will result in the construction of a new organism. (Bowler, 1989, p. 181)

> The cliché that compares DNA to a set of blueprints is another of science's misleading metaphors. Blueprints are drawn up before a job starts, then put in a drawer (or indeed lost. It usually makes very little difference). But DNA is an active administrator of the modern kind: sleeves rolled up, frenetically and intimately involved in the second-by-second running of the cell from conception to the grave, and extremely sensitive to events all around it. (Tudge, 1993, pp. 77-78)

Not only were the analogies (the "brain" or "computer" analogy for the nucleus, the "lookout tower" analogy for DNA structure and the "blueprint" or "architects plan" for the genetic code) that Mr Yulang used rather obsolete, the manner in which he used them was - in passing - not well executed. In their observation of natural classroom lessons, Treagust et al. (1991) found that science teachers employed analogies in a limited way without extension so that the potential for helping students with their understanding of the concept was lost. In a similar way to the teachers observed by Treagust et al., Mr Yulang did not outline any specific features that were similar between the analogy and the scientific concept, and certainly not any features that might be different. Not only are analogies used in this limited manner in classroom discourse, Thiele et al. (1995) found that biology textbooks also frequently include simple analogies that may result in students misunderstanding the concept that is being discussed. It is now well documented that analogies need to be presented in a systematic, extended and useful way for students to gain benefit from their use (Glynn, 1991; Harrison & Treagust, 1993; Treagust et al., 1996) and this is certainly not something Mr Yulang did in this class. Even more notable than the analogies that Mr Yulang used to explain gene structure and function, is the small amount of time he devoted to helping his students understand these concepts. When this is taken into consideration, the lack of progress made by his students, like Sandra, along the pathway of models is not surprising.

Mr Counter's Teaching Approach and its Influence on Conceptual Change

The third teacher, Mr Counter, specifically concentrated on the structure and function of genes and chromosomes. He did this by organising his students to work in groups so that they could construct paper cut-out models of the structure of DNA. The DNA models were detailed enough to show how the nucleotides represented a code. The students used their model of DNA to determine the order of amino acids in a protein, which they also constructed from cut-out paper shapes. The amino acid chains constructed by the students were displayed at the front of the class. Mr Counter used a second model which demonstrated how the genetic code is transferred from the nucleus to ribosomes for protein synthesis. Mr Counter spent a total of at least two, 50 minute lessons on these models. A detailed description of Mr Counter's teaching strategies was presented in the Chapter 6.

Mr Counter commented to the researcher that he believed that, by using the paper cut-out models, his students could understand the idea of protein synthesis without detailed knowledge of transcription and translation. He said that he felt that it is important for introductory level students to make the connection between genes and protein synthesis, so that they can see how genes have an affect on the make-up of living things. The interviews at the end of the genetics course with eight students from Mr Counter's class, described in Chapter 7, showed that two of the eight students had conceptions that were similar to a "productive sequence of instructions gene" model, three had a "sequence of instructions gene" model, and three had an "active particle gene" conception (Table 8.1). If the interviewed students are representative of the other students in the class, it is possible that at least one third of Mr Counter's students had a intelligible conception that a gene is a "productive sequence of instructions". The students in this class appeared to be actively involved in thinking about the idea that a gene is a sequence of instructions because they had to construct the model of a chromosome's DNA and then work out for themselves the chain of amino acids for which their DNA would hold the code. They had to cut-out the paper model themselves and collaborate and discuss their work with other students. In addition, the protein synthesis concept was put in the cell context by Mr Counter having the students construct a second paper model of the cell. This second model showed the ribosomes and a "messenger" going to the nucleus to get the code and coming back with the information for the ribosomes to use for protein synthesis. The result of the two models together displayed clear links between the important concepts of the nucleus, the genes and their DNA and the production of proteins in the cytoplasm of the cell. These extended modelling activities that served to link genetics concepts probably contributed to students in Mr Counter's class being able to construct a "productive sequence of instructions gene" model.

It is interesting, however, that unlike Ms Prentice, Mr Counter did not pay particular attention to fostering modelling ability (Grosslight et al., 1991) in his students, even though he relied on models to a large degree in his classroom teaching. In the observed classes, he did not explicitly or systematically outline the similarities between the features of the paper models and the real DNA - although the similarities were implicit in his classroom discussion. Nor did he discuss the limitations of models or the purpose of the models with his students. While circulating among the students doing the modelling activities, the researcher noted that some students had no idea that the paper they were cutting out represented chromosomes. This is probably a factor contributing to some students in the class not progressing to a "sequence of instructions gene" conception. The interviews with students from Mr Counter's class supported this idea because they showed that some students, like Douglas (as shown on page 163 in Chapter 7), could make clear connections between the modelling activity and the "real life" situation while others could not. Douglas was one of the two students who progressed to a "productive sequence of instructions gene" conception. Other students, like Alastair (see page 159 in Chapter 7), did not seem to understand the modelling activity and could not explain what the paper representations of the amino acids were. It follows logically, that by the end of the course, Alastair's conception of a gene had only progressed to an "active particle gene" model.

It is important to note that only one interviewed student from the three classes was judged in Chapter 7 to have a fruitful conception of a "productive sequence of instructions gene". What does this mean in terms of the teachers' approach and conceptual change? Analogies and models often are necessary to facilitate intelligibility and plausibility of new concepts in the students' minds in order that conceptual change can take place (Posner et al., 1982). However, based on the data presented in this thesis, a conception attaining the status of fruitfulness requires more than simply the presentation and assimilation of an analogy or model into the students' cognitive structures. The students need to be given the opportunity to work with and test their new conception and to use it to solve new problems. These opportunities were not provided in any of the three classes, and hence the conceptions of one of the two students in Mr Counter's class who were able to think of genes as a "productive sequence of instructions" did not have the high status of fruitful. This is very significant in terms of conceptual change because until the status of a new conception is fruitful in the mind of the learner, conceptual change in terms of students progressing along the pathway of student learning (Figure 8.1) has not been achieved.

Teachers' Emphasis on Problem Solving

The three teachers' classes examined in Chapter 6, and teachers of other classes visited as part of this study, spent a great deal of classroom time during the course on problem-solving activities. The problems, similar to the two examples below, generally were solved by basic Mendelian genetics using a Punnett square.

> 1. Two hybrid organisms are mated. Both have the genes [alleles] T and t. T stands for tallness and dominates t, which stands for short. Work out the phenotype and genotype of the offspring using a Punnett square.
>
> 2. In guinea pigs a rough coat is dominant to a smooth coat. If the offspring ended up so that half of them had rough coats, what are the genotypes of the parents. (Williams & George, 1988, p. 63)

Other problems presented involved pedigrees, often of the incidence of haemophilia among descendants of Queen Victoria, and questions similar to the following:

> 1. Explain why Leopold's son Alexander does not have the disease and is not a carrier even though his father has it. (Williams & George, 1988, p. 68)

These problems are solvable with a "passive particle gene" conception. To solve these problems, a student does not need to understand that genes are a sequence of instructions nor that they are involved with controlling protein synthesis. These kinds of problems are probably important and interesting for students to be exposed to; however, it should be recognised by teachers that such problems perpetuate a simplistic conception of a gene and do nothing to raise the status of more sophisticated models of genes in students' minds. A related point was made by Tudge (1993) who noted that "we will sometimes talk of genes as if they were just abstractions, like beads on a string, and sometimes as specific chemical entities which can be manipulated in specific ways" (p. 70). The point is that it is possible to think of genes in different ways, as different models and those with expertise in genetics move between different contexts and use appropriate models easily. Based on the data from this thesis, this ability to utilise different models of genes is probably something that does not come easily to Year 10 students of genetics. This phenomenon should be further explored, particularly with regard to conceptual change.

In summary, the different teaching approaches seemed to have an effect on the conceptual change process. Appropriate, extended models and analogies that establish links between otherwise isolated ideas about genes, like the paper models that Mr Counter used, seem to be more likely to foster conceptual change than brief, unexplored analogies and models, like those used by Mr Yulang. Students in Ms Prentice's class were able to utilise the analogies in the teaching process as a useful tool probably because Ms Prentice had fostered good modelling abilities. On the other hand, even though the analogies used by Mr Counter were appropriate and extended, they did not seem to help some students because those students were not able to make connections between the analogy and the real situation. Students probably were not able to make the connections because Mr Counter did not explicitly make the connections in class discussions. Fruitfulness of a "productive sequence of instructions gene" was not encouraged in these classes as appropriate problem-solving tasks and strategies were not used, and students generally were not given extended classroom time to consolidate the more sophisticated models of genes.

Student Interest in Learning Genetics

Pintrich et al. (1993) brought attention to the less rational aspects of conceptual change, such as motivation, and the way that "students' interest" (p. 182) influences conceptual change. During post-instruction interviews in this study, many students were asked whether they had enjoyed the genetics course and why. Generally, students said that they had enjoyed their genetics course and some of the reasons are indicated in the transcript excerpts below.

Jacinta: Um, I don't know, I suppose I've always been kind of interested in when you hear it like on the news and about, you know, when they've discovered all this stuff and you can, I don't know, make your baby have blond hair or blue eyes or whatever you wanted to do. I've always thought it is pretty interesting.

Stephanie: I just find it quite interesting, I don't like physics and maths and all that kind of stuff, but it's about the body.

Nathan: [I was interested] all about heredity stuff and learning how to do Punnett squares and all that stuff.

Brooke: Um you just, like, learn about the way that things are passed on through families and it's interesting to learn about it and that.

Peter: Oh find out how people, how you, can figure out what diseases and all.

Fiona: Um about genes, my mum thinks it's really interesting. I can tell her what genes she might have.

Most of the students were interested in the human heredity aspect of genetics, as Christine put it "because it's about us, life". They were interested in answering questions about where their blond hair or green eyes had come from, diseases, and how you can "make your baby have blond hair or blue eyes." None of the students commented that they had found the microscopic or process aspects of genetics such as genes, chromosomes, DNA and protein synthesis interesting. Pintrich et al. (1993) suggest that personal interest is a motivational factor related to the process of conceptual change. It appears that the concepts of genes, chromosomes and DNA were not high on the personal interest agenda for these students, and it is possible that they did not easily become cognitively engaged when the teachers were teaching these concepts. Hidi (1990) explains that students' selective attention, effort and willingness to persist at a task and their activation and acquisition of knowledge are influenced by their personal interests. A correlation also has been shown between students who find a subject interesting, important and useful to them and the use of deeper processing strategies like elaboration and metacognitive control strategies (Pintrich, 1989; Pintrich & Garcia, 1991), all of which are important to the process of conceptual change.

During interviews, students often focussed on simple Mendelian dominance and recessiveness of alleles when asked how genes control characteristics. They liked to use Mendelian genetics, that is dominance/recessive inheritance, to deduce how they got a certain characteristic from their parents or grandparents. This seems to be intrinsically interesting and intriguing to many students because they seem to be able to answer questions about themselves. The following excerpt from the transcript of the interview with Kylie demonstrates her interest in genetics because she can trace her blue eyes and blond hair using dominant/recessive Mendelian genetics to her grandfather.

Interviewer: Yeah, and have you enjoyed the genetics course?

Kylie: Yes, it's really interesting actually.

Interviewer: Why do you find it interesting?

Kylie: Um, because I can kind of work out where I've got bits and pieces [from], like my hair and my eyes and stuff from. So I can trace it back down my family and stuff.

Interviewer: So you've got blond hair and blue eyes is it?

Kylie: Yes.

Interviewer: Where did you think you got that from?

Kylie: Um well neither of my mum and dad, my mum and dad both have brown hair and brown eyes. My dad's Dutch, I think he's got a blond gene. My mum doesn't though. And my blue eyes, I got it from my dad's side as well I think, I'm still trying to work that out.

Interviewer: Ok, so it's helping you to understand things in your life. Let's have a look at this sheet here. Tell me what you know about the actual genes. You said you've got a blond gene from your dad and stuff.

Kylie: Ah the genes are just like um, ah, they you know they have the dominant and the recessive gene. And I think my dad, I'm not sure because the brown eye gene is the dominant one and my dad must have had a dominant and a recessive, so I suppose my mum must have had a recessive one as well for me to get it.

Interviewer: So you got one recessive one from your dad and one from your mum?

Kylie: Yeah I must have. My grandpa's got blue eyes, so yeah that would work. Yeah.

Kylie was indeed quite within the rules of Mendelian genetics with her deduction. At this Year 10 level, understanding the rules of Mendelian genetics is an important goal to achieve. The problem is that hair colour and eye colour do not usually follow these simple rules because they are controlled by several genes.

> Eye colour depends first on whether there is any pigment present. If there is none the eye is pale blue. Other colours vary in the amounts of pigments controlled by several distinct genes. Comparing eye colours is, perhaps fortunately, not a dependable way of working out who is related to whom. The inheritance of hair colour is also rather complicated. Apart from very blond or very red hair, the rest of the range is genetically confused and also involves age and exposure to the sun. The range of colours of the children of African and European parents suggest that

> around half a dozen genes control their differences in skin colour but not much is known of the details. (Jones, 1993, p. 25)

Another student, Jackie, said that "dominant and recessive things" were one of the most important things that she had learnt.

Interviewer: Ok and what do you think the most important things are that you've learnt?

Jackie: Um meiosis and mitosis and probably dominant and recessive things. I just thought it was pick of the draw, you know what I mean. Not just, you know, one overpowers the other one.

Interviewer: So you thought you only had one gene [allele] for each characteristic?

Jackie: Yeah. Yeah, you either got it from your mum or your dad, there wasn't two like put there.

A point to make from this discussion is that in addition to Mendelian dominance/recessive patterns in genetics there are many other forms of inheritance. There seems to be a preference for simple explanations from the students, and perhaps this is encouraged by the way the teachers approach genetics, a phenomenon also noted by Finkel (1996). However, this is not necessarily the most appropriate approach because "most geneticists have had their fingers burned by simplicity once too often to believe that Mendelism explains everything" (Jones, 1993, pp. 49-50). The students interviewed in this study seemed to prefer a Mendelian explanation of how genes express themselves and neglected, ignored, or simply did not understand or know the microscopic, process-related idea that genes are a message coded in the DNA and expressed through protein synthesis.

Skemp (1976, 1987) described a similar situation in mathematics education involving two kinds of understanding, instrumental and relational. Skemp (1987) describes instrumental understanding as "rules without reasons" (p. 153) and relational understanding as "knowing both what to do and why" (p. 153). The advantages of instrumental understanding are that it is apparently easier to understand, one can often get the right answer more quickly and reliably by instrumental thinking and hence the rewards are more immediate and more apparent. The advantages of relational understanding are that it is more adaptable to new tasks, concepts are easier to remember once you understand them and, relational understanding is effective as a goal in itself. Further, the relational schemas seem to have a quality by which they act as an agent of their own growth, that is, people get satisfaction from relational understanding and actively seek out new material and explore new areas. There seems to be some resonance between algorithmic methods of solving Mendelian genetics problems and the instrumental kind of knowledge. When simple Mendelian genetics is taught in an algorithmic way it is easier to understand and students can often get the right answer quickly and reliably. Understanding the function of genes and the various nontraditional forms of inheritance seems to be of the relational kind of understanding. Students, like Kylie, want quick answers to problems and teachers want to help students do well in examinations. Consequently, instrumental approaches to genetics problems are working against the development of relational type understanding of genetics concepts (Skemp, 1987). As indicated by some of the comments from teachers in this study, an instrumental emphasis is justified by saying that relational understanding takes too long or is too difficult. These excuses are often attributed to the pressure of examinations, an over-burdened syllabus and the difficulty of assessing relational understanding (Skemp, 1976, 1987).

Process Aspects of Genetics

The process aspects of genetics are related to the nature of the content (White, 1994b). In this sense, the ontological properties of the content include such things as whether a concept is an object or event, whether it is a cause or an effect or whether it is localised or place-like (Bliss, 1995). Chi et al. (1994) view learning and conceptual change from an ontological perspective where students need to change the way they view a concept from one ontological category to another. In the case of science, this often involves students changing their view of concepts such as electricity and light from belonging to an ontological category of "matter" to a "process" category, or more specifically a "constraint-based interaction category". From this point of view, students have to stop thinking of concepts like heat, light, force, and current as material substances and start thinking of them as processes.

Ascribing the concept of the gene to either a "matter" ontological category or a "process" ontological category as described by Chi et al.'s theory is difficult because it has ontological attributes which belong to both categories. Genes have "matter" attributes, for example, they can be passed from one generation to another, and they are made up of the chemical DNA which has a double helix shaped structure. Genes also have "process attributes", for example, genes are made up of a code which is responsible for the production of proteins, they can be "switched on" and "switched off" and they also are involved in the process of replication. Meiosis is another concept in genetics which is important for its process attributes; however, it is often represented as static drawings in textbooks and examinations and the process nature is lost to students. Kindfield (1992) comments that:

> Typically, students are provided with verbal descriptions of relevant processes, conventional diagrams illustrating the stages of the process, with films and still photographs if possible. They are often asked to describe the process in question, list its outcomes, and compare it with other similar processes. What is missing from this approach to learning about process is any systematic active engagement in reasoning about the process, by piecing together old and newly acquired bits of information into a more or less coherent model. Further, using diagrams primarily as illustrative devices, does not expose students to the value and scientific use of diagrams as reasoning tools and as actual components of the model being built. (p. 40)

Understanding the process nature of genetics content is not easy for students and teaching these processes is not easy for teachers. Technology such as video and computer simulation can help, as can models which involve the processes. Video demonstrations of meiosis and video animations of protein synthesis were utilised in some of the classrooms visited as part of this research; however, they are a passive representation which does not engage the students in thinking through the process as Kindfield recommends. Two teachers taught the process of protein synthesis to their students using student-constructed models. As described above, Mr Counter used a paper cut-out model of DNA which involved the students in constructing a protein from paper cut-outs of amino acids using the DNA code. Another teacher, Ms Hardie (See Chapter 5, Table 5.2) organised her class to act out a role play, and the students also interpreted the DNA code to construct a "student" protein. From the researcher's observations, the students clearly knew what they were doing and understood that the role play was analogous to protein synthesis because the participants held signs depicting the cell components they represented. Unfortunately, detailed student interviews were not conducted with this group of students about this particular activity; therefore, it is difficult to comment further on the effect the role play had on the students' understanding. The paper cut-out activity was enjoyed by students in the class; however, some of the students interviewed clearly did not understand what they were doing and did not make connections between the paper model and the chromosomes and genes. As discussed above, this observation may have been due to the teacher not explicitly connecting the model and the real world situation.

For conceptual change to take place, students need to assimilate ideas about gene function which include processes such as protein synthesis. Teachers interviewed as part of the data collection of this thesis agreed that the process of protein synthesis is difficult to teach and learn. Ms Jackson has had 14 years experience teaching biology at the secondary school level and five years at the university level.

Ms Jackson: Well basically it [a building house analogy] arose because this is a very difficult concept to teach, okay. It's very hard for students to grasp the idea of making a protein, so it needed an analogy. ... In some sense, some [students] get some idea of the fact that genes only control cells by making proteins. Even if you forget all the details, you can end up with a real understanding that the only way that genes control the cells is through their production of proteins. Proteins are so variable that they have all these effects on cells. If students understand that, then they've grasped something important. Otherwise crosses and things make no sense at all, really. Because how does a gene make you tall or short or yellow or green or you know whatever, if you can't see how that's going to have an effect. You know then it just becomes a routine mathematics problem, literally, and I can't see the point in handling genetics that way.

Because the process of protein synthesis is so difficult, Ms Peterson, another experienced biology teacher, chooses to teach it by using diagrams of the cell.

Ms Peterson: I find that they [students] find that [protein synthesis] very complicated. Usually I would just stick to the basic diagram of a cell with the nucleus in one section, with the DNA in there and then the ribosomes in the cytoplasm, and I would just do diagrams showing the direction of, you know, showing the activity that goes on, and I talk about linking the amino acids together.

Mr Booth thought that protein synthesis was important; however, he complained of the amount of time needed to teach the topic effectively.

Mr Booth: A [paper cut-out] model is good to do [for protein synthesis]. The kids actually get down to actually physically do it and cut it out. But its more a therapeutic exercise than it is really [useful] and the kids have fun, and that's good for them to have fun, but it's very time consuming because they've got to sit down and cut-out. ... They arrange them, but you've got to go through the structure of DNA first or they don't know how it works. So they do get an appreciation, but these other models [using overhead transparencies] are sometimes more time effective. ... Yeah a lot of teachers do that [use paper cut-out models], but it costs you time, you see, and you're under pressure all the time for time.

The content of genetics includes many processes which are difficult for teachers to teach. The teaching of these processes requires the engagement of students in thinking about the process and this often requires models such as role plays or student constructed models (Kindfield, 1992). Teachers claim that this is time consuming and difficult for them to manage and organise. If students are to progress along the pathway of models developed in Chapter 6 (Figure 8.1) then they must learn about the process of protein production by genes. Venville and Treagust (1995) reported that few biology teachers in Western Australia actually use any models or analogies to present this topic. The process of conceptual change is, therefore, inhibited in many classrooms because of the difficulty perceived by teachers in teaching the key process concepts.

Linkage Between Concepts

In a similar way that White (1994b) discussed complexity, Fensham et al. (1994) discuss the importance of students perceiving links between concepts in a topic for the process of conceptual change. According to Fensham et al., concepts vary in how linkable they are, but:

> good learning incorporates linking, and good teaching promotes it. Even better learning follows when students comprehend why links are important, and actively seek them for themselves between topics and across subjects. (p. 7)

When students are learning about the concept of the gene, the case studies presented in Chapter 7 have shown that for conceptual change to take place, students must integrate their knowledge and understand the connections between the pieces of content knowledge that they have learnt. The comparison of two students' post-instructional conceptions in Chapter 7 demonstrated how Beth, unlike John, had made the necessary connections between the ideas of protein synthesis and the phenotype of the characteristics. This resulted in Beth's post-instruction conception, unlike John's, being considered to be like a "productive sequence of instructions gene" model. The case study of Douglas (Chapter 7) is another example that demonstrates that making the connections between concepts facilitated conceptual change, and the case study of Jacinta (Chapter 7) demonstrates that failing to make such connections inhibited the conceptual change process.

Cavallo and Sheperson's (1995) findings concur with this study inasmuch as they found that many students of genetics, like Jacinta and John, learn by memorising isolated facts and not formulating relationships between concepts and information. In a study of two independent samples of 140 and 156 students, Cavallo and Sheperson (1995) used mental modelling, an open ended assessment technique, to reveal the extent and nature of students' understanding of the relationships between meiosis and Punnett square diagrams. The authors found that the majority of students in both samples could not explain such relationships and concluded that students need help in attaining more interrelated understandings of relationships between meiosis, fertilisation, the use of Punnett square diagrams and the inheritance of traits.

The researcher in this study interviewed many students who demonstrated this lack of "connectedness" (White, 1994b) similar to that reported by Cavallo and Sheperson (1995). Students often knew isolated facts and pieces of information, but failed to put it all together in a coherent picture. The examples of such students discussed so far in Chapter 7 have been from Year 10. Evidence collected from Year 12 classes showed that students at this level also have difficulty establishing the "big picture" and connecting isolated concepts in genetics. A student from Ms Davies' Year 12 Human Biology class (See Chapter 5, Figure 5.2) who was interviewed at the end of the Year 12 genetics course is used to demonstrate that such a phenomenon was not isolated to the Year 10 level. Helena, a particularly articulate and reflective student selected by purposeful sampling (Patton, 1990), learnt some genetics during the topic about cells in Year 11 and then more in Year 12 of the human biology course. Early in the interview Helena demonstrated that she understood that the gene is made up of DNA and that the DNA has bases in it that are responsible for determining the characteristics of an individual. She said that the genes are in the nucleus and the nucleus "makes the cell look like that". At that stage of the interview Helena could not think of a way that the genes actually determine the phenotype and could not represent what a gene does in a drawing and said " I think it [a gene] just sits there and influences the cell. I guess there has to be some way of it telling the cell what it looks like, I just don't know how". Helena was unable to make any connections with protein synthesis or the genes being codes for different proteins. At that point in the interview, the interviewer began to ask Helena about an analogical activity that her teacher did with the class when she demonstrated protein synthesis in the cell.

Interviewer: Do you remember Ms Davies using Duplo at all, the Lego type stuff to build up things.

Helena: Yeah.

Interviewer: Do you remember what she was building at all, I think she's done a lot of this?

Helena: Oh was that like with the ribosomes. I think she did it when she did the DNA and RNA like the DNA. The RNA comes and takes a mirror image of it and it takes it to the ribosomes in the cell and then messenger RNA goes and gets the bases or whatever it is it puts together and takes them and it makes up amino acids or proteins or whatever it is.

Interviewer: Okay, it makes something, amino acids or proteins.

Helena: Something like that.

Interviewer: Something like that. Alright, what's most of our body made up of, do you know?

Helena: What do you mean water?

Interviewer: Water, it's made of a lot of water, and what else?

Helena: Muscles.

Interviewer: Muscles, and what's our muscles made of?

Helena: Protein.

Interviewer: So what, what's a hair made out of?

Helena: Hair?

Interviewer: Do you know?

Helena: No.

Interviewer: Proteins as well. So you're describing to me how Ms Davies did the Duplo and it went out into the cell and it went to the ribosomes and on the ribosomes it's putting together amino acids and proteins. And now you're telling me that the body's made of a lot of protein. Can you make any connections there? (pause) What do you think the gene code is for?

Helena: Oh the amino acids, it coded for the amino acids and the proteins.

Interviewer: So it coded for the amino acids and the proteins. You said before that it makes something but you didn't know what it makes, but now you remember about it sending a message to the ribosomes to make the ...

It is fascinating that, initially, Helena had no idea about how genes can influence a cell but when questioned from a different direction, from the point of view of the classroom analogical activity that the teacher did to demonstrate protein synthesis, it becomes evident from Helena's answer that she had knowledge about protein synthesis. After some discussion about the importance of proteins in the body and some probing from the interviewer, Helena finally made the connection between genes and proteins. "Oh the amino acids, it coded for the amino acids and the proteins." Helena was reflective at this point, discussing her inability to put the pieces of information that she had learnt in class together into interconnected knowledge.

Helena: That's the thing you can't, you don't, you learn it so separate that it's really hard if you think about everything, it's really hard to put it together. I mean because we learnt this and then we learnt that when we did cells and things and you don't really think to put it together because it's not taught that way.

Interviewer: And when did you do cells?

Helena: In Year 11.

Interviewer: Yes, the beginning of Year 11.

Helena: Yes, it's the first thing you do.

Interviewer: And now you're doing genetics, you sort of start to pull that together.

Helena: Yeah.

It is difficult for students, like Helena, to put together the pieces of information they learn in genetics. Teachers should be aware of this and plan and implement strategies that encourage "connectedness" between separate ideas in genetics. Indeed, Mr Booth, a teacher of biology for 17 years feels very strongly about this.

Mr Booth: I think students have got to see the link between the gene and the protein. Otherwise they don't really know, there's a sort of a gap between the DNA and the characteristic like hair colour or eye colour. In fact, I remember it myself, when I learnt that or found that out it made genetics understandable because I could never understand the link between the DNA and what was actually happening to the organism in terms of its characteristics. So when I realised that, I kind of thought well that makes sense, so I think kids need to know that too.

Levels of Representation

Different levels of representation present in science content are discussed in chemistry by Bucat and Fensham (1995). These different levels place demands on students because they are expected to switch between

> (i) recollections of real phenomena (ie. *macro* visible behaviour and (ii) images of the abstractions that chemists use to explain these phenomena (the *sub-microscopic* level), as well as (iii) the descriptions that we use, in the form of chemical formulas and equations, to represent either the real of the abstract (the *symbolic* level) (p. 3).

A similar situation occurs in genetics. Students are expected to switch between real phenomena, microscopic entities, sub-microscopic explanations and symbolic representations as they discuss and solve problems in the content area. There are the *macro, observable phenomena* such as the phenotypic expression of genes, the *microscopic entities* such as the nucleus and chromosomes, the *sub-microscopic, explanatory phenomena* such as DNA and the genetic code, and *symbolic representations* such as the letters A, G, C, and T to represent the bases of the genetic code, capital and lower case letters to represent dominant and recessive alleles, and the Punnett square. Switching between these levels is automatic for most teachers; however, students often may be unaware of the different levels of operation (Bucat & Fensham, 1995).

One Year 10 student, Anna, who was interviewed after her class participated in an introductory reproduction and genetics course, was able to describe the structure of DNA. "It's like a spiral ladder, kind of thing, it goes around and it's got little spokes across it." When probed about the "little spokes" she couldn't elaborate further about what they are and what they do. Later in the interview, the interviewer asked her about DNA being a code:

Interviewer: Have you heard any mention or have any ideas about DNA being a code?
Anna: Oh yes.
Interviewer: Tell me what you think.
Anna: Oh because it's like it gets mapped out somehow.
Interviewer: What gets mapped out?
Anna: The DNA, or the chromosomes or something like that and it, they have little numbers underneath and they number it and that's the code, I think.
Interviewer: The code, what for?
Anna: I'm not sure, for the DNA or something.

Anna demonstrated confusion between the microscopic level when discussing DNA and the symbolic level of the genetic code. She says that "the DNA, ... they have little numbers underneath and they number it and that's the code, I think". This indicates that Anna somehow imagines that DNA has numbers on it which is the genetic code. She is unable to separate the microscopic phenomena from the symbolic representations (which are usually letters, not numbers) that are used by biologists to represent the genetic code. For a student to be able to work with a "sequence of instructions gene" model (Figure 8.1) it would be necessary for them to be able to freely move between discussion of macroscopic traits, the microscopic explanations of these traits such as the different allelic forms a gene can take, and how the different alleles produce different proteins. Students who think of genes as being a sequence of instructions also would be expected to be able to draw or write symbolic representations of these ideas such as using upper and lower case letters to represent different alleles of a gene or to be able to use the Punnett square to show how these alleles have been inherited in problem solving. This kind of demanding situation makes any kind of conceptual change in genetics difficult.

Another example of a student who was confused by the levels of representation in genetics is from a Year 10 class that had been learning about sex-linked inheritance of diseases and conditions such as colour blindness. One of the students interviewed after the course, Steven, was able to give a reasonable verbal explanation of how a male child could have the sex-linked disease Duchenne muscular dystrophy, while neither of his parents had the disease.

Interviewer: Another example, Duchenne's disease is a kind of muscular dystrophy which is a sex-linked trait. If a boy has Duchenne's disease and neither of his parents have it, what did his parents' sex chromosomes look like and what do the boy's sex chromosomes look like? Can you draw some diagrams (Figure 8.2) to show me that?

Steven: I think so.

Interviewer: Have a go anyway. Explain as you're going along what you're drawing. ...

Steven: So the mother must be the carrier.

Interviewer: Ok, so this is the mother's genes here. Can you tell me what this is here?

Steven: That's like you've got two X chromosomes. The top one is damaged [ie. has the Duchenne's disease allele] but the bottom one isn't. Like that's just representing two, and they're like one of them is damaged, but she hasn't got it so that thing carried on to the boy, and he hasn't got a backup, so he will get it [Duchenne's disease].

Interviewer: Ah hum, and what about the father here?

Steven: He must just have the normal sex genes or Y gene because if he had a damaged one then it would carry on to his son.

Interviewer: Alright, and can you label them X and Y for me. And what about in the boy, with the disease, what's the X and Y?

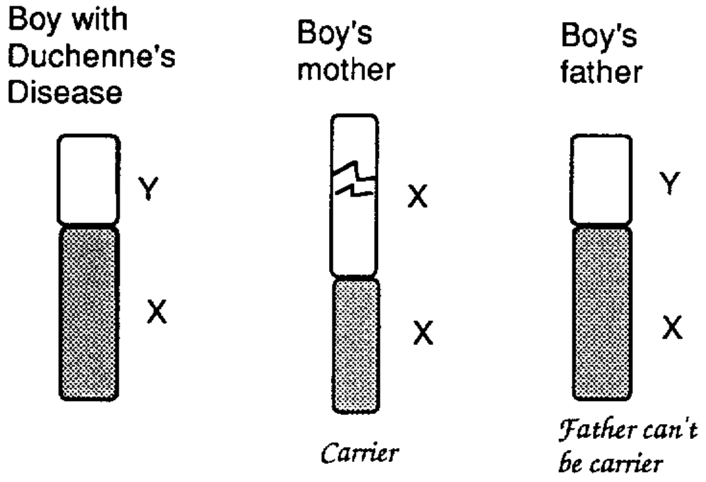

Figure 8.2: Steven's drawing explaining Duchenne muscular dystrophy, a sex-linked inherited disease.

Steven made some comments which are not consistent with an expected answer to this problem. For example, "He [the father] must have the normal sex genes or Y gene because if he had a damaged one then it would carry on to his son." This statement seems to indicate a misunderstanding because the damaged allele, or the one with Duchenne's disease, is carried on the X chromosome and not on the Y chromosome. From the interview transcript, however, it seems that Steven understood how the female parent is able to carry the Duchenne's disease allele without having the disease. He understood that the mother has two chromosomes, one with the Duchenne's disease allele and one without and that the damaged one is passed on to the child. Steven also understood that because the boy doesn't have another gene, the "backup" gene on the other sex chromosome then the boy has Duchenne's disease. Steven therefore, made a reasonable connection between the macroscopic phenomenon which is Duchenne's disease and the microscopic explanation of the kinds of alleles the boy and his parents have. The problem is that Steven was unable to represent his microscopic explanation with accepted scientific symbolic representations. If Steven was to draw diagrams like the ones he drew in this interview (Figure 8.2) in a test he would probably get no marks, or very few marks, for his effort. This is because he drew the two chromosomes for each person one on top of the other as if they were linked together. When we look at the diagram that was presented to the students in the classroom (see Figure 8.3) it is possible to understand why Steven used such a diagram. His problem seems to be that he has yet to master the accepted scientific way of representing what he is trying to explain.

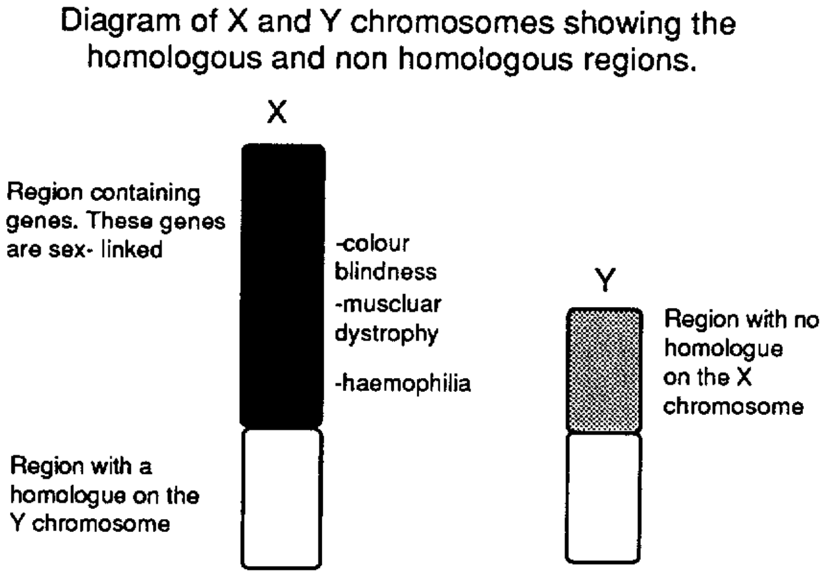

Figure 8.3: The diagram of X and Y chromosomes on one of Steven's teacher's handouts.

Genetics content includes macroscopic phenomenon, microscopic explanations and symbolic representations and students, like Anna and Steven, are likely to be confused as teachers move freely between these representations without detailed and adequate explanations. For students to make progress along the pathway of genes (Figure 8.1) students need to be able to differentiate between levels of representation.

Conclusion

Research Question 3 asked what factors influence the process of conceptual change when students are learning about genes? The discussion in this chapter has identified five factors that influence the conceptual change process in genetics. This is not intended to be a finite list, however, there are many implications from these five factors for the teaching of genetics.

The first of these factors is the teaching approach. Models and analogies need to be used to represent ideas in genetics like genes, chromosomes and DNA that are not open to common experience. Models and analogies, in turn, have problems associated with their use and in order for conceptual change to be enhanced, teachers should endeavour to choose appropriate analogies and establish a systematic method when using them. At the same time, teachers also should be concerned about fostering modelling ability in their students so that they will understand and make maximum cognitive use of analogies and models used in their classes. Teaching that emphasises only Mendelian problem solving is not conducive to conceptual change when students are learning about genes because algorithmic problem solving encourages a simplistic "passive particle gene" model in students minds.

The second factor that influences conceptual change is that students are interested in simple solutions to genetics problems because they feel they can answer questions about their own inheritance even though this is not usually the case. Students like to solve genetics problems and discuss heredity in terms of simple Mendelian dominance/recessive patterns and this makes explaining the more complicated patterns of inheritance and the microscopic explanations difficult. Less emphasis should be placed on rote, algorithmic methods of solving genetics problems, and teachers should place more emphasis on students understanding the underlying concepts such as protein synthesis and meiosis (Smith, 1992).

The third factor influencing conceptual change learning is that concepts such as protein synthesis are processes that need to be assimilated into students' minds for conceptual change to take place. However, these concepts are often represented statically; explaining the process aspects of these concepts is difficult and hence is something that teachers often neglect. To address this deficiency, teachers should be searching for and utilising models and other teaching strategies that engage their students in thinking about the process aspects of genetics so that conceptual change is fostered.

The fourth aspect is that it is possible to explain units of information about genetics without integration. The integration, or linkage between ideas, is where true understanding begins, and this is a difficult aspect of genetics for teachers to teach and for students to learn. Strategies for integrating concepts and developing a "big picture" such as concept maps and appropriate revision tasks should be utilised by teachers to address this problem.

Finally, the fifth factor that influences conceptual change is that students are expected to switch between macroscopic phenomena, microscopic entities, sub-microscopic explanations and symbolic representations. Teachers need to be aware of this phenomenon and not expect that students will be able to do this without time and practice.

The next and final chapter of this thesis, Chapter 9, reviews the findings by directly addressing each of the research questions posed in Chapter 1. In addition, an examination of the possible similarities and differences between the historical development of the concept of the gene and the student learning elucidated by this study is presented. Finally, the implications for genetics teaching and for conceptual change theory are discussed.

CHAPTER 9
SUMMARY, CONCLUSIONS AND IMPLICATIONS

> [O]ne should wade through one conceptual quagmire at a time.
>
> (Strike & Posner, 1983, p. 43)

Introduction

The purpose of this final chapter is to summarise the conclusions of this thesis and discuss the implications for genetics education and conceptual change research. Initially, a summary of results is presented which addresses each of the research questions proposed in Chapter 1. In the second section of this chapter the historical development of the gene concept, that was presented in Chapter 2, is brought into juxtaposition with the student learning elicited by this study. Similarities and differences between the historical development of the gene concept and student learning are discussed in light of the "learner as scientist" metaphor made popular by the conceptual change literature. The implications of the results of this study for the teaching of genetics are proposed, as are the implications for research in conceptual change. Finally, the possibilities for further research in this area and the limitations of this research are discussed.

Summary of Results

Research Question 1: What happens to Year 10 students' conceptions of the gene when they learn genetics?

An ontological perspective of conceptual change (Mariani & Ogborn, 1990, 1991, 1995; Martins & Ogborn, 1997) was initially used in this study to investigate what happened to students' conceptions of genes when they learnt genetics. Work-sheet and interview data from three Year 10 classes suggested that the changes in the ideas that students had about genes could be narrowed down to three basic trends. These trends were described as ontological shifts because they represented changes in the way that the students perceived the ontological nature of genes. The first trend was from a passive gene to an active gene. Initially, genes were seen by the students as being passive, they were passed from generation to generation, but genes were not generally seen to do anything themselves. Following study in the genetics course, this passive view of genes changed to a more active view of genes because students described genes by saying that they "determine", "control" or "influence" characteristics.

The second trend observed in students' conceptions was with regard to the physical nature of the gene. Before the course, students used words like "thing" or a "cell" to describe genes which indicates that initially genes were viewed as being particle-like. For some students, this particle-like view of a gene changed to being more like a sequence of instructions. The third trend observed, for a small number of students, was that the process aspects of genes became evident, they no longer saw a gene as simply an entity, but understood that genes are part of a process, that is, the students associated the gene concept with protein synthesis. These changes were summarised in a pathway that proposes that Year 10 students' conceptions progress through more sophisticated models of genes (Figure 9.1).

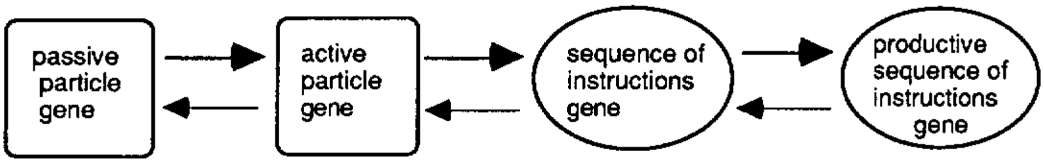

Figure 9.1: The pathway, proposed in Chapter 6, representing the progress of Year 10 students' conceptions through more sophisticated ontological models of genes.

The data suggested that the majority of students in the three classes completed their genetics course with a conception of a gene similar to the "active particle gene" in the pathway presented in Figure 9.1. This means that they visualised a gene as being a particle or entity which is transferred from parent to offspring. Students with this conception attributed some kind of action to the gene such that it has an effect on the characteristics of an organism. For example, the students with this conception said that the gene will "influence", "determine" or "control" a certain characteristic. The case study of Alastair presented in Chapter 7 is probably the most typical of the case studies in terms of the majority of students in the three classes. Alastair began the genetics course with a conception similar to a "passive particle gene" model because he did not make any connections between genes and DNA and he said that genes "come from the parents". By the end of instruction, Alastair was able to articulate and explain the idea that genes control or determine characteristics. Alastair did not have any notion of a mechanism by which genes could control characteristics and even though he had learnt that DNA is a ladder like structure, he had no idea about the significance of the double helix. For these reasons Alastair's conception of a gene did not progress to the "sequence of instructions gene" model in the pathway.

Of the 29 students from the three classes who were interviewed, only five completed their genetics course with a conception like the "sequences of instructions gene" model. With this conception, students saw a gene as being a sequence of instructions rather than a particle and understood that the sequence of instructions holds a code for a characteristic or the phenotype of an organism. Case studies of Jacinta, John and Tan, presented in Chapter 7, are examples of students who completed their course with a conception similar to a "sequence of instructions gene" model. Jacinta, for example, began the course with a conception similar to an "active particle gene" model because she wrote that genes are "something that you inherit from your parents" and they "determine your looks, intelligence, diseases, etc." By the end of the genetics course, Jacinta had learnt important content knowledge about chromosomes being made of a code to determine characteristics. Jacinta also was able to explain protein synthesis, but there was no evidence that Jacinta had made vital connections between protein synthesis, proteins and the determination of characteristics. Consequently, it was concluded that Jacinta's conception had progressed to a "sequence of instructions gene" model and not a "productive sequence of instructions gene" model by the end of the course.

Very few students in the three classes had a conception of a gene similar to the "productive sequence of instructions gene" model in the pathway. Only two of the 29 Year 10 students interviewed were judged to have this conception at the end of their genetics course. These students saw a gene as a sequence of instructions which is made up of a code and which determines the phenotype of an individual. Most importantly, they also understood that the genetic code is responsible for controlling the process of protein synthesis and that the proteins, which are constructed from the code, are one of the major determinants of the phenotype. Douglas's case study, presented in Chapter 7, is an example of a student who completed the genetics course with a "productive sequence of instructions gene" conception. Douglas began the course with a "passive particle gene" model because he said that "genes are features that a child picks up from its parents." Although he did not distinguish between a gene and a characteristic in any way at the beginning of the course, by the end of the course, his conception had changed to a "productive sequence of instructions gene" model because he clearly made connections between genes on chromosomes, a code, protein synthesis, and characteristics.

The pathway of learning (Figure 9.1), therefore, evolved from the work-sheet data and interviews and presents the broad spectrum of changes that occurred in the Year 10 students' conceptions of the gene over the period of an introductory genetics course. The majority of students' conceptions did not change from one extreme of the pathway to the other. The data from the series of case studies indicate that the majority of students' conceptions did not progress beyond the "active particle gene" model in this pathway.

From an epistemological perspective of conceptual change (Posner, et. al., 1982; Strike & Posner, 1992), the status of the students' post-instruction conceptions was able to be determined (Hewson, 1991, 1992, 1996). Even though there were difficulties in doing this, which are outlined in Chapter 7, determining the status of the post-instruction conceptions was valuable because it was possible to establish a great deal more information about the process of conceptual change in each student's mind. For example, the low status of intelligible for some students' conceptions suggested that further opportunity for the students to utilise and apply their conceptions was necessary for the status to be raised in the learners' mind.

Research Question 2: When Year 10 students learn genetics, do the changes, if any, that occur in their conceptions of a gene constitute conceptual change, and if so, how can these conceptual changes be described?

The pathway of models (Figure 9.1) developed to represent Year 10 students' conceptions of genes as they learnt genetics represented a model of conceptual change. For students to progress along the pathway, it was necessary for them to create links between concepts, and this is one aspect of learning that differentiates between simple rote learning and learning as conceptual change (White, 1994b). Making connections between ideas, such as protein synthesis and phenotype, seemed to be the most important factor in giving the students in the case studies the impetus to make progress along the pathway to more scientifically apt models of genes. Posner, et. al. (1982) state that conceptual change learning involves the interaction of new knowledge with existing knowledge. For students to progress along the pathway of models of genes, learning was not simply a case of addition, it did indeed require a process of reconciliation to link old with new conceptions.

Few students actually progressed the full length of the pathway; Beth and Douglas were the only interviewed students who were considered to have a post-instruction conception of a gene that was similar to a "productive sequence of instructions" model, the final model in the pathway (Figure 9.2). Douglas's post-instruction conception was classified as having a high status of being fruitful, but Beth's conception was classified as having the low status of being only intelligible. Each of the other students who participated in the case studies completed their genetics courses with a variety of conceptions with varying status as can be seen in Figure 7.26, which is presented again here for the reader's convenience in Figure 9.2. Figure 9.2 can be considered to represent a spectrum of conceptions at different stages of progress along the pathway or at different stages of an evolutionary process of conceptual change.

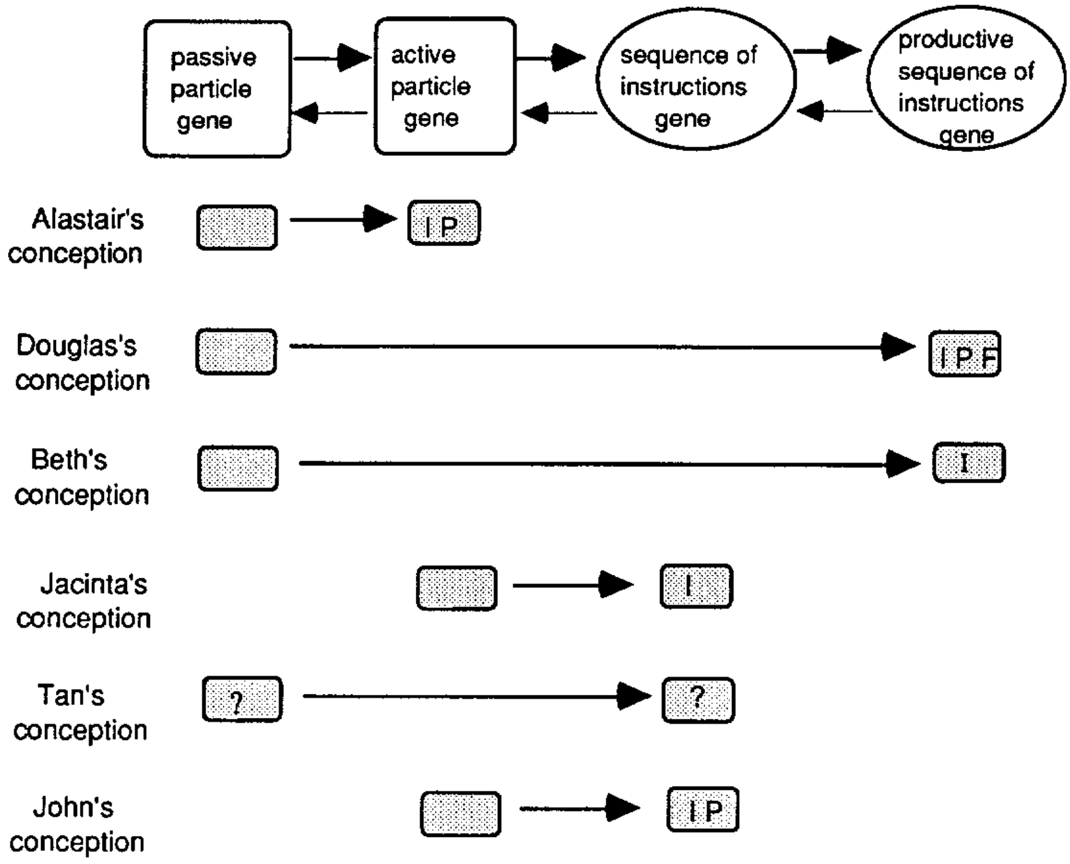

Figure 9.2: A composite figure representing the six case study students and their progress on the pathway of ontological models of genes from before to after instruction.

How can the Conceptual Changes be Described?

The evidence from the three Year 10 classes suggests that the conceptual changes that occurred in the students' ideas about genes can be described as the weaker kinds of conceptual change such as conceptual capture (Hewson, 1981, 1982, 1986), or assimilation (Posner et al. 1982, Strike & Posner, 1992) because previous conceptions are reconciled with new conceptions. This is a better description of the kind of conceptual change that occurred in this study compared with stronger descriptors such as conceptual exchange (Hewson, 1981, 1982, 1996) or accommodation (Posner et al. 1982; Strike & Posner, 1992), where previously held conceptions are discarded.

From an ontological perspective of conceptual change (Chi et al., 1994), the changes also can be described as the weaker kind, that is, within and not across the ontological groups that Chi describes. Examples of the stronger kinds of conceptual changes that Chi et al. use such as learning about electricity, result in students discarding the idea that the phenomenon is matter and accommodating the idea that the phenomenon is a process. Data from this study has shown that when students learn about the concept of the gene, linking between the matter features of genes with the process features of genes is an important component of the conceptual change process. However, the idea that the gene is a material entity was not discarded by students. In this sense, the weaker, branch-jumping form rather than the more radical, tree-switching form of Chi et al.'s theory of ontological conceptual change is a more appropriate description of the kind of conceptual change happening in the case studies in this thesis.

The conceptual changes that were observed in the series of three Year 10 classes can be described as being evolutionary rather than revolutionary. The case studies of students showed evidence that their learning formed an evolutionary pattern where they maintained substantial elements of old conceptions while gradually incorporating elements from the new conceptions. Students like Beth and Douglas were able to visualise genes as being a sequence of instructions while, at the same time, maintaining the idea that a gene is passed down from parents to offspring. These and other students were able to build up content knowledge and make links with existing knowledge that enabled them to change their conceptions in a gradual, incremental way. However, there is not enough detail in this study to make claims about how consistent the evolutionary process was; further data collection at many points in the genetics course would reveal any reversals in direction or leaps or static points during the conceptual change process (Mortimer, 1995).

Research Question 3: What factors influence the process of conceptual change when students are learning about genes?

Data collected from the series of eight case study sites were used to support assertions about five factors which directly influenced the conceptual change process. Factors influencing conceptual change were considered to be those that would facilitate or hinder the progress of students' conceptions along the pathway of models of genes (Figure 9.1). The teaching approach was one factor that influenced students' progress along the pathway of models, and this was best illustrated by Mr Counter's approach that seemed to be the most successful in facilitating conceptual change (Table 6.3). He overtly addressed the need for students to understand the process aspects of genes such as their role in protein synthesis. Mr Counter used a cut-out paper model of

DNA to illustrate the code nature of the DNA structure and a second paper model to demonstrate the role of the genes in providing the messages for protein synthesis. Even though Mr Counter's modelling approach was probably the most successful of the three approaches examined in Chapter 6, many students in his class did not develop a very sophisticated or fruitful understanding of the gene concept. This observation was attributed to the inability of some students to make connections between the paper model and the scientific conception which may be a consequence of the connections not being explicitly made in the class. Students also were not given the opportunity to utilise their conceptions with appropriate problem-solving tasks or revision lessons in a way that would raise the status of their newly acquired conceptions.

Ms Prentice's teaching approach encouraged her students to develop clear ideas of the structure of DNA; however, these ideas were limited because many of her students did not understand the significance of the double helix structure - they did not know why it was important. Mr Yulang did not cover gene structure and function in a detailed manner, using only short, cliché-style analogies for explaining DNA structure and the genetic code. Consequently, none of his students who were interviewed progressed beyond the "active particle gene" model in the pathway by the end of the genetics course.

The teachers observed in this study tended to emphasise simple problem solving. A great deal of classroom time was set aside to practice simple monohybrid crosses that can be solved with a Punnett square. These problems are more meaningful when the Punnett square is put into context and students can explain the relationship between the Punnett square and allele-containing gametes (Smith, 1992). The problem with these tasks in genetics is that teachers and students often approach them in an algorithmic manner, and the student simply puts the Punnett square to use to find solutions without understanding the underlying principles (Smith, 1992; Stewart, Hafner & Dale, 1990). One aspect of this approach to genetics problems is that they can be solved with a "passive particle gene" conception. To get the right answer, students do not need to understand the microscopic structure or function of genes. This approach does not encourage the progress of students' conceptions along the pathway of models and hence the evolution of conceptual change about the concept of the gene.

Interest was identified as a factor that inhibited students' progress to more sophisticated models of genes in their conceptual structures. Students, generally, were interested in the human heredity aspect of genetics and during interviews, students focussed on simple Mendelian ideas of dominance and recessiveness of alleles when asked how genes control characteristics; they responded without understanding the underlying sub-microscopic, explanatory mechanisms. Mendelian patterns were seen to be intrinsically interesting and intriguing because students seemed to be able to use these ideas to answer questions about their own inheritance. Ironically, many of the students' questions about human heredity are not really solvable with this kind of simple logic. It appeared that the concepts of genes, chromosomes, DNA and protein synthesis were not high on the personal learning agenda, and it is probable that these students did not easily become cognitively engaged when the teachers were teaching these concepts.

The third factor identified as having a significant influence on the process of conceptual change when students were learning about genes was the process aspects of genetics. For students' conceptions to progress to more scientifically proficient models of genes along the pathway of models (Figure 9.1) and hence for conceptual change to take place, students need to assimilate the ideas about gene function which includes processes such as protein synthesis. The teaching of these processes requires the engagement of students in thinking about the process and this often requires teaching approaches such as role plays or other student-constructed models (Kindfield, 1992). The teachers in this study claimed that this teaching approach is time consuming and difficult for them to manage and organise. The process of conceptual change is, therefore, inhibited in many classrooms because of the difficulty for teachers to teach key process concepts.

The lack of linkage between concepts seemed to be an important factor that inhibited students' progress along the pathway of gene models and hence inhibited conceptual change. Interviewed students clearly showed that they had learnt isolated concepts such as protein synthesis, or the double helix structure of DNA, but they did not have any notion where these concepts link with the big picture of heredity or with the concept of the gene. Some students knew that the double helix was a code, but they did not know what for. Other students could describe the process of protein synthesis, but they did not know that proteins are important in heredity because they help to control the characteristics of an organism.

Finally, the fifth factor that was found to influence conceptual change was another aspect of the nature of genetics content. Genetics is made up of three levels of representation, the macroscopic visible phenomena such as the phenotypic expression of genes, the sub-micro, explanatory phenomena such as DNA, and the genetic code and symbolic representations such as the letters A, G, C, and T to represent the bases of the genetic code. There was evidence from the larger series of eight case study sites that switching between these levels of representation is not as easy for students as it is for the observed teachers. Students seemed to be confused by the different levels of representation, and such confusion is likely to inhibit their learning of and differentiation between concepts.

Research Question 4 : How can different theoretical perspectives of conceptual change be optimally used to describe the changes that occur in students' conceptions of a gene?

Initially, the perspective of conceptual change theory used in this study to describe the changes that occurred in students' conceptions of a gene was an ontological perspective of conceptual change based on the work of Martins and Ogborn (1997) and Mariani and Ogborn (1995, 1991, 1990). The value of using this perspective of conceptual change was that it allowed the researcher to look beyond the simple learning of content knowledge and to examine how the students' basic notions of the fundamental nature of a gene changed during their genetics course. Using this ontological perspective of conceptual change as the primary interpretive framework also was necessary because the students' pre- and post-instructional conceptions needed to be established before the status of the conceptions could be investigated.

An epistemological perspective of conceptual change was used in this study to determine the status of the post-instruction conceptions of the students in the case studies presented in Chapter 7. The value of using this perspective of conceptual change was that it allowed the researcher to examine the epistemological commitments that the students had for their various conceptions of genes. Through this examination, it became clear that few students in these classes had a conception that had a high status and this, in turn, suggested that teaching strategies need to be adopted in order to raise the status of appropriate scientific conceptions in students' minds. Content knowledge also was discussed in Chapter 7 and increased content knowledge alone did not necessarily result in the students changing their conception of a gene.

In addition to the epistemological and ontological perspectives, a social/affective perspective was used in Chapter 8 to examine the data. This perspective was of value to the research process because it revealed information about how the teaching approach and student interest influenced the process of conceptual change. The nature of the content, such as the process aspects of genetics and the different levels of representation, was another perspective used to examine conceptual change. Each of these multiple perspectives of conceptual change contributed valuable insights necessary for developing a comprehensive, multifaceted picture of the process of conceptual change.

If we reflect on the student case studies presented in Chapter 7, the multidimensional approach enhanced the view of conceptual change. For example, from an ontological perspective of conceptual change, Beth's post-instruction conception of a gene was like a "productive sequence of instructions gene". This information by itself gives the impression that Beth had achieved a great deal in terms of understanding the gene concept. However, when the data were examined from an epistemological perspective, it was discovered that the status of Beth's conception was only intelligible and not plausible or fruitful. This kind of information resulted in the researcher asking questions about why Beth's conception did not have a higher status. When the situation was viewed from a social/affective perspective, which included the teaching approach taken in Beth's class, it was found that the lack of strategies used by Beth's teacher to consolidate a sophisticated view of a gene in the students' minds was a possible reason for the low status. Beth had not had an opportunity to articulate her conception of a gene prior to the interview. Each of the student case studies presented in Chapter 7, dovetailed with information on the factors that influenced the process of conceptual change in Chapter 8, demonstrate similar stories where the multidimensional approach enhanced the picture being built up about conceptual change.

In the development of the multidimensional framework for conceptual change, Tyson et al. (1997) presented a pictorial representation with the three main perspectives, epistemological, ontological, and social/affective, being represented as the sides of a triangular figure (Figure 9.3). In this study, although the three main perspectives were utilised, another important perspective of conceptual change was used to interpret the data. It is difficult to establish where the nature of the content perspective could fit into this original triangular diagram.

It seems that the different perspectives of conceptual change utilised in this study can be divided into two groups, the first being those perspectives that describe the cognitive changes and the second being those perspectives that are useful for describing the influences on the conceptual change process. Epistemological and ontological perspectives of conceptual change are included in the first group that describe the cognitive changes; and perspectives such as social/affective and the nature of the content are included in the second group that describe the influences on conceptual change.

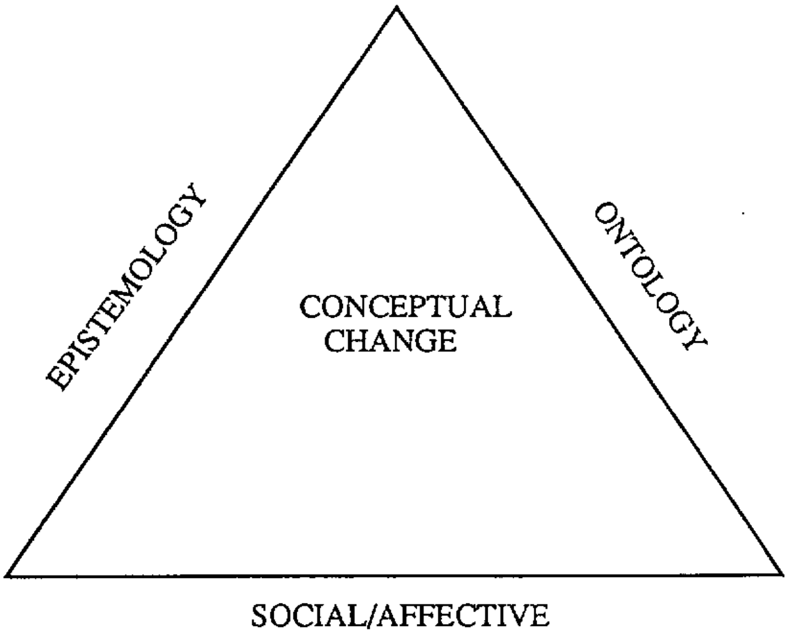

Figure 9.3: A pictorial representation of the three main perspectives of the multi-dimensional framework as presented in Tyson et al. (1997).

If we look closer at this division, however, it becomes superficial. For example, determining the status of students' conceptions from an epistemological perspective may seem to be a description of the cognitive aspects of conceptual change. However, it naturally follows that the status of a conception influences the process of conceptual change. The division into these two groups of perspectives is clearly unsuitable and Strike and Posner's (1983) warnings are once again heeded.

> Trying to group the factors involved in conceptual change into categories like rational and nonrational or (heaven forbid) cognitive and affective (as though motives and feelings were not highly conceptualised states) is on a par with doing brain surgery with a jackhammer - messy and lethal (p. 43).

The division of the various theoretical perspectives into separate groups such as cognitive perspectives or those that describe the influences on conceptual change, is probably not important. What is important is the multi-dimensional nature of theory in conceptual change and the complex and unique learning situations that the multiple dimensions can be used to interpret; it is the process of interpreting conceptual change from multiple dimensions that is important. Figure 9.4 is a diagrammatic representation of the multidimensional approach taken in this thesis to examine student learning of the concept of the gene.

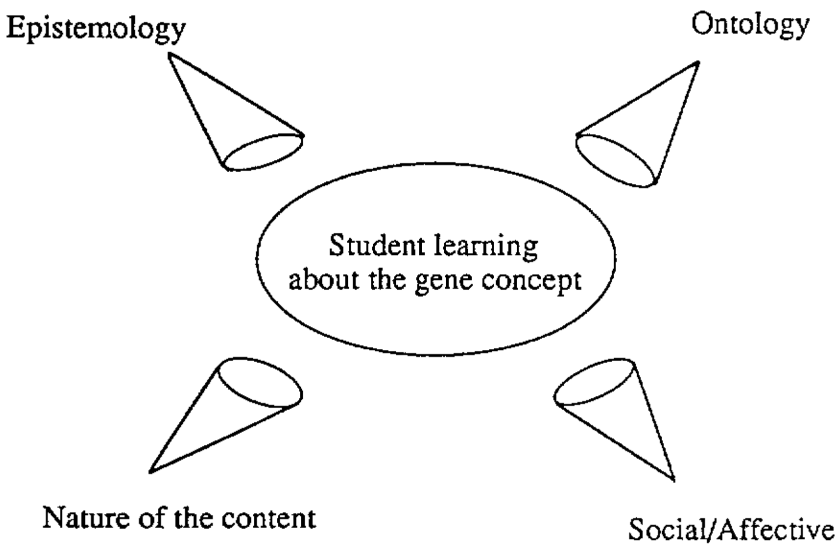

Figure 9.4: A diagram representing the multidimensional approach taken in this thesis to examine student learning of the concept of the gene.

Similarities between the Historical Development of the Gene Concept and Students' Learning

It is interesting to compare the kind of conceptual changes that took place in the Year 10 students' conceptions with the historical development of the concept of the gene that was presented in Chapter 2. At the outset of this doctoral research study, there was no intention of making this comparison. Towards the end of the research process, however, it became clear that there are some similarities between the learning that the researcher observed among the student participants and the historical development of the gene concept. Because of the important place that the metaphor of the "science learner as a scientist" has played in the conceptual change research literature (Caravita & Halldén, 1994; Posner, et. al., 1982; Strike & Posner, 1983, 1992; Wandersee, 1985), an investigation of the similarities and differences between the historical development of the gene concept and student learning is worthwhile and informative for both research in genetics teaching and learning and in conceptual change research. Evidence from this study about students' learning about genes and historical accounts of the development of the gene concept (Falk, 1986; Mayr, 1982; Portin, 1993) seem to indicate some similarities. There also are fundamental differences that refute the metaphor "science learner as a scientist" that support the position taken by some researchers.

Differentiating the Concepts of Gene and Characteristic

The first similarity between the history of genetics and student learning of the gene concept is with regard to the differentiation of the concepts of gene and characteristic. Early in the history of genetics, there was no clear distinction between a genetic factor (gene) and a characteristic. Similarly, there is evidence in this study that some students did not distinguish between these concepts before instruction. Prior to about 1910, when biologists spoke of a unit character, it did not really matter whether he or she meant the underlying genetic entity or its phenotypic expression (Mayr, 1982). Johannsen was responsible for the important distinction and coining of the terms phenotype and genotype, and for the introduction of the word "gene" in 1909 (Dunne, 1965).

There was evidence in the case studies in Chapter 7 (see Douglas's case study for example) and on the work-sheet data that before the genetics courses some students did not distinguish between the concepts of gene and characteristic. It is possible that these students perceived a gene as being similar to what Mayr (1982) describes as a "building blocks" gene (Figure 2.1). In this context, genes were seen by some researchers, prior to the turn of this century, as the building blocks of the organism. Data presented in Chapter 6 (Table 6.1) show that 11 of the 83 students who completed the work-sheet prior to their genetics course wrote that DNA or genes are the "building blocks" of our body. After the course, the number of students who wrote this fell to only three. These data support the idea that before the genetics course some students' lack of distinction between a gene and a characteristic was similar to the geneticists view prior to this century. It is possible that such a conception could form the basis of another model at the beginning of the ontological pathway of learning presented in Figure 9.1. Because students were not involved in detailed interviews prior to their genetics course, however, there is not sufficient data to support such a claim. This is a possible avenue for further research.

The Material but Abstract Gene

A second similarity between the history of genetics and student learning is the understanding that the gene is a material entity on a chromosome, while at the same time, the gene concept is used by the knower as an abstract calculating unit. The period called classical genetics is said to have began with Morgan who, in 1911, confirmed "The Chromosome Theory of Heredity" which consisted of the view that chromosomes are made up of linear arrangements of genes (Dunne, 1965). This theory was to influence genetics for 25 years. The essential part of the theory was the recognition that the gene was the conceptual and physical element in the process of heredity (Dunne, 1965). Falk (1986) describes the idea of an instrumental gene concept understood by researchers during the classical genetics period as being discrete units that obeyed the basic Mendelian laws and had the potentiality for a single trait. In referring to this concept of the gene as "instrumental reductionism" (p. 141), Falk (1986) suggests that it was a useful and flexible concept for the development of genetics research as exemplified by the Morgan school.

Even though the gene had been recognised as physically existing on the chromosome, according to Tudge (1993), for classical geneticists

> the genes themselves, Mendel's "factors," are conceived simply as abstractions - or as beads, threaded on chromosomes. Clearly, classical genetics is immensely powerful and, when combined with the evolutionary ideas of Darwin, provides a wonderfully unifying picture of the endless variety of life. But in genetics there is another, quite different line of inquiry to pursue: 'What exactly are genes, and how do they work?' (Tudge, 1993, p. 45)

Bowler (1989) is of the same opinion as Tudge and suggests that classical geneticists' view of the gene was abstract and that they had a lack of interest in how the gene influences the developing organism.

The majority of students in the three classes studied in detail in Chapters 6 and 7 completed their genetics course with an "active particle gene" conception which is similar to the classical notion of the gene described above. The number of students who wrote on their work-sheet that genes exist on chromosomes increased from four (n=83) before the genetics course to 59 (n=79) after the genetics course (Table 6.1). Students with an "active particle gene" conception visualised a gene as being a particle or entity which is transferred from parent to offspring. These students understood the gene as being a section of a chromosome much like a "bead on a necklace" with the bead representing a gene and the necklace representing a chromosome. The students with an "active particle gene" conception attributed some kind of action to the gene, that is they saw the gene as influencing or controlling characteristics. Most of the students could use their idea of the gene to logically solve basic Mendelian problems, but, like classical geneticists, the students with this conception did not seem to be knowledgable about how the gene influences the characteristics.

The DNA Gene

The emergence of molecular biology as the study of what genes are and how they function constituted a major breakthrough surpassing the research practices of classical genetics (Bowler, 1989). As time moved on through the second World War, techniques improved and biologists started to concentrate more on questions other than those about the patterns of inheritance and the arrangement of genes on chromosomes. They started to investigate more seriously questions about how genes have an effect on the characters of an organism and about the detailed structure of genes.

There are clear similarities between the "sequence of instructions gene" model with which some students completed the genetics course and Portin's (1993) description of the "neo-classical gene" concept, Falk's (1986) description of the "DNA gene" concept, and Mayr's (1982) description of the "conveyor of information" gene concept. Each of these models claim that the gene is made of DNA which holds information about the characteristics of organisms in a code. The major difference between these historical models of genes and the students' "sequence of instructions gene" conception is that at the point in history when the DNA code was discovered, geneticists understood that genes were expressed though proteins. Geneticists understood the significance of the genetic code, something that students with the "sequence of instructions gene" conception did not necessarily understand. The students understood that the genetic code determines characteristics, but they did not understand the process of protein synthesis, how it occurs and how it influences phenotype.

Can Students Understand a "Modern" Conception of the Gene?

The most striking difference between the pathway of models that represents the students' learning and the models of genes in the history of genetics is that there is no equivalent of Falk's (1986) description of a bewildering gene concept or Portin's (1993) description of the modern model of a gene. Portin says that "we are currently left with a rather abstract, open, and generalised concept of the gene, even though our comprehension of the structure and organization of the genetic material has greatly increased" (p. 173). These contemporary models of genes create an image that the gene is not discrete and it is not always a continuous sequence of DNA that only codes for one protein. Falk (1986) suggests that instead of thinking of a gene as a continuous sequence of instructions that makes a polypeptide we should start with the polypeptide and work backwards. That is, rather than the idea "one gene - one polypeptide" we should think "one polypeptide - one gene". Therefore, a gene consists of all the DNA necessary to produce a polypeptide. This means that ideas such as introns, exons, regulatory units, overlapping genes, transposable genes, and split genes can be included in the definition if they are introduced in the high school or later in tertiary biology courses. This notion of "one polypeptide - one gene" would probably be an excellent cental organising concept in introductory genetics classes and in secondary biology classes.

It is interesting that the Biological Science Curriculum Study (BSCS) of the USA has just released a new high school teaching module entitled *The puzzle of inheritance: Genetics and the methods of science* (Cutter et al., 1997). One of the goals of this teaching module is to

> update the genetics curriculum to include some of the nontraditional concepts of inheritance that address processes not adequately explained by classical Mendelian genetics. It is, of course, our view of inheritance that is 'nontraditional' rather than the genetic mechanisms themselves. (Cutter et al., 1997, p. 4)

Some of the non-traditional concepts that this teaching module addresses are concepts such as mitochondrial inheritance, genomic imprinting, uniparental disomy, transposable genes, and multifactorial inheritance. Another of the goals of this teaching module is to involve students in classroom activities that require explicit opportunities to apply scientific methods in a thought-provoking context. This approach, embracing the methods of science, is incorporated in this teaching module because the developers felt that recent discoveries of nontraditional modes of inheritance exemplify the processes that scientists use to test and expand scientific explanations. It is probable that such a teaching unit could develop a conception akin to the "modern" concept of the gene in students' minds.

Implications for the Teaching of Genetics

The Gene as a Central Organising Concept in Introductory Genetics

The results of this study indicate that most of the Year 10 students' conceptions of the gene had not progressed along the ontological pathway of models by the end of their introductory genetics course. One of the main factors that influenced student learning about the gene concept was the teaching approach. Mr Counter's approach seemed to be more effective than Ms Prentice's or Mr Yulang's in terms of enhancing student understanding of the concept of the gene; however, all three teachers were teaching within the guidelines of the syllabus. Perhaps then, part of the problem lies within the syllabus. An implication of this study is that syllabus material should use the gene concept as a cental organising concept in introductory genetics courses. The functional aspects of genes should not be given a merely cursory mention, but clearly stated. The development of links that this cental organising concept of the gene has with other concepts in genetics (such as the cell, meiosis, chromosomes, DNA, proteins and patterns of inheritance) also should be encouraged by the way the syllabus is written and consequently by the way that teachers teach.

The importance of central concepts such as the gene also has been highlighted in the literature. According to Smith (1992), teachers of genetics should be more concerned with teaching the fundamental concepts in genetics thoroughly than trying to cover too much material in introductory courses. He suggested teachers should be focusing on the important things and omitting the rest (Smith, 1992).

> In this age of knowledge explosion (especially in genetics), the time has come to focus our instruction more on meaningful understanding of foundational concepts than on shallow "exposure" or "coverage." (p. 78)

The concept of the gene is indeed a central organising concept in genetics, but it is surprising how syllabus materials in the various states of Australia address the concept, usually with little more that a simple objective. As explained in Chapter 6, the syllabus used by Mr Counter and Mr Yulang states: "Give a functional definition of a gene and explain the relationship between genes and chromosomes" (Secondary Education Authority of WA, 1996, p. 71). Another example from a secondary syllabus in South Australia simply states that students should understand that: "A gene is a sequence of nucleotides in a DNA molecule" (Senior Secondary Assessment Board of South Australia, Biology, 1990). In Western Australia, the outline of the Year 12 Human Biology syllabus includes the topic of "Genetics and Mechanisms of Evolution" but what students are to understand about the gene concept is not explicitly stated at all. Other terms such as genotype, phenotype, patterns of inheritance, alleles, DNA and proteins are included, however, the term "gene" is not mentioned.

The Queensland Biology Syllabus (Board of Secondary School Studies of Queensland, 1987) states that the major concept in the Year 12 biology core topic "Genetics" is:

> While the characteristics of organisms are subject to environmental influences, they are ultimately determined by information contained within genes located in the organism's chromosomes. This information is transmitted from one generation to another. (p. 17)

The Queensland syllabus then continues to list fours areas of core subject matter including patterns of inheritance, chromosome activity and environmental influences on gene expression. The final section reads

> Scientific models exist which account for the storage, replication, mutation, translation and implementation of heredity information carried by molecules of DNA. (p. 17)

Even though the term "gene" is not specifically mentioned in this final section of the core subject matter, it is clear from this statement and the major concept that the approach taken to genetics in Queensland is going further than the other state syllabuses examined to utilise the gene as a cental organising concept in the genetics course. As with other syllabuses, it is unfortunate that the topics of DNA, mRNA, tRNA, ribosomes and the role they play in protein synthesis are taught in the separate core topic "Cell Biology". This separation of genetics-related content knowledge into different topics in biology courses is seen, in the light of the results of this study, as a major concern for the learning of genetics and is discussed later in this chapter.

This research suggests that for teachers to be able to encourage students to construct a "productive sequence of instructions gene" conception in their cognitive structures they must include certain strategies in their teaching. Examples of these strategies include linking concepts in genetics, improving the teaching of genetics processes, and raising the status of students' conceptions. These teaching strategies are discussed below.

Linking Concepts in Genetics

One of the findings of this research that has clear implications for the teaching of genetics is that students have difficulty linking concepts in genetics. The linking of the concepts such as protein synthesis and gene also was an important avenue for conceptual change (see Chapter 7 and 8). Further, the teaching approaches employed by teachers in this study did not encourage an integrated view of gene structure and function in the students' minds. The reflections of Helena, presented in Chapter 8, are a poignant reminder of this phenomenon.

> That's the thing you can't, you don't, you learn it so separate that it's really hard if you think about everything, it's really hard to put it together. I mean because we learnt this and then we learnt that when we did cells and things and you don't really think to put it together because it's not taught that way.

This implication could have immediate impact on classroom teaching if teachers employ teaching strategies that will facilitate the connection of concepts about genes and about genetics in general. Understanding a concept means, among other things, to know its relationships with many other concepts, yet instruction in introductory courses tends to stress concepts at the expense of relationships (Fisher, 1986). Students can often "get by" with shallow, rote learning about concepts, and yet know very little about the relationships between those concepts (Fisher, 1986). This problem is one that should and can easily be addressed by biology teachers.

Much has been written in the science education research literature about strategies that will facilitate the process of integration between concepts and conceptual change. One of these strategies is concept mapping. Concept maps are a tool that allows the student to link ideas and create a physical picture of a large topic (White & Gunstone, 1992; Novak, 1996). Novak (1996) claims that concept maps are an important tool for improving science teaching and learning because they "serve to show relationships between concepts, and it is from these relationships that concepts derive their meaning" (p. 32). Fisher (1986) points out that genetic systems are very complex and cannot generally be reduced to simple relationships such as those used in other science fields (such as the relationship between force, mass and acceleration). Concept maps comprise a selection of terms that are linked by sentences that explain the relationship between the terms. In this sense, the complexity that Fisher (1986) describes in genetics can be better represented by concept maps. Concept maps could be used by teachers to help students learn and be explicit about the links between concepts in genetics such as gene, DNA, chromosome, allele, genetic code, protein, protein synthesis, and characteristic, that all would form part of an interconnected topic. Limiting the terms to be mapped also can focus the strategy for developing links between a wide or a narrower field of knowledge depending on the needs of the students and the teacher. Concept maps also are an excellent tool for assessment, especially in-class assessment, which can replace traditional methods such as essay writing (Novak, 1996; White & Gunstone, 1992).

White and Gunstone (1992) suggest a number of strategies that are useful for guiding students in constructing understanding. A number of these strategies would be particularly useful for genetics in light of the findings of this study. For example, word associations and rational diagrams could be utilised by teachers to increase the links that students perceive between the specific and isolated concepts that make up genetics.

Drawings (White & Gunstone, 1992) are a useful strategy to probe understandings that are hidden from other procedures. In this study, to probe students' conceptions of a gene, drawings were useful when other strategies such as the work-sheet and verbal interviews did not provide enough information about the student's understanding (see Chapter 8, for example). Kindfield (1991b, 1992, 1993/94) suggests that diagrams are essential for externalising pieces of models of genetic processes and that diagrams might play a role in building knowledge about meiosis. Specifically Kindfield (1991b) states that diagrams may be useful for adding pieces of meiosis knowledge to a learner's knowledge base, breaking inappropriate connections and establishing appropriate connections between the learner's interconnected knowledge. Student drawings of genes, DNA structure and protein synthesis could be utilised by teachers to facilitate learning and to probe students' understanding of these concepts. There are problems associated with the use of diagrams in instruction and Kindfield (1991b) makes suggestions about the use of diagrams to facilitate the teaching process. Some of the suggestions include: explaining the meanings of representational objects in diagrams, treating diagrams as learning tools rather than just illustrations; interweaving verbal and pictorial descriptions, and encouraging students to draw diagrams of verbally presented information and vice versa.

Metacognition is something that can be encouraged in genetics classes to improve the interconnectedness between concepts. Gunstone (1994) describes metacognitive learners as those who undertake the tasks of "monitoring, integrating and extending their own learning" (p. 135) and claims that one of the advantages of metacognition is that it promotes conceptual change learning. Student learning behaviours which have been identified as illustrative of appropriate metacognition include: seeking clarification, planning strategies, checking work against instructions, raising errors or omissions with the teacher, rectifying errors or omissions, risk taking in order to increase understanding, considering the viability of explanations in different situations, and not seeing the teacher as the sole source of information (Gunstone, 1994). These behaviours in students can be encouraged in classrooms by teachers, for example, by encouraging students to ask questions of the teacher, by allowing students time to plan learning activities, by providing a range of sources of information and encouraging students to test their own conceptions in different situations. These strategies are likely to improve the connections made by students between genetics concepts by encouraging them to be metacognitive and to assess the epistemological status of their conceptions.

Evidence from this study indicates that the curriculum can contribute to concepts in genetics being taught in an unconnected manner. One of the teachers who participated in this study expressed her concern about the separation of some of the content in genetics into the topic "Cells" and the topic "Genetics" in the Human Biology course in which she had been instructing her students (Secondary Education Authority of Western Australia, 1996). Such a unitised curriculum resulted in the teacher teaching her students about the nucleus, DNA and protein synthesis in Year 11 as part of the Cells topic and the rest of the genetics content in Year 12. This division of content is not uncommon in Australian state syllabuses (Senior Secondary Assessment Board of South Australia, 1990; Board of Secondary School Studies of Queensland, 1987), and this phenomenon is something that would erode attempts by teachers to help students construct an integrated knowledge of genetics. Teaching genetics in a cell cycle/life cycle perspective, is suggested as one way to enhance the connections between genetic concepts and underlying processes (Kindfield, 1992, 1993/4; Stewart & Hafner, 1991). The implication for the teaching of genetics is that genetics should be closely and systematically linked with the structure and function of the cell. Similar problems have been identified in other biology topics such as respiration and photosynthesis (Haslam & Treagust, 1987)

All the above teaching strategies can be used in the genetics classroom with relative ease. The recommendation here is that teachers of genetics should start employing strategies that will impact on the relational type of understanding of genetics that students can attain. Learning in a relational way results in students building up conceptions that allow them to process plans for solving new problems rather than relying on algorithms that only solve one type of problem (Skemp, 1987). A relational understanding of genetics by students is surely a goal to which teachers of genetics should aspire.

Improving Approaches to Teaching Genetics Processes

The finding in this study that understanding genetics processes is a key link in the conceptual change process has important implications for the teaching of genetics as a topic in secondary science. Teachers had difficulty teaching processes involving genetics concepts and students had difficulty learning and integrating processes into their genetics knowledge. The difficulty of teaching and learning biological processes has been identified by other researchers such as Fisher (1986), who noted that

> genetics language consists almost entirely of nouns. Even though genetics at all levels is concerned primarily with dynamic processes and the elements engaged in them, these processes are for the most part associated with noun labels (meiosis, transcription, evolution). (p. 11)

Fisher points out that we rarely speak of processes in genetics by verbs such as transcribe, mitose, meiose or protein synthesise. This interesting aspect of the language used in genetics in part may reflect the difficulty that teachers have with teaching genetics processes.

In making recommendations to promote the understanding of genetics processes that are applicable to meiosis, protein synthesis, transcription and translation, Kindfield (1992) sees learning about subcellular processes as fundamentally model-building. The first recommendation is for teachers to treat learning as model building and to view students as model builders. Kindfield views learning "as a constructive process in which students must be engaged actively" (p. 40). She states that what is missing from most conventional teaching about genetics processes is that students are not actively engaged in reasoning about the process, "by piecing together old and newly acquired bits of information into a more or less coherent model" (p. 40). Active engagement in reasoning about processes can be encouraged by asking students to talk about or explain their thinking and attempt to persuade others, which is one of the recommendations of the Teaching Genetics Conference sponsored by the National Science Foundation (Smith & Simmons, 1992). Unfortunately, none of these activities were observed in the classrooms that were part of this study.

Kindfield (1992) explains that one of the difficulties of learning about subcellular processes is that the students and the teacher have virtually no direct experience of them; this lack of experience aspect of science content is also noted by White (1994b). To compensate for this lack of experience, Kindfield suggests that teachers can utilise strategies such as role plays to act out the various processes (c.f. Stencel & Barkoff, 1993). Once the processes have been learnt, the knowledge can be utilised as a base for the further development of more "robust" models so that students can move from a basic model toward a more elaborate model of a particular process.

Further, on the topic of model building and processes, another recommendation that emerged from the Teaching Genetics Conference (Smith & Simmons, 1992) is that DNA models should be built by asking students to explain how structure explains function. This is something that was missing from Ms Prentice's approach to teaching DNA structure; there was no connection to genetic function and many students failed to understand the significance of the double helix. According to McInerney (1996), "it makes little sense for students to memorise the structure of DNA if they do not understand that its function is to store, copy and make available the information in biological systems" (p. 44). If Ms Prentice had adopted a process approach to her teaching of DNA, the result may have been a better understanding of the gene concept by her students.

Raising the Status of Students' Conceptions

One of the important issues of teaching for conceptual change is that the status of the appropriate conceptions has to be raised so that they will be successfully incorporated into the conceptual structures of the learner (Hewson, 1981, 1982, 1996). According to the conceptual change model (Posner et al. 1982, Strike & Posner, 1992), the highest, and most desirable, status that an appropriate conception can hold in the learner's mind is the status of fruitfulness (Hewson, 1981, 1982, 1996). This means that the conception is not only intelligible and plausible, it achieves something of value, it solves otherwise insoluble problems, and it suggests new possibilities, directions or ideas to the learner (Hewson, 1981, 1982, 1996). One of the important findings of this study is that students' conceptions of the gene as a sequence of instructions or the gene as a productive sequence of instructions did not have a high status. Only one student, Douglas, was found to have a fruitful conception of a "productive sequence of instructions gene". The status of fruitfulness for Douglas's conception was because he was able to solve otherwise insoluble problems. Questions were raised in the discussion in Chapter 7, however, about the validity of the status of fruitfulness and the number of Hewson's (1981, 1982, 1986) criteria that a conception must meet before it can be deemed fruitful. There was no evidence that Douglas's conception suggested new ideas to him. Douglas needed to be challenged further so that his conception suggested new possibilities, directions or ideas. Beth was the only other student who completed the course with a "productive sequence of instructions gene". Beth's inarticulate use of appropriate scientific terms and her lack of confidence in her own explanations resulted in her conception being classified as intelligible, but neither plausible nor fruitful. It seemed that until the interview Beth had little opportunity to clarity her own conception of a gene and extend herself to answer problems that would require use of the more sophisticated model of the gene. Therefore, it is not surprising that her new conception did not have a high status because it is probable that she had not put it to use.

The students in the classes in this study had not been given opportunities to apply their newly acquired knowledge to solve meaningful genetics problems or to explain their ideas to other people. Kindfield (1992) asserts that realistic genetics problem solving means problems that are more consistent with the kinds of reasoning activities in which geneticists engage, like determining modes of inheritance from experimental or pedigree data as opposed to working standard textbook cross problems. Smith (1992) asserts that "while the Punnett square is probably the single most useful tool in classical genetics problem solving, it is also the algorithm most widely misunderstood and misused by students" (p. 72). While discouraging the use of algorithmic procedures without understanding the underlying cytological procedures, Smith (1992) speaks specifically of using the Punnett square as modelling the process of meiosis. In accordance with Smith's recommendations, the findings of this study suggest that mindless application of the Punnett square to solve genetics monohybrid and dihybrid type problems gives students the illusion that this is all they need to know about how genes determine characteristics. The students seemed to be attracted to the simplistic algorithmic solutions that can be equated with Skemp's (1987) notion of instrumental learning.

In order to raise the status of scientifically proficient models of genes such as the "productive sequence of instructions gene" model, students need to utilise their knowledge about the structure and function of genes. For example, students could be encouraged to follow the footsteps of researchers in genetics as Kindfield (1992) suggests by researching scientific information on specific genes, their effects on the phenotype of an individual, the metabolic pathway that results in the phenotype, pedigree information that explains the inheritance of the gene and the different allelic representations of the gene. Different students in a class or a group of students could be encouraged to investigate different genes and share the information. This sharing of information would result in students gaining an appreciation of the nature of genes and allow them to explain and defend their ideas to others. It also would result in the integration and consolidation of separate genetics concepts and, most importantly, the investigation process would help to raise the status of scientifically sophisticated models of the gene such as the "productive sequence of instructions gene" model.

Implications for Conceptual Change Theory and Research

The utility of using an ontological, an epistemological, a social/affective and a nature of the content perspectives of conceptual change to analyse and interpret the data of this thesis were outlined in the "Summary of Results" section presented at the beginning of this chapter. The multidimensional nature of theory in conceptual change and the complex and unique learning situations that the multiple dimensions can be used to interpret are important and have implications for conceptual change theory and research.

The Importance of Multiple Dimensions

The pilot study reported in Chapter 4 provided a starting point for the use of multiple perspectives of conceptual change in classroom research. This idea was developed in Chapter 5 into a multi-dimensional framework that was used to guide the research process in the main part of the study. Why are multiple dimensions of conceptual change important? Conceptual change is not simply changes in content knowledge, it is not simply changes in the ontological image that a student has of the content in question, nor is conceptual change simply changes in the epistemological status of certain conceptions. Conceptual change is a complex mixture of all these things and probably more. For this reason, it is imperative that researchers view the conceptual change process as a composite of perspectives and that research about conceptual change take several perspectives of conceptual change into consideration. If the purpose of a certain investigation is to focus on one of the perspectives of conceptual change, then this should be stated at the outset of the study so that the other perspectives are acknowledged as not being considered and reviewers are aware of the limitations of such research. It is clear from this study that by using the multidimensional framework of conceptual change to interpret classroom data, a more complete picture of the process of conceptual change can be painted.

It is important to note that utilising the multidimensional framework for conceptual change does not mean that a researcher can try one perspective and if it doesn't seem to fit the data, try another, ad infinitum, until a suitable perspective is found. Rather, it is the convergence of different perspectives on one set of data that makes a multidimensional approach powerful. There is a huge variety of concepts that can be viewed from a conceptual change point of view, every student is different, every student's background knowledge is solitary, and every teaching situation is a singular event. In sum, each conceptual change learning situation is unique. Utilising different perspectives of conceptual change to view each learning situation enables triangulation of the theoretical interpretations of the data (Patton, 1990). Such triangulation can be likened to creating a three dimensional picture of the learning situation at hand rather than what would be equivalent to a linear or planar representation of a complex three-dimensional phenomenon. Figure 9.5 represents a diagram showing the possible perspectives of conceptual change that can be used for analysing student learning.

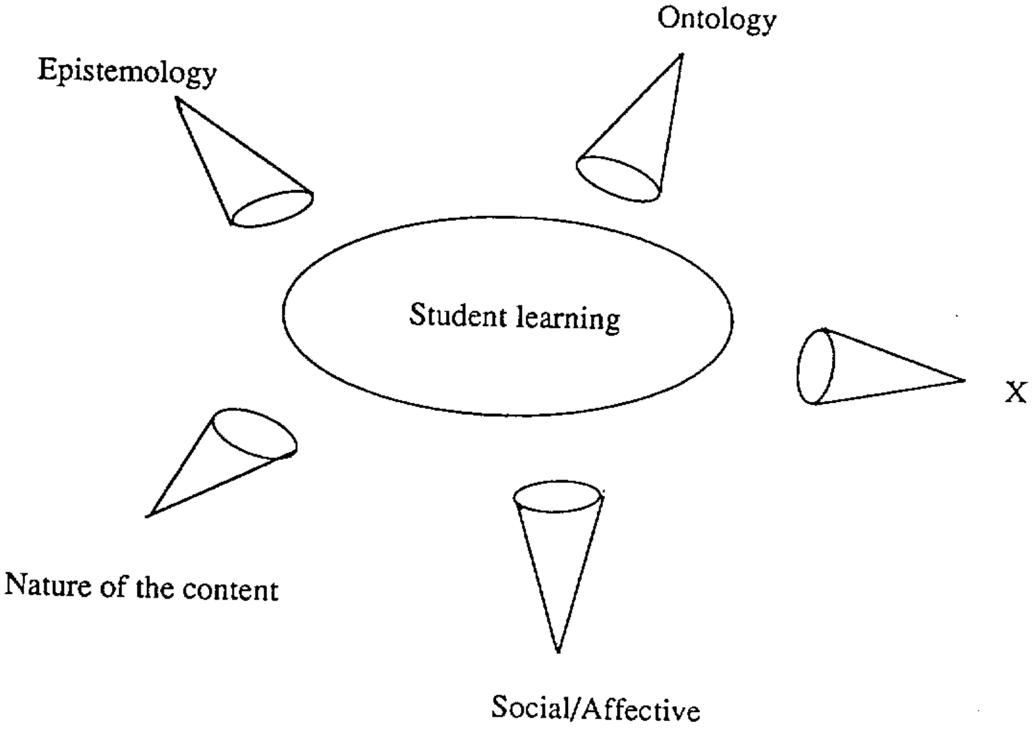

Figure 9.5: A diagram representing the multiple dimensions that can be used to examine student learning about a concept.

The Fluidity of a Multidimensional Approach to Conceptual Change

In this study, ontological, epistemological, social/affective, and the nature of the content perspectives of conceptual change were found to be particularly informative. In other research, these dimensions may or may not be useful. An important implication for research in conceptual change from this study is that a multidimensional approach should not be fixed to a specific number or kind of dimensions. The perspectives utilised in the multidimensional approach to conceptual change should be considered to be mutable, that is, they may vary depending on the kind of research and the content under investigation. Figure 9.3 above, which represents the three main perspectives of conceptual change as a fixed triangular diagram, does not allow for this fluidity of a multidimensional approach. Figure 9.5, however, is a representation that can be altered to demonstrate the number and kind of perspectives that are deemed important for an examination of a particular learning situation.

The fluid nature of a multidimensional approach to conceptual change does not mean that a researcher can simply select perspectives that would suit his or her purposes. In this study, the researcher herself became an important part of the research process. In order to view the conceptual change learning situation from various perspectives, the researcher needed to be intimately familiar with the multiple theories of conceptual change. The researcher also had to become intimately familiar with the learning situation that was being studied so that decisions about when, how and from what specific theories of conceptual change the research situation could be most appropriately analysed. Therefore, it is important to mention that if Figure 9.5 is used as a guide to conducting research in conceptual change, it is the informed researcher who makes decisions about which lenses to utilise to view the student learning situation.

An Orientational Grounded Theory Approach to Conceptual Change Research

In order that the multidimensional framework could be utilised in this study to interpret the learning situations, several aspects of methodology needed to be addressed. The researcher embraced an orientational grounded theory approach to the inquiry that was found to be a particularly useful approach for this classroom-based research. As explained in the methodology in Chapter 5, orientational inquiry is undertaken with an explicit theory, and the research is designed to describe specific manifestations of the general patterns in that theory (Patton, 1990). This study began by explicitly describing the multidimensional approach to conceptual change and resulted in the description of conceptual change when students learn about genes. This is a specific manifestation of the general patterns predicted by the multidimensional framework for conceptual change. Describing specific manifestations of conceptual change can be likened to Strike and Posner's (1983) recommendation that "one should wade through one conceptual quagmire at a time" (p.43). The ultimate result of this process is that some generalisations and patterns will emerge as different learning situations are studied from a multidimensional approach.

Possibilities for Further Research

Several avenues of further research, based on the findings of this study, are possible. Firstly, the pathway of student learning presented in Chapter 6 is a "proposed" pathway supported by the collective data from three classrooms. The case study data support the idea that students start their genetics course with one model and complete their genetics course with another model, however, there is no direct evidence that individual students' conceptions progress through each of the four models of the gene proposed in the pathway. Because of the exploratory nature of this study, further research is necessary to confirm or refute the proposed pathway of learning. It is possible that a different model, such as a set of concentric circles with outer circles including the inner circles, may be a better representation of student learning about the gene concept (M. Hackling, personal communication, December 16, 1997).

Another possibility for further research that has become evident from this study is the investigation of students' conceptions of genes at different ages or with different amounts of education. This study focussed on Year 10 (14 and 15 year old) students, although some Year 12 students were interviewed. This final chapter includes evidence that younger students may not distinguish between genes and characteristics in a manner similar to that of early geneticists. Further research with younger students is required to determine if this is the case, and if there are any other alternative conceptions that these students have about the gene. There is also a possibility that genetics experts are able to move between different models or conceptions of genes in different contexts. For example, when experts solve classical genetics type problems, they may visualise the gene as a particle, but when they are dealing with the biochemical processes of genes they may visualise a gene as a "productive sequence of instructions". This ability to utilise different models is referred to as relativism by Perry (Finster, 1989) and whether reaching this stage is itself a form of conceptual change is worth investigation. By examining the conceptions of the gene of a range of people including primary students, post-compulsory secondary students, university students and experts, a more complete picture of the way that students of different ages learn about the concept of the gene could be developed.

A third possibility for further research in genetics education would be to investigate the effects of applying the recommendations about the teaching of genetics that made up a large section in this final chapter. It would be informative to investigate the effects of using the gene as a central organising concept in an introductory genetics course and the effects of putting in place strategies aimed at linking concepts in genetics, improving the teaching of genetics processes and raising the status of scientifically adept models of genes in students' cognitive structures. Research on these teaching strategies also may have implications for learning in other subject areas.

This study has brought attention to the similarities and differences between student learning and the historical development of the gene concept. A possible avenue for further research is the utility of an historical approach to the teaching of genetics. Cornish (1995) enthusiastically suggests teachers should "Forget kings and queens, let's teach our kids the history of science" because understanding "the processes of the subject is to understand the development of philosophical ideas: it is a journey through the history of social change" (p. 53). The possibility that such a journey through the history of social change would facilitate the journey of students through the pathway of conceptual change is a possibility worth exploring (Matthews, 1994).

Finally, there is much scope for further investigation of student learning utilising a multidimensional framework for conceptual change. Such an approach has been used as the theoretical framework to investigate student learning about atoms and molecules (Harrison, 1996) and chemical equilibrium (Tyson, 1997), as part of the collaborative research group at Curtin University. The multidimensional framework for conceptual change has the potential to enable researchers and teachers to better understand the process of conceptual change in many fields.

Limitations of this Study

An important limitation of this study is related to the exploratory nature of this investigation of student learning about the concept of the gene. The pathway of student learning proposed in Chapter 6 indicates that students' conceptions progress through four ontologically distinct models of the gene concept. The case studies presented in Chapter 7 support the idea that students start their genetics course with one model in the pathway and complete their course with another model further along the pathway. However, there is no direct evidence that individual students' conceptions progress through each of the four models during the conceptual change process. The idea of the pathway was not evident until the data had been analysed.

The data did not trace students' conceptions at several points during their genetics course because it was not evident until the completion of the analysis that this would have been useful to confirm or refute the learning pathway.

As outlined in Chapter 1, the original purpose of this thesis was to examine the use of analogies by teachers and the role that they played in student learning in genetics. During the course of the study, the purpose changed to focus on conceptual change and student learning about the concept of the gene. Because the original focus was not specifically on conceptual change, detailed interviews were not conducted with students at the beginning of the genetics courses. As outlined in Chapter 7, this meant that work-sheet data alone had to be relied upon to determine the case study students' pre-instructional conceptions of the gene. In some cases the data were difficult to analyse because the precise meanings of students' statements on the work-sheet were not clear. In an interview situation, meanings can be negotiated, and the interviewer is able to probe the interviewee until he or she is confident in understanding what the student is describing. Another weakness of the work-sheet data was that if a student did not write something down, the researcher made the assumption that he or she did not understand the idea in question. A lack of understanding was probably not always the reason why students failed to write something on the work-sheet, and the results may have been different if more directed questions had been given to the students prior to instruction.

For these reasons, and in retrospect, it would have been better to have interviewed the case study students before their genetics course. On the other hand, interviewing students prior to their genetics course would have meant that they would have been selected without the researcher observing them in the classroom. This may have resulted in choosing students who were less interesting and less revealing as far as the purpose of this research was concerned. Even though the lack of interviews before the genetics course can be seen as a limitation of this study, the selection of students for the case studies at the end of the course allowed the researcher to identify students who represented a broad spectrum of learning experiences.

Methods for determining the status of students' conceptions are not well established in the research literature (Treagust et al., 1996) and the difficulty of determining the status of students' conceptions and the limitations of associated data collection methods were acknowledged in the discussion of Chapter 7. It is possible that the post-instruction interviews in this study were not adequate for assessing the status of students' conceptions and, the interview may not have provided students with the opportunity to demonstrate the full extent of their understanding. A further limitation of the post-instruction interviews was that they may not have been adequate to assess the degree of linkage among concepts that was the focus of one section in Chapter 8. Such a limitation is, once again, related to the exploratory nature of this study and that it was not until after the analysis that the researcher was cognisant of the importance of linkage between concepts for student learning about the concept of the gene.

Even though criteria were used to select students that would represent a broad spectrum of learning experiences for the case studies, it is possible that Douglas, Jacinta, Beth, Tan, John and Alastair were not the best students in the class to interview. Other students may have provided information that resulted in different interpretations and results. Through triangulation of work-sheet data, interview data and classroom observation it is intended that the results of this study are an accurate representation of the learning that occurred in the classes. Due to the nature of the research, however, and the need to select a limited number of case study students, it is possible that this is not a balanced representation.

The teachers were selected on the basis of being willing to participate in the research by having the researcher observe their classes, interview them and their students and collect work-sheet data from their classroom before and after their teaching. Because of these selection criteria, the researcher had no control over the way that the teachers conducted their lessons, selected the material to teach and the strategies with which to teach them. However, as outlined in the methodology in Chapter 5, the purpose was to observe naturalistic, non-intervention teaching. It is possible that the teachers participating in this research were not typical of the general population of science teachers and the results of this study are not transferable to other genetics classrooms. The "thick description" of the data (Guba & Lincoln, 1989, p. 241) does, however, allow the readers to make their own decisions about the transferability of the results to other classroom situations. The teachers who participated in this study had idiosyncratic approaches to the way they taught genetics and may not have been the best teachers to have selected, but the requirement that participation in the study was voluntary limited the choice of teachers.

Just as the teachers in this study had idiosyncratic teaching styles, the case study students also were individuals that may not have been representative of the broader population at this Year 10 level. Further investigation with more students would be desirable to validate the ontological pathway of learning described in this study. In addition, the constructivist research paradigm necessitates the acknowledgment that all that has been presented in this study is the researcher's construction of the participants' constructions. Unfortunately this is the nature of inquiry; however, Chapter 5 outlines the triangulation techniques that have been utilised with the purpose of enhancing the rigour and minimising the problems associated with interpretive research.

In this study, multiple perspectives of conceptual change were utilised to analyse the data including ontological, epistemological, social/affective and the nature of the content. The majority of research that is conducted to investigate conceptual change takes only one of these perspectives to analyse data. The results indicate that by using several perspectives of conceptual change, a more insightful picture of the kinds of conceptual changes that occur can be illuminated. A limitation of this study with regard to different perspectives of conceptual change is that there may be perspectives that have not been utilised. It is possible that there are alternative ways to view a conceptual change situation that have not yet been developed and that there are alternative perspectives of conceptual change that would better demonstrate how Year 10 students learn about genes. It is comforting and exciting, however, that although this is a limitation of this study, the multidimensional approach to conceptual change can accommodate new perspectives that may be on the horizon.

Conceptual change theory was considered by the researcher to be the most appropriate theoretical framework for interpreting the data in this study. The results could, however, have been analysed within different theoretical frameworks to render different conclusions. For example, from a Piagetian perspective (Piaget, 1950), students who are concrete-operational would not be able to relate ideas learned from a model to the actual, more abstract phenomena. It is possible some of the students in this study who did not extrapolate their ideas from the physical models were those who could not effectively use abstract, hypothetical-deductive reasoning or formal operational thought (A. Cavallo, personal communication, December 4, 1997).

Postscript

As I have waded through the conceptual quagmire that is Year 10 student learning about the concept of the gene, the most rewarding moments have been when I have communicated the findings to classroom teachers. The importance of classroom-based research and the relevance it has for teaching have become very clear to me through this study. The implications of this study for the teaching of genetics are not complicated, indeed they are not necessarily new ideas. To have the findings of classroom based research explicitly linked to the implications for teaching of genetics, however, is a very powerful image for teachers. Recently, I was discussing the findings with one of the participant teachers and she was very interested in the transcripts of interviews with her students. The teacher commented that she had no idea that her students had difficulty linking the concepts that she had been teaching in her class. Further, the teacher said she would make every effort during this current year to make the connections between the concepts explicit and clear for her class. The results of the study were relevant to her, and the implications were obvious and achievable in the classroom setting. This is a small example of the possible improvements that could be made to classroom teaching as a result of this thesis. As a researcher, this is a very rewarding outcome of the research and a rewarding aspect of ongoing communication with teachers.

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APPENDIX 1

Author's publications and presentations related to this doctoral thesis.

Author's Publications and Presentations Related to this Doctoral Thesis.

Journal Papers

Treagust, D. F., Harrison, A. G., **Venville, G. J.** & Dagher Z. (1996). Using an analogical teaching approach to engender conceptual change. *International Journal of Science Education, 18*(2), 213-229.

Tyson, L. M., **Venville, G. J.**, Harrison, A. G. & Treagust, D. F. (1997). A multidimensional framework for interpreting conceptual change events in the classroom. *Science Education, 81*, 387-404.

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Conference Presentations

Treagust, D. F. & **Venville, G. J.** (1995, April). *Consistency between the roles of analogies in biology teaching and different perspectives of conceptual change.* Paper presented at the annual meeting of the American Educational Research Association. San Francisco, CA.

Treagust, D. F., **Venville, G. J.**, Harrison, A. G. & Tyson, L. M. (1997, March). *A multidimensional interpretive framework for understanding conceptual change.* A paper presented at the annual meeting of the National Association for Research in Science Teaching, Chicago.

Treagust, D. F., **Venville, G. J.**, Tyson, L. M. & Harrison, A. G. (1996, July). *A multidimensional framework for understanding conceptual change.* A paper presented at the annual meeting of the Australasian Science Education Research Association, Canberra, ACT.

Venville, G. J. & Treagust, D. F. (1995, November). *Changing students' conceptions of genes.* Paper presented at the annual conference of the Western Australian Science Education Association. Perth, Western Australia.

Venville, G. J. & Treagust, D. F. (1995, September). *Is DNA really like a twisted ladder? Analogies used to teach genetics re-examined and revitalised.* Paper presented at the annual conference of the Australian Science Teachers' Association. Brisbane, Queensland.

Venville, G. J. & Treagust, D. F. (1996, April). *An analysis of the use of models and analogies in the teaching of secondary school genetics.* A paper presented at the annual meeting of the American Education Research Association, New York; NY.

Venville, G. J. (1996, April). *An analysis of the use of models and analogies in the teaching of secondary school genetics.* A paper presented at the annual meeting of the American Education Association. New York, NY.

Venville, G. J. (1996, April). *Learning about genetics: Using a multi-dimensional interpretive framework for understanding conceptual change.* A paper presented at the annual meeting of the American Education Research Association. New York, NY.

Venville, G. J. (1996, April). *What is it about the nature of the content that makes explaining genetics difficult for teachers?* A paper presented at the annual meeting of the National Association of Research in Science Teaching. St Louis, MO.

Venville, G. J. (1997, June). *Students' evolving conceptions of genes.* A paper presented at the annual conference of the Australian Science Teachers Association, Melbourne, Victoria.

APPENDIX 2

An Example of a Student Interview Protocol

An Example of a Student Interview Protocol

Part A Inheritance

1. Why do most people look like their parents? (probe genes)
2. How do genes get passed from parents to offspring? (probe egg, sperm, ie. gametes)

Part B Genetic Structure

3. Tell me what you think a gene is. Can you draw a picture of a gene and explain what you are drawing?
4. Where is a gene located in human's bodies?
5. What is a gene made of? (probe DNA)
6. What is the relationship between genes anad DNA?
7. What is the relationship between genes and chromosomes? (if student has difficulty with "relationship" ask her: what are the differences and similarities between genes and chromosomes?)

Part C Genetic Processes

8. What do you think a gene does? (probe controls characteristics)
9. How does it do this (control characteristics)? Can you draw a picture to represent this? (probe genetic code, protein synthesis) (student may answer dominant/recessive alleles, then ask how the alleles are dominant or recessive, or how do the genes control the dominant characteristic eg. brown eye colour is dominant to blue eye colour).

Part D Extension

10. If you were reduced down to a very small size and you could walk around your genes, what do you think you would see? (ie. what would the genes look like?)

    Do you think you would see anything happening? What? Where?

Part E Problem Solving

11. Only students who have studied phenylketonuria in class should be asked this question. Student is given handout explaining phenylketonuria to read before the question is asked. (See over)

    Imagine a friend of yours had a baby who was diagnosed with phenylketonuria. The doctor told your friend that the baby had to go on a special diet low in phenylalanine because the baby's cells produced defective phenylalanine hydroxylase which normally breaks down phenylalanine in the blood. Your friend comes to you and asks you why the baby's cells produce defective phenylalanine hydroxylase. What would you answer?

Student Handout Information

Phenylketonuria is an inherited disease that babies are born with. Symptoms of the disease are caused by the build up of a chemical called phenylalanine in the blood. Sufferers of the disease have a defect in the enzyme phenylalanine hydroxylase, which normally breaks the phenylalanine down. As a result dietary phenylalanine builds up in the blood and the sufferers show mental retardation, convulsions and behavioural disorders. All Australian children are routinely tested for the disease by analysis of a small blood sample taken within 24 hours of birth. If necessary they are put on a special diet immediately. Early detection and an appropriate diet allow phenylketonuric individuals to develop normally.

APPENDIX 3

Student Work-sheet

Student Work-sheet

Name: ______________________ Date: ________________

This is a simple quiz to work out what you know about inheritance before you start studying genetics. It does not count for your assessment.

Term	What do you know about these things?
Genes	
Chromosomes	
Mutation	
DNA	

APPENDIX 4

Examples of Letters to Principals and to Parents

Example of a Letter to a Principal

Thursday 18 July 1996

The Principal
Ms P. Stevenson
East High School
East Street
Perth WA 6002

Dear Ms Stevenson

I have recently been in contact with one of your science teachers, Ms Susan Davidson. Ms Davidson has agreed to allow me to visit and observe her Year 12 Human Biology class for the purpose of collecting data for my doctoral research program. The research involves observing and documenting the ways teachers explain difficult and abstract science concepts in genetics and the way that students understand those explanations. I envisage visiting Susan on several occasions during the next few weeks while she is teaching material pertaining to my research. I will not be interfering with the normal progress of the Human Biology course. I may sometimes use an audio tape in the classroom to help with my data collection.

Part of the data collection will involve individual interviews with about five students from Ms Davidson's class. The interviews will take about 20 minutes and will be conducted at recess or lunch time so they will not miss any important teaching time. I have found in the past that these discussions are beneficial to students because it helps them reflect on the things they have been learning. Student participation in the discussions will be voluntary and any student's wish not to be involved will be respected. The data collected from the classroom and students will be anonymous and reported in my thesis. The data might also be reported at educational conferences and in scholarly journals.

The purpose of this letter is to request your permission to enter your school for this research. I trust this request is satisfactory to you. If you have any difficulties with the request, or would like further information concerning this research study please contact me at the Science and Mathematics Education Centre on 351 3594.

Yours sincerely,

Grady Venville (Ms)
Doctoral Student.

Example of Letter to Parents

Dear Parents and Guardians

The purpose of this note is to inform you about my visits to your child's Year 10 science class. I am a doctoral student at the Science and Mathematics Education Centre at Curtin University and the reason for my visits is to collect data about the way teachers explain difficult science concepts and the way that students understand those explanations. Mr Yulang, your child's science teacher, has been kind enough to invite me into his classroom and I have permission from the Principal, Mr Davies, to enter the school for the purpose of my research. I will not be interfering with the normal progress of the science course. I may sometimes use a video camera or an audio tape in the classroom to help with my data collection.

At some stage in the next few weeks I would like to talk to some of the students in Mr Yulang's class about some of the things they have been learning in genetics. The discussion will take between 10 and 20 minutes and will be conducted at a time when the students are involved in individual work so they will not miss any important teaching time. I have found in the past that these discussions are beneficial to students because it helps them reflect on the things they have been learning. The information collected in the discussions will not contribute to assessment and will not affect the students' grades. Student participation in the discussions will be voluntary and any student's wish not to be involved will be respected. The data collected from students will be anonymously reported in my thesis. The data might also be reported at educational conferences and in scholarly journals.

If you have any questions with regard to my visits, the student discussions or to any other aspect of my research please contact me at Curtin University on 351 3594. If you can't contact me personally please leave a message and I will return your call.

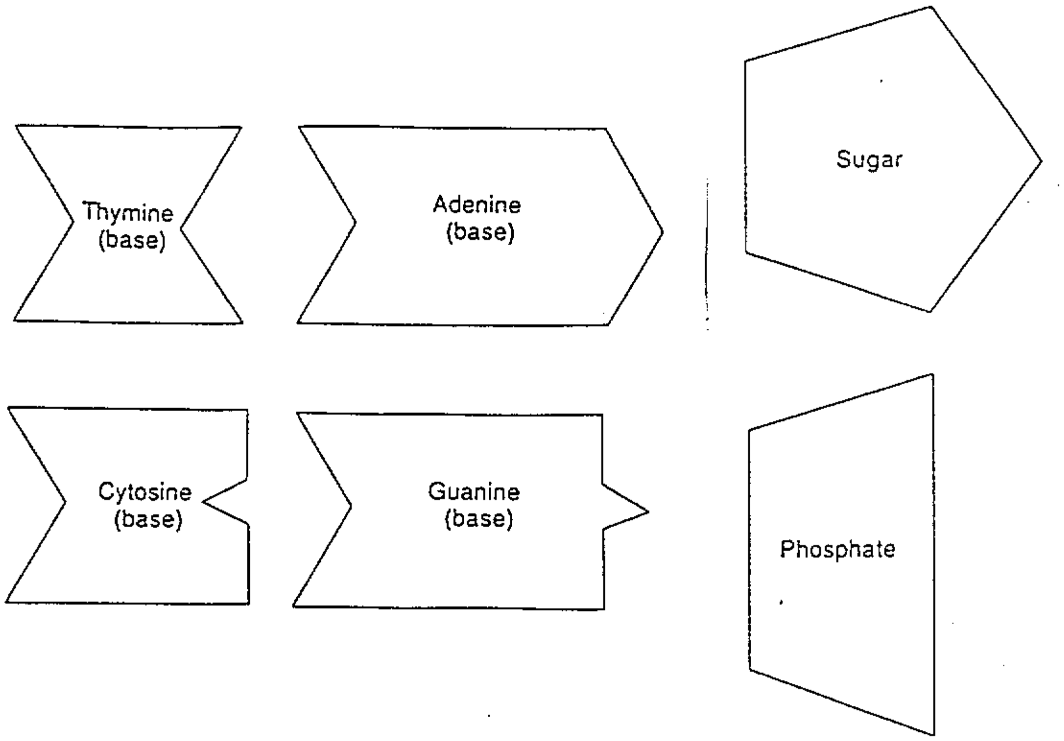
Yours faithfully

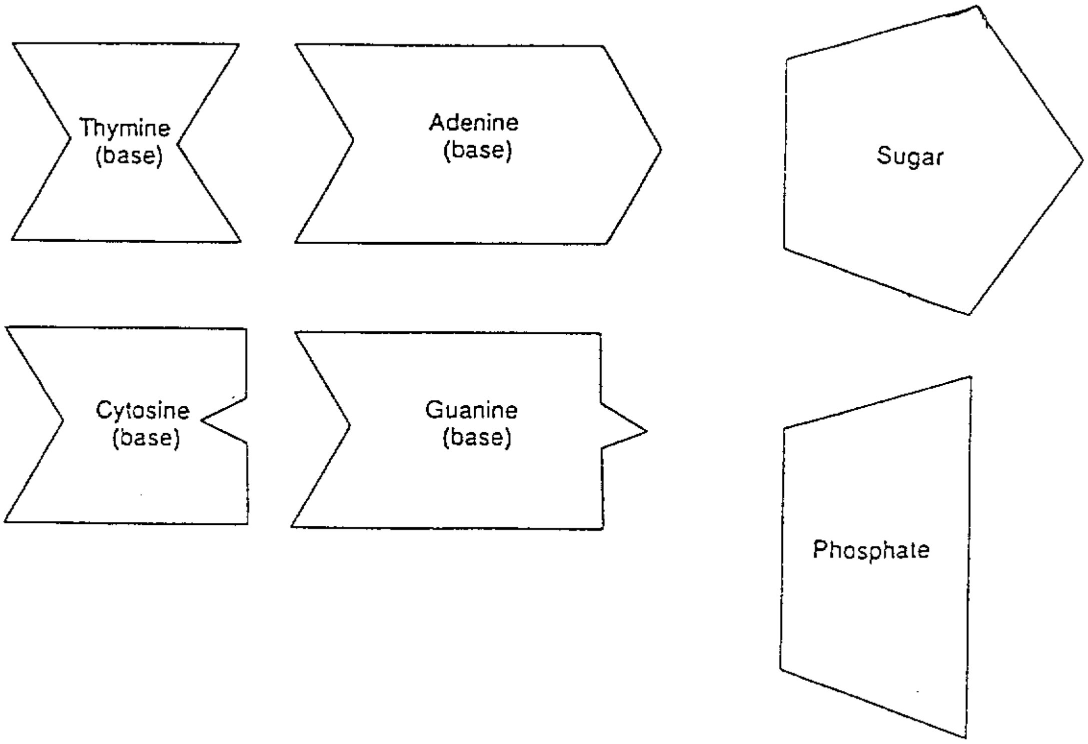
Grady Venville (Ms)
Doctoral Student

APPENDIX 5

Mr Counter's Work-sheets

Mr Counter's Work-sheet





Mr Counter's Work-sheet

△	Phen	purple	○	ser
△	leu	Cream	○	pro
△	ile	Red	○	Thr
△	val	Blue	○	ala
△	gly	Green	○	Arg
□	Tyr	purple	▱	lys
□	his	Cream	▱	Asp
□	gin	Red	▱	glu
□	asn	Blue	▱	cys
□	ser	Green	▱	Arg

Decoding the genetic instruction

The information in mRNA is present in coded form as sets of three bases o triplets. These triplets, such as AGG and UCU, are called codons. Mos codons contain the information to add one specific amino acid to a protei chain. In addition, one codon (AUG) is a START TRANSLATION instruction and three different codons (UAA, UAG and UGA) are STOP TRANSLATIO instructions (table 11.4).

Table 11.4: Genetic code shown as the 64 mRNA codons and the amino acids that they specify. (See Appendix for the full names of the amino acids.) The codon AUG is a start signal and it also codes for the amino acid, *met*. The genetic code in mRNA codons is complementary to that in DNA (see table 10.5).

mRNA codon	Amino acid	mRNA codon	Amino acid	mRNA codon	Amino acid	mRNA codon	Amino acid
UUU	*phe*	UCU	*ser*	UAU	*tyr*	UGU	*cys*
UUC		UCC		UAC		UGC	
UUA	*leu*	UCA		UAA	STOP	UGA	STOP
UUG		UCG		UAG		UGG	*trp*
CUU	*leu*	CCU	*pro*	CAU	*his*	CGU	*arg*
CUC		CCC		CAC		CGC	
CUA		CCA		CAA	*gln*	CGA	
CUG		CCG		CAG		CGG	
AUU	*ile*	ACU	*thr*	AAU	*asn*	AGU	*ser*
AUC		ACC		AAC		AGC	
AUA		ACA		AAA	*lys*	AGA	*arg*
AUG	START/*met*	ACG		AAG		AGG	
GUU	*val*	GCU	*ala*	GAU	*asp*	GGU	*gly*
GUC		GCC		GAC		GGC	
GUA		GCA		GAA	*glu*	GGA	
GUG		GCG		GAG		GGA	