

School of Education

**A Critical Evaluation of the Thinking Frames Approach as a
Teaching Strategy for Multidimensional Conceptual Change in the
Science Classroom**

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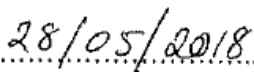
Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number # SMEC-53-13

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Abstract

This study grew out of my dissatisfaction with my teaching practice and my concern about the limited degree to which students adopted and communicated scientific conceptions. I sought a structured approach which would encourage students to replace their alternative conceptions with scientific ones and support them in writing elaborated causal scientific explanations. This thesis critically evaluated the effectiveness of such a structured approach, the Thinking Frames Approach (TFA) (Newberry, Gilbert & Cams Hill Science Consortium, 2011), to address students' conceptual change, explanatory writing and its effect on my own teaching practice.

The literature indicated the effectiveness of addressing students' alternative conceptions using strategies based on multidimensional conceptual change theory. This theory suggests that students' alternative conceptions in the epistemological dimension should be challenged by presentation of discrepant events and that they should be made aware of the ontological categories underpinning these beliefs. Attention should also be paid to supporting the social aspects of learning, such as working co-operatively in small groups, facilitating dialogic interactions and feedback, as well as addressing student characteristics, such as intentionality, motivation, self-efficacy and emotions. However, there were few studies applying this theory in the regular classroom. This may be as a result of the daunting complexity of multidimensional change theory to classroom teachers. It was proposed that the TFA may address this complexity by challenging students' alternative conceptions, supporting social construction of understanding using student-generated multiple representations in small groups and promoting self-evaluation of written explanations.

This study used a two-year explanatory sequential mixed-methods design to critically evaluate the effect and mechanism of action of teaching with the TFA. To determine conceptual change in the epistemological and ontological dimensions (Research Question 1a) pre-, post- and delayed post-test data were gathered from experimental and comparison groups in Grades 8-10 students in Chemistry, Physics and Biology topics. Research Question 1b probed changes in students' written explanations over the learning period using evaluation rubrics. Results were compared using statistical tests such as paired t-tests and multiple regression analyses. Research Questions 2a and b investigated students' and colleagues' perceptions of learning using the TFA through thematic coding of interview data and audio and video recordings of lessons. Three case studies were presented to obtain a more fine-grained understanding of the student experience in response to Research Question 3. Research Question 4 investigated my experience teaching with the TFA using data from reflective journals and audio/video recordings of lessons.

The results from pre- and post-tests revealed that students who learned using the TFA

underwent statistically significant epistemological conceptual change in all topics, with Cohen effect sizes of 0.94-2.04. Conceptual change was sustained over the six-month period after teaching in the topics of thermal energy, Newton's laws, and energy. Comparison of results from the experimental groups with comparison classes also showed significantly greater conceptual understanding attained by students who learned using the TFA.

Students of the experimental group also showed statistically significant transfer in allegiance to scientific ontological models, such as adoption of the principles of Newton's third law and natural selection. An added benefit of learning using the TFA was statistically significant improvement in the ability of students of all three grades to write elaborated causal explanations linking claims and evidence with the underlying ontological models.

Probing of the mechanism of action of the TFA (Research Question 2 & 3) indicated that the TFA supported students' epistemological understanding through step-wise scaffolding of understanding as students produced multiple representations. Ontological understanding was built over a series of lessons through teacher questioning and application of the model in various contexts. Both students and teachers stressed the benefits of working in a small group environment, which led to interthinking, greater opportunities to express ideas and ask for support. As a result, many instances of increased intentionality and engagement were reported. Many students developed mastery goals as opposed to performance goals which led to greater attention to meta-cognitive strategies, such as production of multiple representations. Increased self-efficacy in understanding new concepts and writing explanations were reported. Positive activating emotions, such as excitement and enjoyment of lessons were adopted and students expressed increased personal interest in learning science. These observations were confirmed in the case studies. My experience teaching using the TFA indicated ways in which it supported me in implementing multidimensional conceptual change theory within the constraints of the normal classroom. Limitations and future improvements in the methodology were suggested.

This research provided evidence that the TFA is indeed a powerful approach to address multi-dimensional conceptual change in the regular classroom. A mechanism of action of the TFA: the interaction between the Predict-Discuss-Explain-Observe-Discuss-Explain (PDEODE) aspect of the approach with the power of socially constructed multiple representations in small groups which resulted in students being constrained to intentionally engage with the meta-cognitive strategies presented. Learning with the TFA facilitated a change in several student characteristics: intentionality, motivation, interest and self-efficacy, a result which is rarely noted in the literature. Further elucidation of the mechanism of action on student characteristics of learning with the TFA would be valuable. As a result of this study it is also suggested that ways to support student creativity in drawing be further investigated.

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Glossary

Achievement goals: describes why a student decides to engage with an activity. They may be motivated by a performance or a mastery orientation, avoiding or seeking closure (Sinatra & Mason, 2013, p379).

Alternative conceptions: ideas about the world which students hold and are inconsistent with scientifically acceptable concepts. They are ‘personally viable constructive alternative’ understandings of observed phenomena (Gilbert & Watts, 2008, p67).

Authoritative-interactive discourse: discussion between teacher and students which does not encourage exploration of ideas and where the teacher focuses on their point of view (Mortimer & Scott, 2003, p34).

Category mistakes: attributing concepts to an incorrect ontological category, for example a belief that hot air rises as a result of a naïve or pre-instructional ontological belief that this is an intrinsic property of ‘hot air’ rather than due to an understanding of the kinetic theory of matter (Chi, 2013, p50).

Dialogic-interactive discourse: discussion between teacher and students which encourages students to explore and discuss ideas, either in whole class or small group settings (Mortimer & Scott, 2003, p36).

Epistemic motivation: motivation to obtain new knowledge and understanding and restructure knowledge –seeking closure or avoiding closure (Sinatra & Mason, 2013, p381).

Epistemological conceptual change: change in status of students’ specific beliefs or conceptual knowledge. ‘The student is looking ‘in’ at their own knowledge’ (Tyson, Venville, Harrison & Treagust, 1997, p399)

Inaccurate knowledge: due to ‘false beliefs’ or ‘flawed mental models’ (Chi, 2013, p50)

Incommensurate knowledge: knowledge that includes category mistakes or missing schemata (Chi, 2013, p50)

Intentionality: conscious processing and bringing full attention to an activity, including self-regulation of learning by paying attention to metacognitive steps (Sinatra & Pintrich, 2003, p4).

Interthinking: student-student dialogue to solve a problem, where the resultant explanation is better than the individual explanations (Mercer, 2000)

Missing schemata: Ontological categories which students are entirely unaware of, for example, a Grade 9 student may be unaware of the emergent processes involved in natural selection (Chi, 2013, p50).

Models (scientific): a model is a ‘representation of an idea, an object, and event, a process or a system’ which allows theories to be tested and deductions to be made. Historically models are developed and change as research expands understanding. Those models which

are widely accepted by the scientific community are deemed to be scientific or consensus models (Gilbert & Boulter, 1998, p53).

Models (mental): an internal representation or schema which is held by the student and constructed on the basis of such things as their experiences, reading, pictures and explanations from others (Glynn & Duit, 1995)

Multidimensional conceptual change: Viewing conceptual change from multiple perspectives: cognitive perspectives – epistemological and ontological change, together with social and emotional perspectives of the context of change (Tyson et al., 1997, p398)

Ontological category: conceptual frameworks or models of the nature of the world which underpin beliefs about phenomena. These may or may not be coherent (Vosniadou, 2013, pp.13-14)

Ontological conceptual change: change in beliefs about the fundamental nature of the world (Tyson et al., 1997, p399)

Placemats: One page pictorial summaries of the most important concepts and elements of the underlying ontological model which were given to students in the original Thinking Frames Approach lessons designed for primary and early secondary school students. (Newberry et al., 2011)

Self-concept: Although self-concept can include self-efficacy, I am defining self-concept more specifically as a students' *identity* in relation to science – “Science is not my thing” versus “I see myself as a science student/scientist” (Barmby, Kind & Jones, 2008, p1082).

Self-efficacy: A measure of a students' belief in their ability to successfully complete tasks in science (Sinatra & Mason, 2013, p385).

Social/Affective dimension of conceptual change: the social context and a students' affective characteristics form an integral part of the conceptual change process (Tyson et al., 1997, p401)

Thinking Frames Approach: A structured methodology which challenges students' alternative conceptions by presenting discrepant events. Students work in small groups to predict and explain the outcome of these events and then explain their observations. They use multiple representations to construct explanations of their understanding – keywords, drawings, dot-point summaries and written paragraphs. They use a rubric, called the Levels Mountain to self-evaluate the causal and persuasive nature of their written explanation (Newberry et al., 2011).

Chapter 1. Introduction

Supporting students to develop scientific understanding of concepts and replace their strongly held alternative conceptions with those based on scientific models of the world remains an essential goal of science teaching. A vast body of research has shown the benefits of recognising students' alternative conceptions and implementing conceptual change strategies that address those conceptions and persuade students to adopt understanding based on scientific models. However, according to classroom teachers, rather than making students aware of their alternative conceptions and challenging them to construct understanding based on scientific models, science lessons continue to be teacher-directed and focus on teaching a set of information based on a list of topics from the curriculum (Danaia, Fitzgerald, & McKinnon, 2013; Goodrum, Druhan, & Abbs, 2012; Rennie, Goodrum, & Hackling, 2001).

Research to understand how students can be supported in constructing understanding of scientific models over the past fifty years has led to the development of multidimensional conceptual change theory (Duit & Treagust, 2003; Tyson, Venville, Harrison, & Treagust, 1997). Multidimensional conceptual change addresses students' naïve beliefs about the world, based on their everyday experiences, such as that metals are intrinsically cold. Students need to be persuaded to replace such alternative concepts with scientific concepts. In order to do so they must also become aware of the inconsistencies in their alternative conceptual frameworks and recognise the utility of the scientific model which underpins explanations of these phenomena. This involves students undergoing conceptual change in the ontological dimension. It has become evident that students are most likely to embrace conceptual change in the epistemological and ontological dimensions when they are supported to do so through social interactions which encourage greater intentionality of engagement- the social/affective dimension of conceptual change. Despite the evidence, the complexity of multidimensional conceptual change theory has mitigated against implementation of such strategies in the normal classroom (Duit & Treagust, 2012a). How then can teachers be supported in introducing best practice based on multidimensional conceptual change ideas into the classroom in the science curriculum?

The aim of this thesis is to critically examine use of a multidimensional conceptual change strategy, the Thinking Frames Approach (TFA) (Newberry et al., 2011), in a classroom setting and to document its strengths and limitations. The effects of teaching with the TFA are presented in terms of: the conceptual gains of students in the epistemological and ontological dimensions; changes in students' communication of their understanding through written scientific explanations; changes in student characteristics that may inhibit or

support conceptual change. Interaction between epistemological, ontological and social/affective aspects of the TFA are analysed. Finally, my perspective as a teacher, on how the TFA supported me in addressing multidimensional conceptual change, is examined.

1.1 Rationale of the Study

This study grew out of my dissatisfaction with my own pedagogy and students' experience within the classroom. As an experienced high school science teacher, I was aware of the benefits of using constructivist teaching strategies as discussed by educational researchers and impressed upon classroom teachers (Driver & Oldham, 1986; Duit & Treagust, 2003) during pre-service instruction. However, I found that I was inconsistent in implementing such strategies. Despite implementing a number of well-known strategies, such as inquiry-based learning and problem-solving, within the classroom to improve students learning, I frequently reverted to more teacher-centred pedagogies. For instance, I often found myself quickly providing the "correct" answer rather than allowing students to construct a more scientific understanding for themselves.

I observed a number of problems in students' learning, and the teaching strategies that I used seemed to have a limited effect on these problems. Although students were being given scientific explanations of phenomena, I consistently found that students' answers to higher order questions in tests revealed that many alternative conceptions remained, and that even if they did appear to have adopted a more scientific understanding, they were not able to write coherent explanations of those concepts or apply those concepts in unfamiliar situations. Many students continued to answer simple test questions by repeating the question itself without effectively elaborating their ideas. Students also appeared to have difficulty visualising, applying and articulating their conceptual models and tended to see various science topics as being unconnected with one another and hence were not able to transfer models used in one topic to another. I also noted that a disturbing number of students expressed their belief that they were not good at science and so were unmotivated to attempt to construct a scientific understanding.

My experience is not an isolated phenomenon. National surveys of Australian science teachers and students reveal that the majority of teaching in the classroom continues to be of a didactic, teacher-centred nature, dominated by factual content which seemed irrelevant to students' everyday lives (Danaia et al., 2013; Goodrum et al., 2012; Rennie et al., 2001; Tytler, 2007). In such classrooms students develop a passive view of learning science. Studies of instructional methods have shown that such an authoritarian delivery of science content often results in a transmissive view of science learning amongst students and

encourages memorization of facts rather than conceptual understanding (Duit, Treagust, & Widodo, 2008; Lyons, 2006).

Similarly, my experience of the difficulties in improving student scientific writing, described above, are not, by any means, unique. Even with encouragement to build scientific explanations, science students in Grades 8 and 9 write simple descriptions, use little deductive reasoning or provide few explanations based on theories or models, and exhibit many alternative conceptions (Driver, Leach, Millar, & Scott, 1996; Horwood, 1988; Zuzousky & Tamir, 1999). Students also rarely use the correct scientific vocabulary in their explanations, preferring to use everyday language when describing, explaining or predicting real-world experiences (Fellows, 1994; Hempel, 1991). Even older senior high school biology students mostly failed to give explanations of observations in terms of theory, preferring to describe the procedure carried out and observations obtained (Peker & Wallace, 2011).

So, what is the disconnect between theory and practice? Why do so many teachers revert to didactic methods? It appeared to me that the issue is a lack of systematic teaching models that can be easily adopted in the school environment and that have a strong theoretical background. I began searching the literature for ways in which to support greater conceptual understanding in my students and to improve their written explanations of phenomena. The literature indicates that multidimensional conceptual change theory has a strong evidence base which makes it a suitable theoretical framework to underpin an effective teaching and learning model (Duit & Treagust, 2003, 2012a).

Despite the evidence obtained which suggests that addressing multidimensional aspects of conceptual change may be a highly effective learning strategy, there have been a limited number of studies which implement such approaches. The complexity of each dimension and the multiplicity of elements that must be addressed in order to implement multidimensional conceptual change theory have meant that there is a need for development of a systematic teaching model based on a combination of evidence from each dimension which supports teachers in implementing 'doable' programs in the classroom (Duit & Treagust, 2012a). By studying the implementation of such an approach, the theoretical understanding of conceptual change from multidimensional perspectives may also be improved (Duit & Treagust, 2012a).

From a search for systematic teaching approaches that address each of the dimensions of multidimensional conceptual change, the TFA (Newberry & Gilbert, 2007; Newberry et al., 2011; Newberry, Gilbert, & Hardcastle, 2005) was identified as an alternative teaching framework to support students in epistemological, ontological and social

construction of their understanding while also addressing the affective aspects of student learning. It also provided a framework for improving students' written explanations. I implemented the TFA in my science classes and documented its impact on students' learning, as individuals and as a group, and on my own teaching. The impacts of the study were investigated through statistical and thematic analysis of multiple data collected over two years.

Finally, in order for a teacher to be willing to persist in adopting a new pedagogy, affective aspects must be addressed such as self-efficacy, motivation, approach stance, as well as their belief in the efficacy of the pedagogy, their understanding of its mechanism of action and the underlying theoretical framework (Gregoire, 2003). My experience in adopting the TFA as a multidimensional conceptual change approach is investigated in these terms. This study addresses many teachers' and educational researchers' concerns regarding the effective implementation of multidimensional conceptual change approaches in the school environment.

1.2 The Thinking Frames Approach

The TFA was developed in the UK by the Cams Hill Science Consortium (CHSC) of teachers and researchers for use with gifted students in Key Stages 2 and 3 (primary and middle school) (Newberry & Gilbert, 2007). This group carried out action research within their classrooms, focusing on the use of models and modelling. Although teachers have carried out action research within their classrooms to determine the effects of using the TFA, the only published literature describing the effects on student learning of using the TFA are a paper on the use of the Levels Mountain as a rubric for students to self-evaluate their writing (Newberry et al., 2005) and examples of students' written explanations (Newberry & Gilbert, 2007; Newberry et al., 2011). I recognised that the TFA had potential to act as a framework for teaching any science topic in a way which would systematically address each aspect of multidimensional conceptual change theory. I have taken the principles of the TFA, as described on the AstraZeneca Science Teaching Trust website (Newberry et al., 2011), and adapted it for use in teaching science topics in mixed ability middle and high school classes from a multidimensional conceptual change perspective. In the original TFA 'placemats' were distributed to students with pictorial prompts for the adoption of scientific models. In their place I designed a series of TFA lessons for each topic, based on understanding of different aspects of the ontological models, in order to support students in adopting and applying the scientific model.

The TFA is a systematic approach which makes use of cognitive conflict strategies to make students' alternative conceptions visible and to challenge those epistemological

conceptions. It combines this strategy with the social construction of conceptual understanding in heterogeneous small groups through teacher-student, student-student dialogue. Students predict the outcome of carefully designed demonstrations in their small groups, then present their explanations to the class. After observing the outcome of the demonstration, they return to their small group to revise their explanations. Teacher questioning encourages them to apply the scientific ontological model to the observed phenomenon. Students then work together as they each construct multiple representations of their understanding, through verbal, pictorial and written explanations. Students evaluate their written explanations against a rubric called the Levels Mountain (Newberry et al., 2005) and the teacher also provides rapid, constructive feedback. A series of TFA lessons builds understanding of the ontological model underlying epistemological concepts.

Teachers of the CHSC using the TFA in their classrooms noted that students had gained in confidence as a result of this strategy (Newberry et al., 2011). They also showed greater motivation to engage in producing explanations and in problem solving (Newberry et al., 2011). Thus, the TFA is a strategy that has the potential to act as a scaffold to both the teacher and students in addressing epistemological, ontological and social/affective aspects of conceptual change.

The TFA also has the potential to act as a “writing-to-learn by learning-to-write” strategy (Carter, Ferzli, & Wiebe, 2007) to address concerns about students’ scientific writing. Such a strategy builds conceptual understanding while improving scientific writing skills by involving students in serious writing tasks which help students use the language of science as they develop explanations, argue from evidence and revise claims (Sampson, Enderle, Grooms, & Witte, 2013). The multiple representations that students produce in a TFA lesson, keywords, verbal and pictorial explanations, and dot-points, help students to scaffold, build and refine their final written explanations.

1.3 Research Aims and Related Research Questions

This study was carried out to analyse critically the benefits and challenges of teaching using the TFA in terms of the multidimensional conceptual change theory. The study is designed in four parts.

1. In order to understand the benefits and limitations of teaching using the TFA within the constraints of the classroom, the strategy was used to teach a number of diverse topics within the fields of physics, chemistry and biology to students of Grades 8-10. The effects of teaching using the TFA were examined in terms of changes in epistemological and ontological understanding as measured for each topic by administration of conceptual inventory tests before and after teaching. These results

were compared to those obtained from comparison classes taught using more traditional methods and are presented in Chapter 4 in answer to research questions 1a: *To what extent does the TFA build scientific understanding of concepts and lead to epistemological and ontological conceptual change?* Similarly, changes in students' written explanations were evaluated over the two-year period of the study and are presented in Chapter 4 in answer to Research Question 1b: *To what extent does teaching using the TFA enable Grade 8-10 students to give coherent scientific explanations using written text?*

2. In order to understand the general mechanisms of action, in terms of each of the dimensions of conceptual change, the perspectives of students and teachers present in the experimental classroom were sought through interviews. Data from students were coded for themes and presented in Chapter 5, to answer Research Question 2a: *What do students perceive as the supporting aspects of TFA for learning science in terms of the epistemological, ontological and social/affective dimensions?* Students' perceptions were compared with those of teachers, learning support aides and some parents in answer to Research Question 2b: *What main features and benefits do other teachers observe during implementation of the TFA in terms of how it supports multidimensional conceptual change?*
3. A more fine-grained examination of the mechanism of action for individuals was sought through in depth analysis of the experiences of three students of differing abilities learning with the TFA over a two-year period, presented in Chapter 6. Interaction between aspects of the TFA which addressed the different dimensions of conceptual change were determined in order to answer Research Question 3: *What can be learned about a multidimensional conceptual change approach from analysis of individual students' progress in learning with the TFA throughout the two years of the study?*
4. Finally, in order to understand the support that the TFA strategy gives to the teacher as a systematic approach to address multidimensional conceptual change theory in the classroom, I critically examine my own experience in Chapter 7. This is in answer to Research Question 4: *What were the affordances and limitations of the TFA in supporting me to implement a multidimensional approach to conceptual change?*

1.4 Overview of Methodology

The study utilised a two-year explanatory sequential mixed method design (Creswell, 2014), in order to critically examine the breadth of action of the TFA and its applicability to middle and high school students. I implemented the TFA strategy in 8th and 9th grade in the first year

of the study. In the following year I expanded the study to include students from 8th, 9th and 10th grades and chose a variety of topics from physics, chemistry and biology based on the scope and sequence of the Australian National Curriculum (ACARA, 2013). The study was carried out in the school in which I am employed, a moderate fee-paying, independent K-12 school in the Australian Capital Territory.

In order to explain the effects of learning using the TFA over time, quantitative data from each topic was collected to determine the degree of conceptual change by administering tests of conceptual understanding, before and after teaching. In some cases, delayed post-tests were also administered approximately six months after teaching to determine the persistence of the conceptual change that had taken place. Comparison groups from grades 8-10 were also taught the same topics by experienced teachers using their usual methodologies and the same demonstrations as the experimental group and given the pre and post-tests to determine their level of conceptual change compared to that of the experimental groups. As it was not possible for me to teach both the comparison and experimental groups and students were not randomly assigned to classes this study must be classified as quasi experimental.

In order to understand the changes in students' written explanations as a result of learning using the TFA, student worksheets were collected over the two-year period. Claim, Evidence and Reasoning rubrics (McNeill, Lizotte, Krajcik, & Marx, 2006) were designed and used to score students' written explanations together with use of the modified Levels Mountain rubric (Newberry et al., 2005) in order to examine the changes that occurred over that period.

Qualitative data were collected in the form of video and audio recordings during TFA lessons, student and teacher interviews at several different times throughout the teaching period, and student TFA worksheets. I also kept a journal of my observations and experiences. Data were analysed using a grounded theory framework (Bryman, 2012) by transcribing and coding interviews and lessons for themes. The emerging themes were used to suggest mechanisms of action of the TFA in terms of the epistemological, ontological and social/affective dimensions. Triangulation between student responses, teacher responses and lesson observations was carried out. These analyses are further expanded upon in later chapters.

1.5 Significance

This thesis makes several important contributions to the field of multidimensional conceptual change through implementation of a conceptual change strategy in the normal classroom setting.

1.5.1 TFA is a systematic teaching model addressing multidimensional conceptual change

The complexity of multidimensional conceptual change theory poses a serious challenge for teachers wishing to apply this theory in the classroom (Duit & Treagust, 2012a). If many teachers feel inadequate for the task of implementing constructivist teaching methods (Kirschner, Sweller, & Clark, 2006) and frequently revert to didactic teaching within the constraints of the busy school timetable (R. D. Anderson & Helms, 2001; Duit, Widodo, & Wodzinski, 2007; Hashweh, 1996), they clearly need an approach that supports them in systematically addressing the multiple elements of multidimensional conceptual change theory.

Teachers also need to undergo considerable conceptual change in terms of their understanding of the relevance and importance of conceptual change teaching practices and how to link their own content knowledge and their students' conceptual ecologies with those practices. This study first of all investigates the benefits and challenges of using the TFA as a constructivist multidimensional conceptual change strategy. It also looks at my experience as a teacher in implementing such a strategy, the changes in my conceptual understanding of and attitudes towards socio-constructivist conceptual change which led to changes in my practices as I taught using the TFA. It presents the supporting features and challenges for the teacher of using the TFA as a teaching model that systematically addresses multidimensional conceptual change theory in the classroom in a variety of different science topics.

1.5.2 Analysis of the mechanism of action of a multidimensional framework in the normal classroom

According to Treagust and Duit (2012a; 2008b), further research is required to determine the interaction between the dimensions to better understand the effects of multidimensional strategies in the normal classroom (Duit & Treagust, 2012b). For instance, Dole and Sinatra (1998) suggest that a more detailed picture of the engagement process could be obtained through case studies of students with varying levels of engagement which may generate ideas about how the process takes place. One significant aspect of this study is the extensive analysis of the effects and discussions of possible mechanisms of action of the TFA in the epistemological, ontological and social/affective dimensions and the interaction between aspects of these dimensions. This study was carried out in normal classrooms over a two-year period in Grades 8-10 in a variety of science topics and looks at the results of the intervention through the lens of the stakeholders in those classrooms, including three detailed case studies. This detailed analysis provides important fine-grained insights into mechanisms of action of a conceptual change strategy under normal school conditions, under

pressure to complete a set curriculum in a specified time period.

1.5.3 Effects on student characteristics of teaching using a multidimensional conceptual change strategy

Although researchers in the fields of social psychology and sociocultural studies have investigated many affective factors related to students' learner characteristics and their influence on conceptual change, there are very few studies on changes in the affective dimension as a result of implementing a conceptual change strategy. The literature, however, stresses the barriers to effective conceptual change that student characteristics such as lack of intentionality, mastery avoidance, deactivating emotions, low self-efficacy and negative self-concept can have on the degree to which students engage with the conceptual change strategy and benefit from it (Sinatra & Mason, 2013). Unless these barriers are addressed and overcome, conceptual change will be limited. This study examines the effects of implementing the TFA on these barriers in the affective dimension, through the analysis of three case studies and other student/teacher interview data and describes ways in which the TFA may reduce these barriers to conceptual change for many students.

1.5.4 Addressing difficulties students encounter in building skills in writing explanations

Although there have been many studies investigating the efficacy of strategies to improve students' scientific writing, the TFA as a methodology to support writing of scientific explanations has not been previously studied. Evidence from this study suggests that, not only does the TFA improve students' conceptual understanding, but the TFA may also be a very effective method of raising the level of student engagement with the writing process and improving their ability and confidence in writing elaborated causal scientific arguments.

1.6 Overview of Thesis

Chapter 2 provides a detailed review of the literature addressing cognitive, social and affective aspects of conceptual change. Chapter 3 describes the school setting, participants, data collected, the TFA and the lessons developed for each topic and the methodologies used for analysis of data. Chapters 4-7 present analyses of results. Chapter 8 discusses these results in terms of how the TFA supports conceptual change by addressing epistemological, ontological and social/affective aspects of that change, in relation to the literature presented in Chapter 2. It also looks at the changes that occurred in student characteristics in the affective dimension and the aspects of the TFA process which appear to support those changes. Finally, Chapter 9 summarised the findings of the research questions, discusses implication for further research and teaching and limitations of the study.

Chapter 2. Literature Review

This chapter is divided into three sections. The first section provides a brief overview of the historical development of conceptual change theories, including theoretical considerations in the epistemological, ontological and social-affective dimensions of conceptual change. Literature concerning conceptual change from the perspectives of cognitive psychology, science education, social psychology and social-cultural studies of learning is presented. Within each dimension, a discussion of effective strategies which have been proposed to support conceptual change is presented. This is followed by a summary of studies that have addressed multidimensional approaches to conceptual change. The need for the implementation of conceptual change strategies in the classroom, that address literature from all three dimensions and which analyse such strategies in terms of multidimensional change, is argued. Finally, the Thinking Frames Approach will be proposed as an example of a multidimensional conceptual change strategy which addresses many of the findings in the literature and which is a 'doable' approach, supporting implementation in the normal classroom.

The second section will examine methods that have been used in the literature for measuring and evaluating conceptual change in each dimension. Limitations of these methods and areas for further expansion of analysis in terms of multiple dimensions of conceptual change will be suggested. The final section will summarise the main theoretical considerations which inform this study.

2.1 Theoretical Foundations of Multidimensional Conceptual Change

Since the 1970s a large body of research literature has been produced in the areas of cognitive psychology, science education, social psychology and studies of sociocultural aspects of learning, surrounding how students learn as they develop their conceptual understanding. Each of these branches has addressed conceptual change from quite different perspectives and based on different theoretical frameworks. Much can be learned about the process of conceptual change and the ways in which to support that change from each of these perspectives. Although each of these branches of research remained distinct and only interacted to a limited extent in the early years of research, more recently the benefits of applying findings from each field have been realised, and dialogue between these areas of research have resulted in approaches which synthesise the evidence obtained from each in order to benefit and support conceptual change outcomes (Dole & Sinatra, 1998; Duit & Treagust, 2003; Treagust & Duit, 2008a).

2.1.1 Concepts, mental models and conceptual change

At the heart of constructivist teaching in science lies the goal of supporting students in constructing scientifically acceptable conceptual mental models (Duit, 1999) and effectively applying those explanatory models to produce explanations of observed phenomena (Clement, 2013). A conception is a mental model (schema) or internal representation which is held by the student constructed on the basis of such things as their experiences, reading, pictures and explanations from others (Glynn & Duit, 1995). Concepts are the basic units of learning rather than knowledge (Sfard, 1998) and these concepts are stored, refined and combined to bring about “richer cognitive structures” (p.5). These mental models, or ‘proto-models’ may then be expressed in various representational forms, such as drawings, diagrams, written and verbal explanations (Gilbert & Justi, 2016). Students bring their previously constructed conceptual frameworks, which may be comprised of many alternative conceptions, to their science lessons and these alternative conceptions can be remarkably resistant to change (Duit & Treagust, 2003; Treagust & Duit, 2008b).

2.1.2 Different ways of viewing students’ conceptual ecologies

Beginning in the 1970s and continuing until the present day, multiple studies have been carried out to determine the common alternative conceptions held by students of different ages and on a multiplicity of topics (Duit, 2009; Duit & Treagust, 2003). There have been much research and discussion around the framework within which students hold these alternative conceptions. There are two opposing camps to explain the structure of students’ conceptions: ‘knowledge as theory’ and ‘knowledge as elements’ (Özdemir & Clark, 2007).

The ‘knowledge-as-theory’ camp underpins much of science education research, such as the Conceptual Change Model (Posner, Strike, Hewson, & Gertzog, 1982), some aspects of the Framework Theories of Vosniadou (1994) - based on transfer between students’ naïve or pre-instructional mental models and scientific models - and Chi’s (1992) Ontological Shifts paradigm. These perspectives assume that students hold relatively coherent sets of alternative conceptions which allow them to solve problems or answer questions. Posner et al. (1982) saw students as possessing a set of conceptual beliefs or a conceptual ecology (Toulmin, 1972) which was underpinned by their epistemological beliefs. Carey (1999) noted that even quite young children can make predictions based on schemata or models that they hold, while Vosniadou and Brewer observed that young students consistently refer to a naïve model of the Earth as a flat disc or rectangle (Vosniadou & Brewer, 1992). Similarly, Hatano and Inagaki (1996) observed that young students hold quite elaborated ideas of a topic such as biology through observation and experience which enable them to make predictions and give explanations of phenomena.

It can be argued, however, that it is simplistic to assume that students hold a cohesive set of alternative epistemological conceptions based on an ontological framework. A number of researchers hold a 'knowledge-as-elements' perspective (Özdemir & Clark, 2007) where students' knowledge is made up of semi-independent units composed of elements such as phenomenological primitives, facts, narratives and concepts (Clark, 2006; diSessa, 2006). diSessa (1993) postulated that, as a result of students' experiences in various contexts, students store concepts as phenomenological primitives (p-prims) which are loosely connected but cannot be described as a coherent framework. Different p-prims are activated in different contexts. Clark's (2006) longitudinal study of students' learning thermodynamics indicated that students hold multiple contradictory, context-based ideas which they had difficulty connecting in any coherent framework.

Vosniadou (2013), however, combines aspects of the 'knowledge-as-theory' and 'knowledge-as-elements' perspectives. She sees students' naïve frameworks as being underpinned by strongly held presuppositions which are based on their experiences of the world and are quite coherent (Vosniadou, 1994). Students generate new concepts or synthesise new mental models based on combinations of the scientific model and their alternative model, constrained by those presuppositions. The resultant models are more fragmented and take on characteristics of the 'knowledge-as-elements' perspective (Vosniadou, 2013).

2.1.3 What is conceptual change

Much debate has surrounded the process by which conceptual change occurs. Consistent with Ausubel's (1968) dictum and Piaget's (1957, 1985) ideas of assimilation and accommodation of schemata through equilibrium/disequilibrium, the manner in which conceptual change occurs may be described as existing on a continuum between a wholesale or revolutionary change where one conceptual model is renounced and completely replaced and a piecemeal or evolutionary change where parts of the conceptual model are modified or replaced over time which may eventually result in a major restructuring of the conceptual model (Posner et al., 1982; Thagard, 1991).

At one end of the continuum, cognitive psychologists built on Piaget's ideas of assimilation to describe the incremental ways in which students' schemata can be built upon and modified without radical change occurring in the overall framework of ideas (Chi, 1992; Dole & Sinatra, 1998). Vosniadou and Brewer (1987) describe this change as 'weak restructuring'. This evolutionary approach to conceptual change is consistent with the 'knowledge-as-elements' perspective and would suggest the importance of determining students' existent p-prims, providing experiences that activate and modify appropriate p-

prims in multiple contexts in order to build a more coherent scientific set of elements (Özdemir & Clark, 2007).

At the other end of the continuum students may entirely reorganise their schemata through a process of accommodation leading to abandonment of previously held concepts in favour of new ontological categories (Chi, 1992; Thagard, 1992; Vosniadou & Brewer, 1987) described variously as radical or revolutionary conceptual change or ‘tree-swapping/switching’. The ‘knowledge-as-theory’ perspective suggests that a more revolutionary conceptual change may be possible by making students aware of their naïve theories, providing discrepant events which challenge those theories and giving opportunities to understand and use the scientific framework in order to explain the discrepant event in a more fruitful manner. Carey (1999) suggests that restructuring of naïve theories occurs on a domain level rather than a global level through exposure to new knowledge, experiencing disequilibria and social interactions (Özdemir & Clark, 2007). This change could be through replacement of concepts, splitting or combining of concepts (Carey, 1999).

Recognising that conceptual change may involve elements of both evolutionary and revolutionary change, Chi (1992, 2013) suggested that knowledge that could be categorised as ‘inaccurate’ could be relatively easily addressed by cognitive conflict strategies, where students are made aware of ‘false beliefs’ or assumptions of their ‘flawed mental models’ and hence modify their naïve ontologies. However, she suggests that revision across ontological categories is much more difficult (Chi, 2013) as students may assign concepts to the wrong ontological category or may not possess an appropriate ontological category in which to place newly acquired concepts.

Whether students’ conceptual understanding is held as theories or elements, or whether change is evolutionary or radical, conceptual change in the cognitive dimension involves a process whereby students must dismantle and restructure their previously constructed mental models in order to understand the concepts presented to them (Duit, 1999). Building on research in cognitive psychology, radical constructivist ideas about knowledge acquisition and Kuhn’s (1970) views of paradigm shifts in scientific theories, Posner et al. (1982) developed the Conceptual Change Model (CCM) to explain the persistence of students’ alternative conceptions and ways in which those conceptions could be modified or changed (Duit & Treagust, 1998). In order for students to engage in conceptual change Posner et al. (1982) suggested that both teachers and students must become aware of the students’ alternative concepts. Then, in order for students to consider restructuring these presently held concepts, the competing concept must be presented in an intelligible way to the students, the new concept must give a more plausible explanation and also be more fruitful in enabling the student to solve problems related to the phenomenon.

2.1.4 Changing the status of a concept

Following on from investigations into the structure of the concepts held by the novice science student, there have been many studies of what happens to these concepts after teaching has occurred. The higher the status that the conception holds in the mind of the student the more restructuring of their presently held concept will occur (Hewson & Thorley, 1989). From a knowledge-as-theory perspective, if the new conception does not challenge the previously held one, then both models may be held concurrently or one may be assimilated into the other. If the new conception gains higher status because of its greater intelligibility, plausibility and fruitfulness and if the previously held conception has been shown to have less of these qualities, then students may adopt the new conception (Posner et al., 1982). However, the previous conception remains in the student's memory and may re-emerge at a later date (Hewson, 1982; Hewson & Thorley, 1989). Studies which investigated the persistence of conceptual change found that students had mostly reverted to their previously held alternative conceptions six months after the teaching period (Chinn & Brewer, 1993; Hakkarainen & Ahtee, 2007; Trumper & Gorsky, 1997; Trundle, Atwood, & Christopher, 2007). The status that a particular conceptual model holds may in fact be context driven, one model being used in a specific context while being less useful in another (Treagust & Duit, 2008b). However, it is always the student and not the teacher who determines the status and hence the level of conceptual change that occurs as new conceptual models are constructed (Hewson, 1982; Posner et al., 1982).

2.1.5 The epistemological dimension

Although the term 'epistemological conceptual change' has been broadly used to describe change in understanding of the nature of science (Gilbert & Justi, 2016), I have adopted Tyson et al.'s (1997) definition of the epistemological 'lens' of conceptual change: what is perceived when 'the student is looking "in" at their own knowledge' (p.399). As such, a set of epistemological commitments, based on a student's experiences, make up a student's beliefs about a particular topic and may or may not be underpinned by a coherent ontological framework, linking these beliefs. Thus, a student's epistemological commitments may be seen as the disparate elements of the 'knowledge-as-elements' view or the component beliefs of a more cohesive 'knowledge-as-theory' framework. Early studies of conceptual change focused on the epistemological dimension, addressing individual alternative conceptual beliefs held by students such as that heat rises or that metals are intrinsically cold. The 'classical' CCM of Posner et al. (1982), described above, focuses on addressing these epistemological commitments by introduction of discrepant events to create cognitive conflict and hence promote adoption of scientific concepts. The underlying assumption of this model is that students have relatively stable sets of concepts and that these can be

changed through a revolutionary process as they experience events which challenge those beliefs and render them less plausible and fruitful and the scientific concepts more plausible and fruitful.

Chi (2013) categorizes the types of knowledge that are in conflict with scientific knowledge into two categories: 'inaccurate' and 'incommensurate'. These two categories can be further subdivided. Inaccurate knowledge can either be 'false beliefs' or 'flawed mental models', while incommensurate knowledge can be either 'category mistakes' or 'missing schemata' (Chi, 2013). Incommensurate knowledge means that this knowledge and the scientific knowledge possess different properties or dimensions. One might say that incommensurate knowledge belongs to different ontologies, whereas inaccurate knowledge may be seen as requiring change in epistemological commitments. The type of conflicting knowledge and the level of the conflict will determine the kinds of strategies that the teacher will use to address that knowledge. Incommensurate knowledge will be discussed in section 2.1.6, the ontological dimension.

False beliefs and flawed mental models require change in their epistemology rather than their ontology. Simply providing the correct information in this case by explicitly or implicitly refuting a belief may be sufficient, in some cases, to bring about conceptual change (Chi, 2013). Thus, according to the CCM and Chi's model, strategies that provide cognitive conflict should address these inaccurate epistemological beliefs.

The importance of students becoming aware of their alternative conceptions and undergoing some form of cognitive dissonance when they recognise that their presently held conceptions are not consistent with the evidence is frequently stated in the literature (Chinn & Brewer, 1993; diSessa, 2006; Duit & Treagust, 2003; Limón, 2001; J. Nussbaum & Novick, 1982; Posner et al., 1982). This was confirmed in the meta-analysis of Guzzetti, Snyder, Glass, and Gamas (1993) which showed the success of cognitive conflict strategies in leading to epistemological change. For example, in a recent study comparing conceptual change with and without students' initial conceptions being revealed (Potvin, Mercier, Charland, & Riopel, 2012), significant benefits, in terms of conceptual change, were found for making students' alternative conceptions visible.

Similarly, flawed mental models may also be effectively addressed through cognitive conflict strategies. Flawed mental models are based on flawed assumptions but are coherent and allow students to make predictions and answer questions but in a different way from the scientific model (Chi, 1992, 2013). In order for the flawed mental model to line up with the scientific model the assumptions must be challenged and addressed in terms of the assumptions of the scientific model. An example might be the understanding of electrical

current. Many students assume that electrons stop ‘flowing’ as energy is transferred to a light bulb as light and heat. They therefore predict that the current after the bulb will be zero. Once they see that the current on either side of the light bulb is the same they need to revise the underlying assumption that the electron flow will change and see that the energy of the electrons is transferred in a different manner which does not affect flow. This process does not involve an ontological shift but does require a readjustment of the students’ assumptions. Once again, providing discrepant events to challenge these flawed mental models may be sufficient for conceptual change to occur.

Criticisms of the classical model of conceptual change. However, just addressing one false belief at a time by providing the scientific belief may result in the student inserting that idea into the flawed model which remains flawed (Chi, 2013). This will happen if the underpinning assumptions are not challenged and the result is assimilation rather than accommodation (Chi, 2013). If enough flawed beliefs are refuted and revised then the flawed mental model may evolve to become more consistent with the scientific model (Chi, 2013). However, it may still remain flawed if those assumptions which are not consistent with the scientific model are not challenged (Chi, 2013; Vosniadou & Brewer, 1992). Consistent with this concern it was found that the change that actually occurred, due to interventions based on the CCM, were often short-lived, limited or fragmentary (Duit & Treagust, 1998).

Smith, diSessa, and Roschelle (1993) claim that using cognitive conflict strategies are not likely to be successful in bringing about lasting conceptual change and they criticise this approach as being inconsistent with constructivism as it does not appreciate the value of the students’ alternative conceptions as building blocks for conceptual change, rejecting the characterisation of students’ alternative concepts as wrong or misconceptions (diSessa, 2006).

Some researchers have also disagreed that conceptual change is revolutionary but, rather, believe it to be evolutionary (Thagard, 1992; Vosniadou & Brewer, 1992). A very powerful criticism is that the social/affective aspects of learning are not explicitly addressed in this classical model (Hatano & Inagaki, 2003; Pintrich, Marx, & Boyle, 1993; Sinatra & Pintrich, 2003a). Despite these criticisms, many interventions still only address students’ conceptual understanding by primarily focusing and measuring change in the cognitive dimension, particularly in terms of change in epistemological beliefs and primarily using cognitive conflict strategies (see Appendix A: Conceptual Change Intervention Studies).

2.1.7 Introducing multidimensional conceptual change

In the 1980s and early 1990s studies of conceptual change based on cognitive psychology and the CCM of Posner et al. (1982), as described above, found that conceptual change was

limited and the status of students' alternative conceptions remained high or the change was not long-lasting. As a result, researchers began to incorporate the findings from sociocultural studies and moved away from an approach that mostly focused on cognitive aspects of conceptual change towards a social constructivist perspective (Duit & Treagust, 2003).

An influential paper by Pintrich, Marx and Boyle (1993) examined 'hot' factors, (other than purely cognitive ones) which may influence students in changing their conceptual status, such as motivation, interest, and other aspects of affect. It is simplistic to say that the 'classical' view of conceptual change does not address affective features. They are implicitly addressed as students' experience cognitive conflict and undergo the process of finding scientific concepts intelligible, more plausible and fruitful. However, it was recognised that a greater consideration of social and affective aspects of learning in any intervention must be combined with cognitive aspects in order to more successfully bring about conceptual change (Duit & Treagust, 1998; Tyson et al., 1997).

Learning goes beyond simple knowledge acquisition and requires students to overcome significant barriers, both conceptually and in the affective realm. (Sinatra & Mason, 2008). Consistent with research in the areas of social psychology and socio-constructivist theories, addressing the epistemological and ontological dimensions of conceptual change has limited effect on whether a student will choose to adopt a scientific understanding of phenomena if affective issues are not taken into account (Pintrich et al., 1993). Hence, in order to understand the conceptual change process, it is necessary to investigate the interaction between learner characteristics and the cognitive aspects of conceptual change. Conceptual change relies on students constructing a more scientific model of conceptual understanding and hence it is essential that students are intentional about doing so, are motivated to do so and believe that they possess the ability to do so (Sinatra & Pintrich, 2003b). It is not an either/or but a both/and situation and both cognitive and affective aspects must be addressed. Zembylas (2005), in fact, argued that the affective should have equal importance with the cognitive. However, according to Duit and Treagust (2012a), little work has been done in finding the theoretical links between the cognitive and affective aspects and measuring them.

While cognitive psychologists and science educators were investigating the cognitive aspects of conceptual change, social psychologists were investigating the ways in which attitudes and beliefs are constructed and acted upon. Building on theories from cognitive psychology they proposed that attitudes are constructed from belief subunits (Eagly & Chaiken, 1993), based on experiences, behaviours and propositional concepts, stored in memory as schemata (J. R. Anderson, 1983; Dole & Sinatra, 1998). Studies showed that these attitudes and beliefs can also undergo change and a dual mechanism was suggested

in which attitudes could change through reasoned consideration of issues (central route to persuasion) and/or on the basis of external, peripheral factors (Dole & Sinatra, 1998). Deep or 'elaborated' engagement with issues was found to be dependent on an individual's motivation due to interest, the relevance of the topic and the characteristics of the learner and their 'need for cognition', as well as their background knowledge (Petty & Cacioppo, 1986). Although this elaborated engagement was thought to lead to a greater and more permanent change, other peripheral factors such as social pressure, attractiveness of the presentation, credibility of the presenter/s could also lead to change (Petty & Cacioppo, 1986).

Combining the evidence from cognitive and social psychology with aspects of the Conceptual Change Model, Dole and Sinatra (1998) suggested a Cognitive Reconstruction of Knowledge Model (CRKM) in which the strength, coherence and commitment of students' conceptions are examined and addressed. The CRKM addressed motivation of students by providing experiences that created cognitive dissatisfaction with their presently held conceptions (c.f. the CCM) but also examined the effects of central or peripheral routes of persuasion in terms of students' motivation due to interest, self-efficacy, influence of peers in the social context and intrinsic motivation to learn (Dole & Sinatra, 1998). The student's experience of cognitive dissatisfaction, together with the intelligibility, plausibility and fruitfulness of the scientific model, interacts with these motivational factors, combined with a student's intentionality to engage in metacognitive processes, in order to determine the degree of conceptual change and its persistence (Dole & Sinatra, 1998; Sinatra & Pintrich, 2003b).

Conceptual change is a very complex phenomenon and therefore multidimensional approaches are required which take into account epistemological, ontological and social/affective aspects in supporting students in constructing new conceptions (Treagust & Duit, 2008b). The CRKM model (Dole & Sinatra, 1998), discussed above, contains aspects of a multidimensional framework, although the ontological dimension is not explicitly addressed. Duit and Treagust (2012a) argue that a multidimensional framework that takes into account all three dimensions of conceptual change, the epistemological, ontological and social/affective, is a much more powerful framework for both understanding the conceptual change process and implementing effective conceptual change strategies in the classroom. Each of these frameworks for understanding conceptual change can also be fruitfully used to evaluate student learning over time to obtain a more fine-grained understanding of the complexity of learning and of the conceptual change process (Duit & Treagust, 2012b; Tyson et al., 1997).

2.1.6 The ontological dimension

One of the limitations of the classical epistemological view of conceptual change is that the focus is on conceptual content change rather than change in underlying conceptual models within a context, or change in understanding of the nature of science (Duit & Treagust, 2003; Fensham, 2001). The ontological dimension of conceptual change addresses the larger scale, underlying model or theory which underpins epistemological beliefs held by students (Chi, Slotta, & de Leeuw, 1994; Duit & Treagust, 2003; Thagard, 1992). It assumes that students do hold naïve ontological frameworks based on ‘knowledge-as-theory’ (Chi, 2013; Vosniadou, 1994) and that these require radical conceptual change rather than gradual conceptual change (Chi, Slotta, et al., 1994), which involve students replacing their commitment to matter based ontological understanding to process based ontological understanding. For instance, students may hold a ‘Caloric’ view of heat which sees heat as a substance which flows from one place to another, heat and cold being parts of a spectrum of this ‘substance’. Epistemological commitments are based on this underlying ontology. For example, metal getting colder in contact with an ice cube is seen as due to the flow of ‘cold’ from the ice cube to the metal. This is what makes topics like heat, forces and genetics difficult for students as they have a preference for matter-based ontological conceptions, as they are based on their everyday observations (Chi, Slotta, et al., 1994).

For persistent conceptual change to occur, both ontological and epistemological aspects must be addressed (Vosniadou, 1994). It is in fact sometimes difficult to see how the two aspects can be fully differentiated as understanding of epistemological aspects may rely upon some level of understanding of the underlying ontological model. For instance, in order to understand convection, students need to replace the epistemological belief from experience that heat rises, with the understanding that more-dense gas displaces less-dense gas. In order to make this concept intelligible and plausible to a student they need to recognise that heat is a process rather than a material, that it makes particles of gas move faster, collide more and hence spread out more making the gas less dense. This relies on understanding the energy transfer process based on the kinetic particle model of matter. Although some students may simply learn that heat doesn’t rise and replace this concept with the idea that more-dense gases fall - a change of understanding in the epistemological dimension - it seems that in order to do that, some level of ontological transfer must take place.

There are two major theories which examine and explain conceptual change in terms of both the epistemological and ontological dimensions, Framework Theory of Vosniadou (2013) and Category shifts of Chi (2013).

Chi's (2013) Ontological Category framework of conceptual change identifies the epistemological and ontological factors that are described above, and goes a long way towards clarifying this complexity and explaining the types of interventions that will be effective in addressing each category. I will primarily be using Chi's Ontological Categories in this thesis, together with ideas of representational change from the Framework Theory.

Framework Theory. According to this theory, at quite an early age, as children experience the world around them, they develop conceptual frameworks which are relatively coherent in four areas, physics, psychology, mathematics and language (Vosniadou, 2013). Vosniadou calls these initial frameworks, preconceptions. These frameworks are relatively coherent and can be used to predict and explain. As new knowledge is encountered students may recategorise objects or concepts into new ontological categories which result in considerable epistemological and representational change. Epistemological, ontological and representational change happens very slowly and incrementally, as new, incompatible knowledge is added to the framework. This can result in fragmented knowledge, where students allow the new knowledge to exist in the naïve framework, even though the two are inconsistent. Alternatively, a new framework may result as students try to make the new information and the old framework consistent and produce or synthesise a new framework to accommodate the new knowledge. These synthetic alternative conceptions are an intermediate between the naïve framework and a scientific ontology. They are continually changing as more epistemological knowledge is added.

Vosniadou claims that the framework theory meets many of the objections to the classical model of conceptual change. Framework theory differs from the CCM as it does not suggest that the change that occurs happens in one leap from the naïve theory to the scientific theory through experiencing cognitive conflict. Instead, Framework theory suggests that students slowly construct a series of intermediate synthetic ontologies or alternative conceptions in order to construct a completely new representation by integrating different semi-autonomous concepts found in the fragmented frameworks, not unlike the p-prims of diSessa (2006), into a more coherent whole. In this way the students' alternative conceptions are not seen as wrong and needing complete replacing but rather as stepping stones from pre-conceptions to scientific concepts.

Although the Framework theory shares some commonality with the Ontological Categories of Chi, it does not see students' pre-scientific ontologies as needing to be wholly replaced, nor does it accept that the greatest challenge to conceptual change for a student is to know to which ontological category a new conception needs to be assigned.

There is some agreement between diSessa's model of 'knowledge-in-pieces' and the Framework model. However, the Framework model proposes that students' preconceptions – their initial naïve model- is coherent and based on observations and experiences, becoming less coherent as other epistemological knowledge about the world is added. It is in this stage where the conceptual components are more fragmented and more like p-prims and the intermediate alternative conceptions may be situational and rapidly formed in response to a context.

Vosniadou suggests that cognitive dissonance may only have limited value because of the fragmentary nature of the intermediate alternative conceptions. Rather, she suggests that students should have opportunity to experience and learn about scientific concepts in multiple contexts with different affordances, through a carefully planned program of teaching based on students' learning progressions.

Ontological Category shift. As described in Section 2.1.5, Chi (2013) categorizes the types of knowledge that are in conflict with scientific knowledge into two categories: 'inaccurate' and 'incommensurate'. Incommensurate knowledge, or knowledge that possesses different properties or dimensions, as the result of belonging to different ontological categories, can either be described as 'category mistakes' or 'missing schemata' (Chi, 2013).

The relatively easy ways in which single, 'false beliefs' can be changed were discussed in Section 2.1.5. However, other beliefs, such as that heat rises, require more effort to refute since this belief and the scientific understanding of differential gas densities belong to, what Chi (2013) describes as, different dimensions and are therefore incommensurate with one another and require a categorical shift from one ontological dimension to another. Chi would define the belief that heat rises as a 'category mistake'.

'Category mistakes' can be described as belonging to different branches in the tree analogy of ontological conceptual change, introduced by Thagard (1992). Swapping between ontologically distinct branches is represented as moving between 'lateral' categories (Chi, 1992, 2013). In general, these 'lateral' categories are either matter-based or process-based, the naïve ontological, matter-based model being based on students' experiences of the material world, and the scientific model describing processes (Chi & Roscoe, 2002; Chi, Slotta, et al., 1994; Slotta, Chi, & Joram, 1995). As described above, students' naïve conceptions of heat are based on a belief that heat is a substance that flows, compared with the scientific energy transfer model. Process based phenomena can be further categorised as sequential or emergent processes (Chi, Roscoe, Slotta, Roy, & Chase, 2012).

Unlike knowledge that belongs to an ‘inaccurate category’, simply confronting students at the ‘belief’ level will not be sufficient to persuade them to swap branches, it can only make changes within the dimensions of that category (Chi, 2013). By making students aware of the ontological categories that they hold, and recognising the ways in which the scientific model and their ontological commitments do not agree, they may be willing to revise their ontological categories and presuppositions (Chi, 1992; Özdemir & Clark, 2007) and reassign a concept across lateral categories (Chi, 2013). Chi suggests that this is difficult for students because making category shifts is a rare occurrence in everyday experiences and so students are unaware that a category shift is necessary or possible. Effective teaching to bring about lateral category shifts requires explicit confrontation at the ontological level and teaching about the new ontological category, in order to make students aware of the need to change categories (Chi, 2013; Gadgil, Nokes-Malach, & Chi, 2012). The importance of teacher-student dialogue in supporting category changes will be discussed further in section 2.1.8.

Another reason why some alternative conceptions are so hard to overcome may be that, not only may the student not be aware that they need to change categories, but also they may not have another category available for them to change to. In this case, presenting discrepant events may cause students to change some of the beliefs that they hold but, since they have no other category into which they can transfer the new belief, they just reshape the currently held ontological category (Chi, 2013). In this case the students need to become aware of a new, scientific schema in which to place the modified beliefs. For instance, many students find the topic of natural selection and evolution difficult, possibly because they categorise it as a sequential process, due the action of an agent, rather than an emergent process which is a statistical response to a number of factors (Chi et al., 2012). The category of ‘emergent process’ is most often a missing schema, and well beyond many students’ experiences.

Whether ontological change is best described by the mechanism of Framework or Category shifts, both epistemological and ontological change can be supported through use of student generated multiple-representations, including drawing, writing and verbal representations to bring about representational change, and through class discourse (discussed in Section 2.1.8). In terms of Chi’s model of ontological change, when students are confronted with incommensurate knowledge these activities can be fruitfully used to make students’ ontological categories visible to them, make them aware that a category shift is needed and provide understanding of a missing schema to which they can now assign newly acquired or developed beliefs.

Despite the evidence that addressing both epistemological and ontological aspects is essential in order to achieve lasting conceptual change, the ontological dimension is frequently ignored in the literature. According to Duit and Treagust (2012b) “researchers who use epistemology to explain conceptual changes do not **overtly** emphasise changes in the way in which students view reality” (p109, bold mine). Most papers that focus on the cognitive dimension, do not differentiate between epistemological and ontological frameworks of change, and conceptual change in terms of ontological commitments is rarely measured (see Appendix A: Conceptual Change Intervention Studies).

Supporting epistemological and ontological change through student generated representations. Vosniadou (2013) emphasises the importance of students undergoing representational change together with epistemological and ontological change as they move from commitment to naïve preconceptions towards a scientific ontology. Gilbert and Justi (2016) stress the importance of producing external representations of internal proto-models which allows the testing, evaluation and refinement of these models. When encouraging students to develop new scientific explanations based on an unfamiliar schemata of understanding, a powerful tool to bring about representational change can be visualisation of the explanatory model of the phenomenon through student generated representations (Tytler, Prain, Hubber, & Waldrip, 2013; Van Meter & Garner, 2005). As students produce different representations of a concept they build deeper understanding of that concept (Duit & Treagust, 2012b). Therefore, as students produce multiple external representations (e.g., diagrams, verbal and written explanations) acquisition of new ontological models are scaffolded by providing cues to build multimodal internal representations, both verbal and visual. This supports successful encoding and retrieval of concepts, reduces working memory load and encourages deeper conceptual understanding (Gilbert, 2005; Rapp & Kurby, 2008) and greater conceptual change. For instance, encouraging students to produce a variety of representations to explain their conceptual understanding resulted in high normalised gains on concepts in pre and post-tests in the topics of astronomy (Waldrip, Hubber, & Prain, 2013) and states of matter and substance (Tytler, Hubber, Prain, & Waldrip, 2013).

In order for students to effectively construct and communicate their epistemological and ontological understanding based on a more scientific schema, students should be supported in producing a variety of scientific representations (Boulter, Gilbert, & Rutherford, 2000). Each type of representation carries its own set of constraints or affordances which Tytler and Prain (2013) refer to as “productive constraints” and which they suggest cause students to analyse, select and critique these representations in relation to their currently held explanatory mental models. Students also attain fluency in acquiring,

retaining, retrieving and amending their internal representations of a scientific model as they practise producing their own external representations (Gilbert, 2005). This allows construction of more coherent ontological frameworks which can be fruitfully used to predict and explain phenomena. However, for students to become competent in producing external representations they need to understand the different forms or modes that representations may take and become adept at transferring understanding between these macro, sub-micro and symbolic modes in order to be able to construct both internal and external representations using recognised scientific conventions (Gilbert, 2013).

Although use of student-generated representations can support the development of student understanding of a single concept, they are also powerful tools for developing students' deeper understanding and application of the underlying ontological model. For instance, Bamberger and Davis (2011) noted that the ability to draw and describe the way that a phenomenon happens enabled students to answer 'how' and 'why' questions rather than just 'what' and 'when' questions. They suggest that the use of scientific concept-process representations enhances student ability to understand content, create representations, use meta-modelling processes and understand the purpose and usefulness of scientific models (Bamberger & Davis, 2011). It is also suggested that meta-cognitive knowledge is improved when the same teaching strategies are repeated in teaching different content areas with time for students to reflect (Ben-David & Zohar, 2009). For instance, production of a series of representations by students that illustrated claim and reasoning in response to representational challenges also gave opportunities to students to apply informal reasoning, such as analogies, and encouraged negotiation and communication of meaning in a social context (Tytler, Prain, Hubber, & Haslam, 2013). Hence, production of a series of student generated multiple representations can be a powerful strategy to support students in constructing, applying and modifying their understanding of particular scientific ontological models.

Supporting epistemological and ontological conceptual change through written representations. In particular, achieving representational conceptual change in the form of written scientific explanations is an essential aspect of communication of scientific understanding. The productive constraints of producing written scientific explanations or arguments can be used to strengthen conceptual change on both the epistemological and ontological levels by making internal representations visible (Fellows, 1994; Rapp & Kurby, 2008) and by enabling students to process ideas, find personal meaning and improve complex thinking (Rivard, 1994). Scientific writing persuades others by linking explanation to evidence (Berland & Reiser, 2009) as a sequence of cause and effect, allowing further predictions to be made where appropriate (Yore, Bisanz, & Hand, 2003).

However, most writing tasks in class involve simple recall or summary and little instruction is given to improve argumentation and analysis in writing tasks (Kiuahara, Graham, & Hawken, 2009; Lemke, 1990; Yore et al., 2003). Despite the fact that producing written arguments or explanations is a central practice of science, they are often neglected within the classroom (Kelly, Regev, & Prothero, 2008; Kiuahara et al., 2009; Newton, Driver, & Osborne, 1999) and students find it difficult to clearly articulate their understanding as a coherent argument (Kelly et al., 2008; Sadler, 2004).

Some studies have been carried out which support the benefits of writing using strategies, such as the Science Writing Heuristic, as a process which strengthens student conceptual understanding (Greenbowe, Rudd, & Hand, 2007; Hand, Prain, & Wallace, 2002; Hand, Yang, & Bruxvoort, 2007; Hohenshell & Hand, 2006; Nam, Choi, & Hand, 2011). These “writing-to-learn by learning-to-write” strategies involve students in serious and realistic writing tasks which help students use the language of science as they develop explanations, argue from evidence, revise claims and build conceptual understanding (Carter et al., 2007; Sampson et al., 2013). Effective approaches use modelling, coaching, scaffolding and feedback to support students in improving their written explanations (Sampson et al., 2013).

One way of supporting students in preparing written scientific explanations, is by providing opportunities to plan and practise in pre-writing tasks (Patterson, 2001). A study scaffolding Year 10 students’ planning and pre-writing resulted in an improvement in answers to higher order conceptual test questions (Hand, Prain, & Hohenshell, 2000). Similarly, use of fading scaffolds for construction of scientific explanations resulted in significant improvement in use of reasoning in students’ explanations (McNeill et al., 2006). Thus strategies that support students in writing elaborated, causal explanations may also support both epistemological and ontological conceptual change.

2.1.8 The social-affective dimension

Since the 1990’s there has been greater investigation, particularly from the social psychology perspective, of how affective factors such as motivation, interest, intentionality and self-efficacy support conceptual change. Most studies that focused on social-affective aspects measured conceptual change in the cognitive dimension in response to those aspects, while very few studies examined the effect of a conceptual change intervention on student affect (see Appendix A) (Eymur & Geban, 2016; Franke & Bogner, 2013; Lee & Byun, 2012). Similarly, few studies have looked at the effects of a conceptual change approach on affective aspects in the real classroom (Dole & Sinatra, 1998; Murphy & Alexander, 2008). While affective aspects clearly influence the degree of cognitive conceptual change, it

seems that these affective variables also need to be explicitly addressed and developed so that they in turn undergo change (Duit & Treagust, 2012a).

A summary of social experiences and students' affective characteristics that have been studied in relation to their supportive effect on conceptual change is presented below.

Socio-cultural support for conceptual change. Students learn within a social environment and their understanding is constructed not only cognitively and emotionally but also socially (Zembylas, 2005). Sfard (1998) argues that the two essential features of learning are acquisition of concepts and participation, which she defines as the “process of becoming a member of a certain community” (p6).

Dialogic interaction. One of the social interactions that increases higher-order thinking and supports students in construction of understanding is classroom discussion (Palincsar, 1998). Vosniadou (2013) speaks of the importance of not only carefully designing students' learning progressions to address students' synthetic frameworks, and to support epistemological and representational growth, but also acknowledging the benefits of supporting students' metacognitive awareness and building their intentionality through social support. She suggests that a fruitful way of supporting metacognitive awareness is through providing a sociocultural environment which allows for dialogical interaction in whole-class discussions which can lead to greater engagement with conscious reviewing of beliefs. Likewise, Duit and Treagust (2012b) suggest that, based on a cultural studies perspective, the context of learning and the dialogic elements – discourse in small groups and whole class discussion - should be incorporated into conceptual change strategies. Mercer (2008) argues that the dialogic aspects of conceptual change are of considerable importance but that research has focused more on small group interactions rather than on teacher-student talk.

Teacher-student dialogue addresses the need for providing missing schemata and helping students to address the category mistakes described in Chi's (2013) ontological category shift theory. This occurs as this dialogue allows construction of knowledge and explanations as students' explanations and representations are questioned, evaluated, defended and/or revised (Ford & Forman, 2006; P. Webb & Treagust, 2006). Mercer (2008) suggests that teacher-student dialogue acts as a mediator for ontological shifts from students' everyday experience-based non-scientific understanding to scientific, process-based understanding as the teacher, as relative expert, provides information about the scientific framework, helps students to discover their 'everyday' perspective and engages in discourse to build understanding of the scientific framework. Chinn and Brewer (1993) found that whole class dialogue is effective in encouraging students to think more deeply about their conceptual framework rather than just making small adjustments.

Teacher-student dialogue has been categorized into four types by Mortimer and Scott (2003): Interactive/Dialogic, Non-Interactive Dialogic, Interactive/Authoritative and Non-Interactive Authoritative. Mercer (2008) suggests that each of these forms may be used in combination to productively build students' conceptual understanding (Rojas-Drummond & Mercer, 2003). Scott, Mortimer, and Aguiar (2006) noted the shifts from dialogic exchanges, as a topic is introduced, to authoritative exchanges as the teacher acts as expert in order to introduce new ideas, followed by further dialogic interaction as students apply the new framework to their understanding. As mentioned above, however, further study is needed of the effects of teacher-student dialogue on conceptual change.

In studies of student-student dialogue comparing the effects of dialogue in small groups where members agree with each other compared to ones where members hold differing views, expressing contrasting views within the small group resulted in significant benefit for conceptual change (Ames & Murray, 1982; Bearison, Magzamen, & Filardo, 1986; Howe, Tolmie, & Mackenzie, 1995). In fact, presentation of competing opinions during group work was the greatest indicator for sustained conceptual change over an 18 month period in a study of 10-12-year-olds (Mercer, 2008).

Berland and Reiser (2009) suggest that explanation and argumentation within small group discussions complement each other, in that, explanations are formed within a discussion as students attempt to persuade their peers. As the group argues for a particular explanation, that explanation gains in value, thus increasing the possibility of schemata being modified. This process results in deeper content understanding rather than simple memorisation of facts (Chi, Leeuw, Chiu, & Lavancher, 1994; Coleman, 1998). For instance, studies have shown that engaging in argumentation to defend an explanation improves eighth graders' abilities to express their scientific understandings (D. Kuhn & Udell, 2003). It seems that unless students have the goal of persuading someone else with less knowledge than themselves, they are not motivated to use evidence to support their explanations (Berland & Reiser, 2009). Thus, in order to encourage students to elaborate their internal schemata and produce these in written form, students benefit from opportunities to verbally defend their explanations and present those explanations addressing a real audience. As students attempt to persuade peers within a discussion, their explanations are enhanced (Berland & Reiser, 2009) and the status of the scientific concept may be increased sufficiently to support long-term conceptual change.

The research of Rivard and Straw (2000) displayed the importance of peer discussion combined with writing, particularly for low-achieving students, and resulted in higher achievement in tests on those concepts. Kempa and Ayob (1991) also showed that after participation in small group discussions 40-50% of the science ideas were sourced from

that discussion and that even those who did not actively participate in the discussion benefited.

Heterogeneous small-group interactions. In addition to the benefits of argumentation within the small group environment, there are also several other benefits in being given opportunities to construct understanding in a meaningful way with peers in small groups as a community of learners. It appears that, as students work together, with shared goals and understanding of a task, they don't just share ideas but work together to 'interthink' (Mercer, 2000, 2013). Mercer suggests three mechanisms by which collaborative learning has benefits for students as problem solvers: through sharing knowledge and problem-solving strategies, by arguing productively to co-construct strategies and explanations, as well as through argumentation and justifying claims to bring about a transformation in student reasoning (Mercer, 2013). Similarly, Hausmann, Chi, and Roy (2004) suggest that collaboration with peers within the metacognitive learning cycle improves understanding by three possible mechanisms: the benefits of acting as the teacher gives students confidence in constructing their own explanations and learning independently; "co-construction" strengthens students' metacognitive skills in evaluating their own and peers' explanations through argumentation; and "self-directed explaining" or listening to peers self-explaining strengthens students' monitoring and evaluative skills (Sandi - Urena, Cooper, & Stevens, 2010).

Effective small groups. In order for students to gain the social benefits of small group interactions there are many factors which must be taken into account in choosing the composition of the small group and the types of activities that they are asked to perform. Researchers suggest that the greatest collective benefit to students is when discussion occurs in mixed-ability (heterogeneous) small groups (E. G. Cohen, 1994; Lou et al., 1996). High achievers benefit from participating in heterogeneous small groups by giving explanations to others (Swing & Peterson, 1982) while low achievers have been shown to benefit in recall and problem solving (Hooper & Hannafin, 1988) and higher order thinking (Tudge, 1990), more so than when placed in homogeneous low-achieving groups (Swing & Peterson, 1982). The importance of the teacher in the small group environment is stressed by Schreiber and Valle (2013) in supporting student learning through questioning (Prawat & Floden, 1994) and guiding students until they are able to complete the task themselves (Hodson & Hodson, 1998).

In Cohen's review (1994) of what factors make small groups effective she stresses the importance of choosing problems which are ill-structured and involve conceptual learning where students share their hypotheses and speculate on solutions as a group. Tasks that require abstractions and the production of representations of the concepts at hand benefit

from group collaboration (Shwartz, Black, & Strange, 1991). If students are given thought-provoking questions and encouraged to discuss these to find an elaborated answer within the group, students engage in higher-order thinking during the discussion (A. King, 2002).

Various challenges in instituting effective small groups have been noted. For instance, if positive goal interdependence (Deutsch, 1962) is not achieved, students may not feel that there is a benefit from interacting and may return to individual work. Not all students possess the social skills required to be able to negotiate with others to produce explanations acceptable to the whole group or to support others' learning (E. G. Cohen, 1994). Webb (1984) also found some interesting effects in groups which generally resulted in girls being disadvantaged in terms of achievement in the group if there were boys present.

The importance of feedback. Self-regulated learning and feedback also support social-construction of understanding. Analysis of the efficacy of feedback from a large number of studies (Hattie & Timperley, 2007) has shown that feedback has a high effect size ($d=0.79$) in terms of influencing student achievement. However, not all feedback is helpful. The most effective types of feedback provided students with further information about how to improve their responses or performance, particularly if the feedback gave students information about the correct response rather than the incorrect response and built on feedback given in previous learning experiences (Hattie & Timperley, 2007; Kluger & DeNisi, 1996). Feedback also appears to be most effective when the tasks are challenging and goals are specific, yet the task is not complex (Hattie & Timperley, 2007; Locke & Latham, 1984).

Hattie and Timperley (2007) suggest that there are four levels of feedback that are given to students: feedback about the task (FT), feedback about the process of completing the task (FP), feedback encouraging greater student self-regulation (FR) and feedback about the student themselves unrelated to the task (FS). Of these four levels the least effective is the feedback about the students themselves and this type of feedback was even found to diminish the positive effect of giving task-oriented feedback. FT or corrective feedback, which tells students whether they have the correct answer and provides the student with the correct interpretation, has been shown in several meta-analyses to be very effective with consistently high effect sizes (Lysakowski & Walberg, 1982). Correction of faulty reasoning when giving FT is more effective than simply correcting incorrect information and it is suggested that feedback that leads to rejection of faulty hypotheses and draws students towards searching for better explanations or strategies is the most effective (Hattie & Timperley, 2007). How much use a student makes of the feedback given depends on their commitment to the task but also is influenced by their confidence in understanding the concepts presented (Hattie & Timperley, 2007; Kluger & DeNisi, 1996).

Feedback to students about the processes involved (FP) in completing the task, such as encouraging error detection and strategies to improve a student's performance, has also been shown to be very powerful, particularly when combined with FT (Hattie & Timperley, 2007). Providing both FT and FP has been shown to improve students' confidence in completing the task and their feelings of self-efficacy and supports deeper learning (Earley, Northcraft, Lee, & Lituchy, 1990). More immediate feedback to students on the task has been shown to be of benefit while delayed feedback on the process was shown to be more beneficial (Clariana, Wagner, & Roher Murphy, 2000).

Finally, feedback to students which provides cues to encourage self-assessment, provokes them to question the correctness of their responses (Kulhavy & Stock, 1989), motivates them to complete the task and ask for assistance (FR) supports strategies that are evident in effective learners (Hattie & Timperley, 2007). Willingness to seek help is a very valuable skill that students who complete tasks develop, but many students avoid seeking such help if they perceive that they will look foolish (Karabenick & Knapp, 1991). Any strategy that reduces the cost and raises the benefit of seeking feedback has positive effects for students' learning.

Influence of characteristics of the learner on conceptual change. Since Pintrich et al.'s (1993) influential article was published, which turned attention to the affective aspects of conceptual change, researchers in the field of social psychology have investigated the influence of motivational, and other affective characteristics of the learner on the degree to which they undergo conceptual change. Even though students may have similar background knowledge or hold a similar conceptual ecology they will bring different levels of learning goals, intentions to learn, motivations, feelings of self-efficacy, interest, control beliefs and values to their learning (Sinatra & Mason, 2008). These affective, situational and motivational factors play an important role in whether a student will adopt a scientific understanding of a phenomenon (Sinatra & Mason, 2008) and are strong indicators for success and persistence in studying science (Ting, Sam, Khor, & Ho, 2014). Despite this, Fortus' study (2014) showed an under-representation of publications in major science education journals addressing affective aspects of teaching and learning science.

In order to understand the conceptual change process, it is necessary to investigate the interaction between learner characteristics and the cognitive aspects of conceptual change (Sinatra & Mason, 2008). The effects on conceptual change of a number of these student characteristics are further described below.

Intentional conceptual change. Human cognition is ordered in different levels from unconscious processing to processing as a result of conscious attention (Sinatra & Mason,

2008). Sinatra and Pintrich (2003b) defined intentional conceptual change as “goal-directed and conscious initiation and regulation of cognitive, metacognitive, and motivational processes to bring about a change in knowledge” (p. 6).

Intentional learning is initiated and directed by the student and is underpinned by the students’ goal orientation. Students who choose to intentionally learn, regulate their own learning, are aware of metacognitive strategies and are motivated to focus on the task and are willing to restructure their understanding (Limon Luque, 2003), rather than just being at the mercy of their previously held knowledge or being controlled by the level of difficulty of the task (Sinatra & Pintrich, 2003a). Conceptual change involves the restructuring of conceptual frameworks (Chi, 1992; Dole & Sinatra, 1998; Vosniadou, 1994) and hence engaging of students on an intentional level is believed to be essential for effective and long-lasting change as they encounter discrepant events, and construct new frameworks based on their plausibility and fruitfulness (Sinatra & Pintrich, 2003a; Sinatra & Taasoobshirazi, 2011).

The power of persuasion, via central and/or peripheral routes, in order to encourage student intentionality in considering the plausibility and fruitfulness of the new framework while suppressing their old framework, is suggested through extensive research on attitude change (Hynd, 2003), as discussed above in the Cognitive Reconstruction of Knowledge Model (CRKM) (Dole & Sinatra, 1998). A recent study relating attainment value, attention allocation, cognitive engagement and conceptual change found that utility value for the individual more positively influenced attention allocation than attainment value, and hence was more likely to result in engagement and conceptual change (Jones, Johnson, & Campbell, 2015).

Although unintentional conceptual change is also possible, and may be the most common form of change in classrooms, as students are often unaware of the change that is taking place in their conceptual understanding (Vosniadou, 2003), it is questionable how persistent unintentional change might be (Hatano & Inagaki, 2003; Sinatra & Pintrich, 2003a). Hatano and Inagaki (2003) suggest that, because intentional conceptual change requires a lot of effort, it may only occur when students feel there is no other choice. They note the importance of other factors such as the teacher, peer support of students, external rewards and the sociocultural environment in leading to intentional conceptual change.

Achievement goals. Achievement goals are the motivation behind why a student does or does not engage in learning a particular topic (Elliott & Dweck, 1988). In this respect, understanding students’ achievement goals can be effective in determining the underlying basis for their motivation and intention to learn and the motivational processes that can support conceptual change (Linnenbrink & Pintrich, 2003).

Achievement goals have been divided into two types, mastery and performance goals (Sinatra & Mason, 2008). A student who has mastery goals is interested in learning deeply and engaging with the topic so that the content can be mastered. Rather than giving up when they encounter difficulties, they persist using these mistakes to learn to overcome them. They have also been shown to use more self-regulation strategies and undergo greater levels of cognitive change (Pintrich, 2000; Pintrich & Schrauben, 1992). A study of Ranellucci et al. (2013), based on the CRKM of Dole and Sinatra (1998), showed that a mastery goal approach was linked with use of deep and shallow processing strategies and engagement in these strategies, particularly deep processing strategies, led to conceptual change. Deep processing strategies involve summarising and elaboration of ideas, integration of new ideas into existing knowledge schemata and meta-cognitive strategies, while shallow processing involves memorisation or activation of previously acquired knowledge.

Similarly, Linnenbrink and Pintrich (2003) tested the effects on conceptual change of another dimension of achievement goals, approach vs avoidance, as well as the effect of need for cognition, as suggested by the CRKM. They found that both an approach orientation and possessing a need for cognition led to greater conceptual change.

Conversely, when Hynd, Holschuch, and Nist (2000) studied the effects of conceptual change in physics amongst high school students they found that students who underwent conceptual change developed slightly higher levels of motivation. This was related to higher levels of interest as well as the fact that they received higher grades.

Students with performance goals, however, are more focused on themselves and their appearance as learners to others (Pintrich, 2000; Pintrich & Schrauben, 1992). Their goal is to show others that they are competent learners, and their self-worth is tied up with being able to show that they are good students (or avoid showing others that they are not good students). These students do not persist when they make errors, they avoid challenging tasks as they may not feel adequate when addressing them, they engage less deeply with tasks and have fewer control strategies (Pintrich, 2000; Pintrich & Schrauben, 1992). Possessing performance or performance avoidance goals appears to mitigate against conceptual change (Ranellucci et al., 2013).

In contrast to these results, Qian and Pan (2002) showed that students with *high* performance goals displayed improved conceptual change while Elliot (2005) showed that a combination of performance and mastery goals led to higher conceptual change.

Epistemic motivation. Sinatra and Mason (2008) identified another form of motivation: epistemic motivation which focuses on motivation to obtain new knowledge and understanding and restructure knowledge, rather than on the self. There are two types of

epistemic motivation –seeking closure and avoiding closure (Kruglanski, 1989). The goal of seeking closure is to get definitive knowledge about a topic in order to avoid uncertainty or because there are time constraints. This can lead to students quickly making decisions without truly restructuring their understanding (Kruglanski, 1989).

Avoiding closure is associated with a disposition which continues to search for further clarification and new hypotheses, allowing for greater conceptual change (Sinatra & Mason, 2013). Hatano and Inagaki (2003) suggested that a motivational disposition, which avoids closure when confronted with discrepant events, led to students being willing to consider different explanations, particularly when this takes place in a social environment through classroom dialogues which reviewed and discussed different possible explanations. In order for students to undergo conceptual change they need to undergo some form of epistemic conceptual change towards a stance that avoids closure, whereby they understand that knowledge is by nature complex and evolving (Alexander & Sinatra, 2007).

Interest. Students' level of interest, like achievement goals, has the power to direct students' attention towards the concepts being learned as well as being a motivator for conceptual change (Sinatra & Mason, 2008). Researchers identify a difference between individual and situational interest (Murphy & Alexander, 2008). Individual interest seems to be a stable factor related to a student's long-held attitude towards a subject.

Large-scale longitudinal questionnaire based studies of individual students' interest in science, such as the Relevance in Science Education (ROSE) study, have shown a declining interest in science, with a negative correlation with where the country sits in the UN Development Index (Sjoberg & Schreiner, 2005). Students from less developed countries than Australia hold a much greater interest in pursuing careers in science and technology. It has been suggested that this lack of interest may be due to outdated and overcrowded teaching curricula, use of didactic teaching methods, lack of qualified teachers, and postmodern questioning of scientific method (Gilbert & Justi, 2016; Schreiner & Sjoberg, 2010). The Third International Mathematics and Science Study (TIMSS) of 1999 of eighth grade students showed that less than 30% of Australian students had a positive attitude towards learning science (Martin et al., 2000; Osborne & Dillon, 2008). Students who display a high cognitive capacity are not pursuing science because of lack of interest (Krapp & Prenzel, 2011).

Student interest in science has also been shown to decrease significantly from age 10 to age 14, particularly for girls (Osborne & Dillon, 2008; Osborne, Simon, & Collins, 2003), although attitude towards science in boys declined markedly as they moved from elementary to high school (Grades 6/7) (Potvin & Hasni, 2014). The decline in interest for girls was

most pronounced in the areas of physics, astronomy and earth science (Potvin & Hasni, 2014). However, it must be noted that some studies show that students' attitude towards school in general decreases over this period. Osborne et al. (2003) suggest that the decline in interest in science may not in fact be linear but may reduce much more rapidly after the age of 14. In fact, it appears to be science in school that students don't find interesting rather than science in general and this appears to be related to factors such as perceived relevance and difficulty (Osborne et al., 2003).

In contrast to individual interest, situational interest can be induced under certain conditions, including the learning environment, which brings about a heightened interest in a topic (Schraw & Lehman, 2001). This can be expressed as heightened personal interest – the topic becomes more important to the student – or stimulates the student. Personal interest as interest in a particular topic has been shown to result in greater recall and elaboration of content and stem from students possessing a greater amount of pre-existing knowledge of the topic (Schiefele & Krapp, 1996). However in some cases, greater topic interest may result in students having stronger commitment to their presently held concepts and therefore a resistance to conceptual change (Murphy & Alexander, 2004; Venville & Treagust, 1998). More studies investigating the relationship between interest and conceptual change are needed (Sinatra & Mason, 2013), as well as studies which investigate the effects of conceptual change strategies on student interest. For instance, one study of the influence on interest of a constructivist conceptual change pedagogy which used alternative conceptions to teach about gene technology (Franke & Bogner, 2013) found that students developed greater interest when alternative conceptions were made visible and those students with greater interest underwent more conceptual change.

Self-efficacy. A feeling of self-efficacy is an important factor for learning to take place. A student who feels greater self-efficacy is more confident in his or her own abilities (Schunk & Zimmerman, 2006). Bandura suggests that students' self-efficacy, or belief that they are able to successfully carry out certain tasks in order to achieve a particular outcome, is a major determinant or motivating factor for what students will be willing to expend their effort on (Bandura, Barbaranelli, Caprara, & Pastorelli, 1996). The greater this feeling of self-efficacy the more likely students are to complete or persist with a task, even when they find it difficult (Schraw, Crippen, & Hartley, 2006). High levels of self-efficacy are also related to positive emotional measures – less stress about tasks and greater confidence that they can learn difficult concepts. These could lead to a greater engagement and higher levels of intentional conceptual change (Sinatra & Mason, 2008) but alternately students with high self-efficacy may also believe that their presently held conceptions are better than those presented and so be resistant to change (Linnenbrink & Pintrich, 2003).

Similarly, self-efficacy and the level of engagement in self-regulatory processes go hand in hand (Pajares, 2002). Students with greater feelings of self-efficacy are more likely to use strategies to monitor their learning, persist when confronted with difficult problems and accurately evaluate their work (Bouffard-Bouchard, Parent, & Larivee, 1991). Tasks that include short-term goals where immediate and frequent feedback is provided have been shown to improve students' feelings of self-efficacy by providing them with evidence of their mastery of those tasks (Bandura & Schunk, 1981; Schunk, 1983), particularly when the students attribute these improvements to their own efforts (Schunk, 1987). Provision of informational feedback on tasks also improves feelings of self-efficacy (Hattie & Timperley, 2007).

Affect and emotion. Although the term affect is used in a general sense to refer to 'hot' factors as opposed to cognitive factors (Sinatra & Mason, 2008), it is also used more specifically by researchers such as Rosenberg (1998) to describe emotional predispositions that are relatively stable in a person, whereas, the term emotions refers to temporary, short-lived feelings. Pekrun, Goetz, Titz, and Perry (2002) classified emotions into positive or negative, both of which can have activating or deactivating effects on learning. For instance, emotions such as enjoyment or pride are classified as positive activating emotions and have positive influences on learning by improving motivation, use of metacognitive strategies and by encouraging greater elaboration and critical thinking (Broughton, Sinatra, & Nussbaum, 2013; C.-J. Liu, Hou, Chiu, & Treagust, 2014; Taasobshirazi, Heddy, Bailey, & Farley, 2016).

In comparison, negative deactivating emotions such as boredom and hopelessness undermine motivation, turn student attention away from the task and reduce opportunities for conceptual change (C.-J. Liu et al., 2014; Sinatra & Mason, 2013).

Summary. Sinatra and Mason (2013) summarised the conditions under which student characteristics have the greatest impact on conceptual change as being 1) when students experience cognitive dissonance/conflict between their present understanding and the one presented, 2) when students are purposeful and committed to learning, and 3) when students possess activated emotions in relation to that commitment.

While there have been many studies on the effects of affective aspects, motivation, self-efficacy and interest on students' levels of engagement and conceptual change, many papers do not provide or suggest a way forward to increase the interest, motivation and self-efficacy of students, nor do they provide means by which students can be encouraged to exchange performance goals with mastery goals and increase intentionality of learning.

Importance of student-teacher interactions in conceptual change. In relation to the social-affective dimension of conceptual change, there are two important roles of teacher-student interactions for middle and high school students: providing motivation and encouraging an environment conducive to social-constructivism (Davis, 2003). Students appreciate the support and structure that teachers provide as well as the feelings of success that teacher-students' interactions can develop (Davis, 2003). From the wealth of research on student-teacher interactions, a number of factors arise which enhance student learning. The importance of encouraging student autonomy within the necessary structures of the classroom has been shown in terms of teachers facilitating students in taking responsibility for their own learning, developing students' feelings of self-efficacy and providing strategies to support deeper conceptual understanding (Reeve, 1998). A teacher who supports students' autonomy is less likely to step-in and provide students with the 'correct answer' (Reeve, 1998).

The way in which a teacher evaluates students' work and manages students' use of time also influences student motivation. Students are more motivated when they perceive teachers as being more interested in the quality of their work and their understanding, by using strategies that support them in co-constructing understanding and self-evaluation, than in just getting the work done after receiving the knowledge from the teacher (S. Thomas & Oldfather, 1997). Students also feel more motivated if they perceive their teacher to be caring and supportive by being organised and prepared for lessons, providing students with strategies that support learning, using humour (Moje, 1996), having high expectations for student success (C. Muller, Katz, & Dance, 1999) and giving opportunities for students to authentically express their ideas (Oldfather & Thomas, 1998).

Extensive research has been carried out into the role of the teacher in the social-constructivist classroom. One of the most frequently studied methods of promoting social construction of understanding has been the whole-class or significant group discussion (Nuthall, 2002) (as discussed in this section 'dialogic interaction'). The most effective aspects of the teacher's role within these discussions are as a setter of challenging or significant questions and encouraging cognitive engagement as a facilitator of students in presenting evidence and reasoning to support their views (Smart & Marshall, 2013). Some of the techniques that teachers may use to successfully encourage students to be fully and actively engaged in argumentation and debate are: seeking elaboration and evaluation of a students' argument from peers (Hogan, Nastasi, & Pressley, 2000); relating one student's argument to previously presented evidence or arguments (Varelas & Pineda, 1999); seeking clarification of thinking (Solomon, 2000); rewording a response and adding some

information to it (Nuthall, 2002); using questioning to direct students in organising and clarifying their thinking (Chinn & Anderson, 1998).

Despite the importance of implementing social constructivist methodologies, observational studies of teachers in the UK showed that as little as 2% of science lessons were taken up with serious debate of concepts (Newton et al., 1999) and a further study in the USA indicated that teachers are still doing most of the talking (Stigler & Hiebert, 1999, 2009). Interestingly studies have shown that students themselves will tend to draw the teacher back into more traditional forms of teaching and discussion as they feel that the expectations for their participation are less ambiguous and they resist the higher level of effort that is required in co-constructing their understanding (Varelas, Luster, & Wenzel, 1999; Yerrick, 1999). Consequently, pedagogies are needed which support and encourage both teachers and students in implementing social constructivism in the classroom.

2.1.9 Studies of multidimensional conceptual change

Despite the extensive evidence for the necessity of addressing epistemological, ontological and social/affective aspects of conceptual change, the number of conceptual change studies that overtly evaluate interventions in terms of all three of these dimensions remains small.

Venville and Treagust (1996) successfully used multidimensional frameworks for viewing conceptual change to evaluate the effect of teaching using analogies and to better understand conceptual change in genetics (Venville & Treagust, 1998). By doing so they obtained a more fine-grained picture of the processes involved in conceptual change within the classroom. Similarly Tsui and Treagust (2007) carried out an analysis of an intervention in teaching high school genetics using a computer simulation package which presented students with multiple representations of concepts. They used a multidimensional framework to determine efficacy of the programme in terms of the epistemological (Tsui & Treagust, 2003), ontological (Tsui & Treagust, 2004a) and social/affective (Tsui & Treagust, 2004b) aspects of conceptual change that were observed.

More recently, a few studies have been carried out which attempt to address and/or measure change in all three dimensions of conceptual change (Kock, Taconis, Bolhuis, & Gravemeijer, 2013; Lombardi, Sinatra, & Nussbaum, 2013; Mbajjorgu, Ezechi, & Idoko, 2007). The kind of data collected to show that conceptual change had occurred and the process by which it occurred has generally been made up of quasi-experimental elements such as pre-/post-tests, interviews and sometimes think-aloud protocols.

2.1.10 Implications for further research

According to Treagust and Duit (2008b), further research is required on conceptual change strategies in terms of multiple frameworks, particularly giving equal weight to both cognitive (epistemological and ontological) and affective aspects of learning.

Although researchers in the fields of social psychology and cultural research have investigated many affective factors related to students' learner characteristics and their influence on conceptual change (see Appendix A), most of this research does not explicitly differentiate between the effects on the ontological and epistemological dimensions. Similarly, there are few studies on changes in the affective dimension as a result of implementing a conceptual change strategy in the cognitive realm.

There have also been few models describing ways in which cognitive aspects of conceptual change may be enhanced through addressing the social and affective aspects of that change. The CRKM model of Dole and Sinatra (1998), discussed in Section 2.1.7, combined the cognitive conceptual change model with aspects of persuasion theories in order to increase motivation, self-efficacy and interest through utilising central persuasion and the influence of peers to increase deep engagement. They state that neither cognitive nor social psychology research into conceptual change had described how the engagement process occurred and suggested that more case studies of students who had various levels of engagement may produce a more detailed picture of the process and could generate ideas about how the process takes place in the classroom.

Building on the CRKM model, Sinatra and Mason (2013) suggest a number of steps that should be undertaken in order to address the cognitive and social aspects of learning, together with students' learning characteristics. The first step involves determining the barriers to change in both the cognitive and social/affective dimensions within the cohort. This requires the determination of students' alternative conceptions, both in the epistemological and ontological dimensions. Alternative conceptions in each of these dimensions will require different approaches in order to address them effectively (see Chi, 2013; Posner et al., 1982; Vosniadou, 2013).

The level of commitment and emotional attachment of students to prior conceptual frameworks will also determine the type of intervention required. For example, strongly held alternative concepts may best be addressed through a higher level of engagement (Dole & Sinatra, 1998) such as use of inquiry or problem-based strategies (Sinatra & Mason, 2013). Emotional attachments to concepts may be addressed by use of central and peripheral persuasion (Dole & Sinatra, 1998; Murphy, 2001; Sinatra & Kardash, 2004) through dialogue and argumentation in the whole class and small groups (E. M. Nussbaum & Sinatra,

2003). The classroom environment should also be addressed to support mastery goals by providing a safe, non-threatening environment for questioning and discussion of differing points of view (Sinatra & Mason, 2013). The teacher also needs to ensure that students have enough content knowledge to produce reasoned arguments (Sinatra & Mason, 2013).

Duit and Treagust (2012b) note that there are also few studies on programs that use conceptual change strategies to effectively promote conceptual change in the normal classroom. While some teachers may hold intuitive understanding that students need to construct their understanding, in actual fact most are unaware of students' alternative conceptions and conceptual frameworks and tend to see themselves as the providers of information and scientific facts. A change in view is required in terms of the role of the teacher – reflective, non-transmissive - and the characteristics of the learner – active, reflective, responsible for own learning and working with peers (Duit & Treagust, 2012b).

Indeed, the complexity of the various conceptual change frameworks may result in difficulty implementing conceptual change strategies in the classroom (Duit & Treagust, 2012a). Teachers also may need to undergo considerable conceptual change in terms of their understanding of the relevance and importance of constructivist and conceptual change teaching practices and how to link their own content knowledge and their students' conceptual ecologies with those practices.

Gregoire (2003) proposed a Cognitive-Affective Model for Conceptual Change (CAMCC) to describe and explain teachers' choices to either reject, assimilate or adopt reform teaching pedagogies. Her model suggests that the level of challenge to the teacher must be addressed in terms of teachers' beliefs about self-efficacy, motivational factors and approach-avoidance stance, in order for a teacher to choose to systematically process the proposed change and adopt it (Ebert & Crippen, 2010).

I would suggest, in addition to the factors suggested by Gregoire, that the ontological commitments of a teacher need to be addressed as they will also determine how much restructuring of conceptual understanding and adoption of new pedagogies take place. While teachers can enthusiastically embrace research-based practices, such as a greater use of co-operative learning, they often continue to hold transmissive views of learning rather than socio-constructivist views which result in assimilation with their previously held practices. I would suggest that this is an example of undergoing 'weak restructuring' in the epistemological dimension without switching ontological trees. In order for teachers to undergo more revolutionary conceptual change, they too need to experience persuasive conceptual change strategies which address their feelings of low self-efficacy (Kirschner et

al., 2006) and their avoidance stance, as well as their implicit ontological beliefs about effective teaching to bring about changes in their practices.

Duit and Treagust (2012a) suggest that a central challenge in science research is supporting teachers in learning how to implement multidimensional conceptual change strategies in classrooms by presenting research that describes the ways in which they can use the benefits of conceptual change research in implementing ‘doable’ programs. This thesis attempts to address this challenge.

2.1.11 The TFA as a multidimensional conceptual change approach

As a systematic structure to implement multidimensional conceptual change theory, this study used the Thinking Frames Approach (TFA) (Newberry & Gilbert, 2007; Newberry et al., 2011; Newberry et al., 2005). This approach was designed for use with elementary and middle school students. However, this study takes the principles of the TFA and adapts them for use with Grade 8-10 students over a series of lessons within a topic. The TFA has not previously been formally studied to determine its effect on student conceptual change.

The TFA has a set of guiding principles and activity sequences which support students and teachers in constructivist learning. Students build their own understanding of phenomena through a combination of aspects of the CCM, challenging students’ alternative conceptions through presentation of discrepant events, with social construction of understanding through teacher-student and student-student discourse. This discourse occurs as students discuss predictions of what they think will happen based on explanations using their presently held conceptual framework within a small group environment. After observing the outcome of a demonstration or thought experiment they discuss with their peers possible explanations of those observations using the Predict-Discuss-Explain-Observe-Discuss-Explain (PDEODE) strategy. They then present those explanations to the wider class and the teacher uses Socratic questioning to support students in constructing explanations based on the scientific model.

Students then work in small heterogeneous groups to make use of the benefits of producing multiple representations of their conceptual understanding in verbal, pictorial and written formats to further refine their explanations. It is a structured approach as students work consecutively through a sequence of steps: challenging of alternative conceptions, development of a verbal explanation of observations, brainstorming key words, drawing their conceptual understanding, summarising their explanations in dot point form, writing an explanatory paragraph, self-evaluation of explanations, followed by individual feedback to students by the teacher. A summary of the key steps in the TFA (Newberry et al., 2011) is found in *Table 2.1*.

Table 2.1

TFA Lesson Structure

TFA Steps	Student Activities
Setting the Scene (PDEODE and group/whole-class discussion)	a) Teacher presents a practical demonstration using an everyday context challenging alternative conceptions. b) Students work cooperatively in their groups using the Predict, Discuss, Explain, Observe, Discuss and Explain (PDEODE) framework to explain what happened in the demonstration. Groups use argumentation to produce a verbal explanation to a higher order thinking question based on the observations, which is shared with the class. Teacher uses questioning to prompt consideration of the scientific model.
Worksheet-Based Activities	
1. Brainstorming	Students gather keywords and phrases that they believe will be useful in answering the question.
2. See/Visualise	Students produce and communicate their verbal representations in the form of labelled diagrams or pictorial timelines.
3. Think/Sequence	Building on the pictorial representation of concepts and key words students produce dot points of 'what happens' and 'why'.
4. Paragraph	Using the dot points thus produced, students then produce a paragraph to explain the phenomenon and answer the questions originally posed.
5. Evaluation	Students evaluate their work in terms of how successfully their explanations addressed cause and effect and used scientific language using the Levels Mountain framework.

The features of the TFA in terms of the epistemological dimension of conceptual change. In individual lessons the TFA addresses the epistemological aspect of conceptual change as students experience cognitive conflict to engender disequilibrium with their currently held epistemological beliefs (Guzzetti et al., 1993; Posner et al., 1982), by observing outcomes of carefully designed experiments. These demonstrations challenge students' flawed beliefs or flawed mental models described by Chi (2013). They then engage in small group and class discussions which make their alternative conceptualisations visible to both themselves and the teacher; and they practise explaining their observations, in terms of scientifically acceptable conceptions using pictorial, verbal and written representations using scientific vocabulary. Each of these processes makes the scientific explanation more intelligible to the student. Thus the status of the scientific conception may be raised (Hewson & Thorley, 1989) as it is seen by students as being more plausible, intelligible and fruitful as an explanation for the phenomenon observed (Posner et al., 1982).

The features of the TFA in terms of the ontological dimension of conceptual change. The TFA was originally developed to encourage use of models and modelling (Gilbert & Justi, 2016; Grevatt, Gilbert, & Newberry, 2007). 'Placemats', or one-page

handouts showing pictorial representations of curriculum models or modified scientific models, were provided to the students to support them in linking observations with the scientific model. In place of the ‘placemats’ I developed a set of TFA lessons on a particular topic to continually revisit the scientific model in each lesson, supporting students in establishing a mental model. Over a series of consecutive TFA lessons, designed to build on students’ understanding in a topic, students apply newly acquired, process-driven ontological scientific models to replace the non-scientific ontological frameworks that they previously held. In this way, students become aware of category mistakes and become familiar with the missing schema described by Chi (2013). As Chi and colleagues note (Chi, 2013; Gadgil et al., 2012), this supports lateral shifts in ontological categories which can be difficult and therefore require students becoming explicitly aware of the differences between their currently held ontological frameworks and the scientific framework.

The teacher-student discourse used in the TFA allows the teacher to guide students to consider the implications of their non-scientific, matter-based frameworks and to understand and apply the scientific process-based ontology. As Vosniadou (2013) suggests, supporting representational change is an important aspect in encouraging students to adopt scientific ontological frameworks. Production of students’ own representations in the form of diagrams, verbal and written explanations may support students in confidently developing, modifying and applying their internal and external representations in terms of the scientific model (Gilbert, 2005), supporting the ontological aspect of conceptual change. The “productive constraints” (Tytler & Prain, 2013) of each of these modes of representation may encourage students to analyse and critique these internal representations from different perspectives, enhancing intelligibility of the model. Construction of student understanding through production of their own multiple representations of the scientific conception within heterogeneous small groups may provide the impetus for the development of mastery goals.

The effectiveness of the TFA as a “writing to learn by learning to write strategy” (Carter et al., 2007; Sampson et al., 2013) is also examined by determining changes in students’ ability to write elaborated causal explanations as further evidence of changes in students’ conceptual understanding.

The features of the TFA in terms of the social/affective aspects of conceptual change. It is proposed that the following aspects of TFA may support social construction of understanding and positive aspects of student affect.

Social/group arrangement. The TFA utilises the power of social construction of understanding (Vygostsky & Kozulin, 1989) through communication of ideas amongst peers via the medium of small, mixed-ability group discussions. As students negotiate within the

small group, alternative conceptions become visible and the scientific conception gains status, supporting social construction of explanations (Pintrich et al., 1993; Treagust & Duit, 2008b). This student-student dialogue may result in students benefiting from “interthinking” (Mercer, 2000, 2008) and building meta-cognitive awareness (Vosniadou, 2013). Working in a small-group also provides students with a lower stakes environment in which to present explanations of unfamiliar concepts so that they receive the benefits of forming arguments and persuading peers (Berland & Reiser, 2009), including low-achieving students (Rivard & Straw, 2000). It is also an environment in which they receive support and encouragement from peers, which has been shown to benefit low and high-achieving students (Hooper & Hannafin, 1988; Swing & Peterson, 1982).

Feedback. The TFA gives an opportunity to provide the type of effective feedback described by Hattie and Timperley (2007) – timely and giving further information about how to improve responses to a single, challenging question. Students are provided with a framework to evaluate their own explanations in terms of whether they have produced a persuasive causal explanation using correct scientific language (FR). The teacher provides written feedback on each students’ work in terms of the same criteria, improving students’ explanations by inserting further elaborations or correcting those explanations that still refer to alternative conceptions, building on feedback given in previous TFA exercises (FT & FP).

Possible effect on student characteristics. Teachers in the UK who used the TFA described the following benefits: students gained confidence in visualising models and expressing their ideas, both in verbal and written form, as they understood that their ideas would be valued and they could see specific steps that they could take to improve their written explanations; students were more motivated to improve their written communication of ideas (Newberry et al., 2011; Newberry et al., 2005).

This study investigates these and other effects of cognitive strategies in both the epistemological and ontological dimensions, as well as the aspects of the TFA which support social construction, on student characteristics such as mastery goals, interest, self-efficacy, positive activating emotions and central and peripheral persuasion. As suggested by Dole and Sinatra (1998), this study makes use of case studies in the normal classroom (Duit & Treagust, 2012b) to obtain a more fine-grained understanding of the effects of teaching with the TFA.

Support to the teacher using the TFA. In response to Duit and Treagust’s (2012a) concerns related to the difficulty of implementing the complex aspects of a multidimensional conceptual change approach, my experience as a teacher is critically examined. Affordances and limitations of teaching with the TFA in addressing the epistemological, ontological and

social/affective dimensions are investigated. The TFA provides a scaffold that may support teachers in addressing the steps suggested by Sinatra and Mason (2013) as being essential in adopting an effective conceptual change strategy. For instance, it encourages the teacher to investigate commonly held alternative conceptions of everyday phenomena in the topic under study, to develop higher order questions and discrepant events that encourage conceptual change via central routes of persuasion. Change in my own conceptual understanding and motivation to adopt multidimensional conceptual change pedagogies as a result of teaching with the TFA is examined using elements of Gregoire's (2003) CAMCC.

2.2 Measuring Conceptual Change and Improvement in Written Explanations

In this section the methods that have been used to measure conceptual change in the literature, in terms of the epistemological, ontological and social/affective dimensions are presented and those that are used in measuring these aspects of conceptual change in this thesis are discussed.

2.2.1 Measuring epistemological and ontological aspects of conceptual change

Many studies have focused on measuring cognitive gains through use of instruments such as conceptual inventories as pre/post-tests (Treagust & Duit, 2008b). Likewise, this study uses a number of validated conceptual inventories in the various topics addressed. The degree of conceptual change in the epistemological dimension is generally measured by the change observed in the number of correct answers after a particular intervention (see Appendix A), while other methods, such as the use of worksheets and interviews, have been used (Venville & Treagust, 1998). Although many of the questions on these tests assume the adoption of the appropriate ontological model, many of the questions address epistemological aspects of understanding by challenging commonly held alternative conceptions. It can be difficult, therefore, to determine how successfully students have adopted a scientifically consistent ontological model by looking at conceptual inventories alone.

In order to overcome this problem, some researchers have organised questions within the conceptual inventories into conceptual groups to determine students' more fundamental understanding of ontological concepts. For instance, questions in the Thermal Concept Evaluation inventory (Yeo & Zadnik, 2001) and the Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992) can be grouped in terms of overarching concepts such as Newton's third law and heat conductivity and equilibrium. Individual answers to the Evidence-Based Practice in Science Education – Set 2 (Millar & Hames, 2002), which investigates students' understanding of electrical currents, enables the researcher to identify the specific ontological commitments held by students through analysing their choices of alternative explanations for each question (Millar, 2002; Millar & Hames, 2002). Changes in

these overarching categories are also used to probe the degree of change within ontological categories in this study.

Two examples of topics that have been studied from an ontological perspective are heat and genetics – where ontological conceptual change is one from material understanding to one of process (Duit & Treagust, 2012b). Various methodologies have been used to determine students' ontological commitments: repeated interviews (Lin & Tsai, 2017), analysis of interview and worksheets (Venville & Treagust, 1998), class observations, interviews and online tests (Tsui & Treagust, 2004a), analysis of written text (West & Wallin, 2013) and analysis of both written and oral discourse (Roth & Lucas, 1997), a combination of questions, conceptual test and written discourse (Frasier & Roderick, 2011), three-tiered and other conceptual tests (Kock et al., 2013; Slotta et al., 1995; Taşlıdere, 2013), a world-view survey (Mbajjorgu et al., 2007) and talk aloud protocols (Gadgil et al., 2012).

In this thesis, analysis of responses to conceptual categories in pre/post-tests and changes in written explanations in terms of use of claim, evidence and reasoning are used to evaluate the degree of ontological conceptual change. I also suggest that student generated drawings of their conceptual understanding can be used to identify their ontological commitments. For instance, the Evidence-Based Practice in Science Education – Set 8 (Millar, 2002) test uses a variety of pictorial representational choices to identify students' understanding of states of matter and atoms, molecules and mixtures. It also asks students to draw their own representations of the way in which a gas occupies a space. Changes in response to these items are also used to indicate ontological conceptual change within this study.

Students' perceptions of those elements that supported epistemological and ontological change were obtained from analysis of interviews with students after learning using the TFA. Observations of teachers present in the classroom were also collected and analysed in terms of those aspects.

2.2.2 Evaluating the socio-affective aspects of conceptual change

Studies that investigate the socio-affective aspects are generally of four types (see Appendix A):

1. Observational studies which analyse socio-cultural aspects during a conceptual change intervention. For instance, while students used a small group, problem-solving strategy in a genetics classroom (Furberg & Arnseth, 2009), researchers observed their interactions and discourse. There are limited examples of these types of studies in the conceptual change literature.

2. Studies which investigate the influence of social aspects of learning on conceptual change. In these experimental or quasi-experimental studies, the social environment is often manipulated and the effect is measured in terms of the conceptual gains by administration of a pre/post-test (Adadan, Irving, & Trundle, 2009; Decristan et al., 2015; Eymur & Geban, 2016; Suppapittayaporn, Emarat, & Arayathanitkul, 2010; Yin, Tomita, & Shavelson, 2013).
3. Studies which investigate the influence of affective aspects on conceptual change. These studies are often experimental or quasi-experimental studies where student characteristics such as motivation or other affective aspects of learning are evaluated through use of questionnaires, interviews, think-aloud interventions and observations prior to learning, and their relationship to the degree of conceptual change is determined, often by the administration of pre/post-tests (Broughton et al., 2013; Jones et al., 2015; Linnenbrink-Garcia & Pugh, 2012; Ranellucci et al., 2013). In some cases, students' affect was manipulated and conceptual change measured (Allen, 2010).
4. Studies where the effect of a conceptual change strategy was measured on student characteristics such as motivation (Cetin-Dindar & Geban, 2016; Kock et al., 2013), emotions (Broughton et al., 2013), engagement (Annetta, Minogue, Holmes, & Cheng, 2009; Kock et al., 2013), epistemic beliefs (Chen, 2017), interest and well-being (Franke & Bogner, 2013) and anxiety levels (Lee & Byun, 2012). Methodologies used to determine student characteristics included a multiple-choice test, questionnaires, interviews and classroom observations of interaction and discourse. For instance, Venville and Treagust (1998) and Tsui and Treagust (2003, 2004b) used interviews with students and class observations to determine their level of interest and motivation as a result of conceptual change interventions related to the topic of genetics. These studies tend to focus on specific student characteristics and could be enhanced by further analysis of dialogue to determine other affective and social aspects (Duit & Treagust, 2012b; Mercer, 2008).

This study uses approaches 1 and 4 through a grounded theory methodology to analyse themes from interviews with students and teachers present in the classroom, together with video and audio transcripts of lessons. These are presented as summaries of student/teacher perceptions in Chapter 5 and as three representative student case studies in Chapter 6.

2.2.3 Measuring change in students' written explanations

Students' written arguments justifying their explanations of phenomena have been analysed using frameworks which assess the claim, evidence and reasoning components of argument

based on the model developed by Toulmin (1958). This is based on a two-mark rubric for each category. Students' written explanations in this study were analysed using two rubrics. The first was the original 'Level's Mountain' rubric (Newberry et al. 2005) developed for use with the TFA. The second was two-mark Claim-Evidence-Reasoning rubrics based on those of McNeill et al. (2006).

2.3 Summary

Strategies that address multidimensional conceptual change are now understood to be necessary in order to effectively support conceptual change in students (Duit et al., 2008). The epistemological dimension of conceptual change was developed and described by Posner et al (1982) and involves students experiencing cognitive conflict with their presently held conceptions. Providing students with discrepant events is an effective method for engendering epistemological conceptual change (Guzzetti et al., 1993).

This theory was further enhanced through the development of theories in cognitive psychology to explain the ways in which students acquire and develop conceptual models. This has led to two main theories which describe ontological conceptual change, the framework theory (Vosniadou, 2013) and ontological category shifts (Chi, 2013). In order to achieve sustained conceptual change both epistemological and ontological understanding must be addressed. It is proposed that the affordances provided through production of student-generated multiple representations combined with teacher-student dialogue may support construction of internal representations of ontological models and greater fluency in retrieving and applying those models to address category mistakes and missing schemata.

Combined with cognitive aspects, the importance of supporting greater conceptual change through social engagement and by providing an environment which encourages the development of positive student characteristics for learning, such as intentionality by increasing mastery goals, interest, epistemic beliefs, self-efficacy and positive activating emotions was discussed (Pintrich et al., 1993; Sinatra & Mason, 2013).

The complexity of implementing a multidimensional conceptual change approach which addresses the epistemological, ontological and social/affective dimensions in the normal classroom demands the development of a strategy which supports the teacher. The TFA was identified and developed as such a strategy which combines methodologies that support epistemological and ontological change in a social-constructivist setting and which encourages the development of positive, activating student characteristics. Methodologies for measuring change in each dimension were presented.

Chapter 3. Research Methods

This chapter will discuss the context of the study, including the school, the students and the teachers participating, the research questions, the design of this research, the TFA and how it was implemented and the sequence of lessons within each topic. The various instruments used are described: the pre and post-test instruments, rubrics for analysis of written explanations and the semi-structured interviews. The methods used to analyse the collected data are discussed and issues surrounding validity, reliability and ethics are addressed.

3.1 Context of the Study

3.1.1 The school

The participating school was a co-educational, independent, moderate-fee, faith-based school in the ACT that catered for students from pre-school to Grade 12 and had about 550 students. There were two to three classes in each year level with 20-30 students per class. According to government statistics, the majority of students had a mid-range socio-economic status for the region. Students came from a wide variety of ethnic backgrounds and some spoke a language other than English in the home; however, the majority of students spoke English as a first language. All classes were mixed-ability and most classes included students with special needs who had Independent Learning Provisions (ILPs). Where possible a class of similar ability was used as a comparison.

3.1.2 Participants - the students

A summary of the classes that participated in this study is found in *Table 3.1*. In the first year of the study there was no Grade 8 comparison class.

Table 3.1

Experimental and Comparison classes participating in this study

Year	Experimental Group		Comparison Group	
	Class	Participants	Class	Participants
2014	8E in 2014	25		
	9E in 2014	28	9C in 2014	27
2015	8E in 2015	21	8C in 2015	24
	9E in 2015	23	9C in 2015	24
	10E	28	10C	25

In order to determine whether the Grade 8 experimental and comparison classes were academically similar, National Assessment Plan – Literacy and Numeracy (NAPLAN) reading, writing and numeracy results were compared and are presented in *Table 3.2*. It was

found that there was no significant difference between the results in NAPLAN for reading, writing or numeracy in either of the groups. This indicates that we can confidently compare the results of pre- and post-tests for various diagnostic instruments used with these cohorts.

Table 3.2

Comparison of NAPLAN Results for Students of 8E in 2014, 8E in 2015 and 8C in 2015

Class	Reading Mean (SD)	Writing Mean (SD)	Numeracy Mean (SD)
8E in 2014	577 (70)	547 (77)	573 (78)
8E in 2015	602 (49)	524 (62)	600 (70)
8C in 2015	586 (56)	530 (45)	556 (58)
t-test (8E in 2014 & 2015) (<i>p</i>)	1.29 (0.20)	1.06 (0.30)	1.19 (0.24)
t-test (8E & 8C in 2015) (<i>p</i>)	0.94 (0.35)	0.34 (0.73)	2.07 (0.05)

In order to determine whether the Classes 9E in 2014 and 9C in 2014 were academically similar, NAPLAN reading and numeracy results, and students' previous year's final test and grade were compared and these results are presented in *Table 3.3*. The t-test analysis showed that there was no significant difference as measured by any of these four factors between the 9E in 2014 or 9C in 2014 groups.

Table 3.3

Comparison of Academic Performance of 9E in 2014 and 9C in 2014

Class	Reading Mean (SD)	Numeracy Mean (SD)	Grade 8 Final Test Mean (SD)	Grade 8 Overall Mean (SD)
9E in 2014	579 (50)	619 (66)	72.5 (11.0)	72.5 (10.5)
9C in 2014	578 (59)	609 (74)	73.1 (16.0)	71.7 (11.1)
t-test (9E & 9C in 2014) (<i>p</i>)	0.04 (0.97)	0.55 (0.58)	0.15 (0.88)	0.24 (0.81)

Comparison of NAPLAN results between 9E in 2015 and 9C in 2015 are shown in *Table 3.4* and also show no significant difference between groups. Similarly, comparison of 9E in 2014 and 9E in 2015 using t-tests showed no significant difference between NAPLAN Numeracy results, $t=0.23$ ($p = 0.82$), or between NAPLAN Reading results, $t = 0.49$ ($p = 0.63$). It is therefore appropriate to compare quantitative results from these classes.

In the second year of this study, students who had participated in learning using the TFA in Class 9E in 2014 continued to learn by this method in Grade 10. The experimental group is designated as Class 10E while the comparison group was named Class 10C. Only one student left the TFA group between Grade 9 and 10, while one new student who had not experienced learning with the TFA joined the class in Grade 10. 10E and 10C correspond

substantially with 9E in 2014 and 9C in 2014 and hence we may assume that the two classes are statistically similar in abilities on the basis of the data displayed in *Table 3.4*.

Table 3.4

Comparison of Academic Performance of 9E in 2015 and 9C in 2015

Class	Reading Mean (SD)	Numeracy Mean (SD)
9E in 2015	622 (49)	615 (62)
9C in 2015	633 (82)	638 (74)
t-test (9E & 9C in 2015) (<i>p</i>)	0.51 (0.60)	1.12 (0.26)

3.1.3 Participants - the teachers and parents

The school employed three science-trained teachers who possessed between 5 and 30 years of experience teaching Grades 8-10 science. I taught all the experimental groups using the TFA as a teacher-researcher. I had 10 years' experience teaching students from Grades 8-12 and hold a B.Sc. (Hons) and M.Sc. in Chemistry. I had taught senior physics, chemistry and biology. A male teacher with 30 years' experience teaching Grades 7-10 Science taught most of the comparison classes. The comparison class, 9C in 2015, was taught by a female teacher with a B.Sc. majoring in Chemistry and Biology and 5 years' experience teaching Grades 6-12 Science.

In addition to the science teachers of experimental and comparison groups, five teacher colleagues at the school participated in the study to share their observations and experiences with the TFA. One of those interviewed was an English teacher with a son in one of the experimental classes, another the acting principal of the school and three learning support aides (LSA), one of whom was also a trained primary teacher and another an experienced science teacher. The LSAs were frequently present in the classroom of the experimental group to support the learning of several students with additional needs such as Autism Spectrum Disorder (ASD), cognitive delays and high anxiety.

3.1.4 Design

This study was carried out as a two-year explanatory sequential mixed method design (Creswell, 2014) investigating the effects of the TFA as implemented in the teaching of a variety of science topics in Grades 8-10. Use of an explanatory sequential mixed methods approach in this case was appropriate as I firstly wanted to determine whether the intervention using the TFA resulted in the anticipated improvement in conceptual understanding and written explanations amongst students of the experimental group using

quantitative data (*Table 3.5: Research Questions 1a and b*). On the basis of these results I wanted to determine the degree to which each of the dimensions of conceptual change contributed to students' overall conceptual change through analysis of qualitative data from interviews. Interview participants were chosen on the basis of their quantitative results (*Table 3.5: Research Questions 2a and b*). The influence on the teacher's pedagogical practices due to implementation of the support that the TFA gave in addressing multidimensional aspects of conceptual change was examined through analysis of my reflections.

The choice of a quasi-experimental framework for collection of the quantitative data was appropriate as it allowed for comparison, where possible, between cohorts learning using traditional methods and those learning using the TFA. This was a quasi-experiment as it was not possible to randomly assign students to an experimental and control group, nor was it possible to assign the same teacher to both groups. However, the experimental and comparison groups were identified as similar in ability range. The teachers of both groups were all experienced teachers who consistently ensured that the same content and concepts were covered using the same demonstrations and many of the same discrepant events within the teaching cycle. Students in the experimental groups were taught by myself using the TFA. Students in the comparison classes were taught by experienced teachers using their usual teaching practices. The comparison groups were only used for the purpose of comparing the degree of conceptual change as determined by administration of diagnostic and other tests.

The TFA teaching sequences addressed the Australian Curriculum content descriptors and took place over the normal time allocated for teaching these concepts. The comparison group also had the same number of lessons on each topic as the experimental group. Teachers of the comparison groups used a variety of teaching methodologies: text book reading and answering questions, class discussions, watching explanatory videos, completing experiments as well as observing and discussing the demonstrations developed by myself to challenge students' alternative conceptions. As these lessons were running concurrently with the experimental group's lessons in many cases, it is beyond the scope of this thesis to analyse the methodologies used in detail.

The quantitative data collected compared experimental and comparison groups using diagnostic pre- and post-conceptual tests, evaluated experimental group students' written explanations over the period of implementation of the TFA using evaluation rubrics and compared students' explanatory writing from one test question, from one experimental and one comparison class.

In order to determine what influenced student conceptual understanding, writing and affective aspects of learning as well as the teacher's experience teaching using the TFA (*Table 3.5: Research Question 3*), participants were selected for interview on the basis of their quantitative results, and videos of lessons, semi-structured student interview transcripts, reflective journal entries and interviews with other teachers and parents were thematically coded and analysed.

3.1.5 Research questions

The research questions are organised below in *Table 3.5*, in the order in which they are addressed in the analysis sections of this thesis. Research Questions 1a, and b probe the effectiveness of the TFA on the epistemological and ontological level and are addressed in Chapter 4. Due to restrictions on the size of this thesis analysis of students' writing rather than drawings of their conceptual understanding are included. Research Questions 2a and b look at qualitative interview data to evaluate the experience of stakeholders while implementing the TFA in the classroom and to probe possible mechanisms by which the TFA affects student outcomes. Responses were analysed through the lens of the multidimensional conceptual change theory. These results are presented in Chapter 5. In order to obtain a richer description of learning through the TFA individual students whose results were representative of differing levels of conceptual change and who appeared to gain more or less benefit than expected from the intervention, were chosen for concentrated investigation as case studies (*Table 3.5: Research Question 3*). These results are presented in Chapter 6. Further qualitative data were collected from these students and the questions asked during these interviews were determined by the results of the quantitative data and answers to previous interview questions. The teacher's experience implementing the TFA is examined in Research Questions 4, and results are presented in Chapter 7.

3.2 The Thinking Frames Approach

The TFA was introduced in the teaching of a variety of science topics in Grades 8-10. Students were placed in small groups of 4-5 chosen by the teacher, made up of a key student (KS) who had shown ability to understand new concepts and be willing to explain to others and 3-4 other students who had been shown to work well with that student.

Table 3.5

Research Questions, Data Sources, Collection and Analysis

Research Questions	Data Sources	Data Collection Methods	Quality Measures	Data Analysis
Quantitative data probing the effectiveness of the TFA:				
1a) To what extent does the Thinking Frames Approach build scientific understanding of concepts and lead to epistemological and ontological conceptual change?	Grades 8 and 9 students in 2014 and 2015. Grade 10 students in 2015.	Pre-and post- and delayed post-diagnostic instruments, semi-structured clinical interviews	Peer debriefing, member checks	Comparison of results between pre and post tests and between comparison and experimental groups, analysis of conceptual test results in terms of ontological categories, triangulation with interview material, video recordings and student artifacts.
b) To what extent does teaching using the Thinking Frames Approach enable Grade 8-10 students to give coherent scientific explanations using written text?	Grades 8 and 9 students in 2014 and 2015. Grade 10 students in 2015.	Students' written explanations, other students artefacts	Prolonged engagement, persistent observation, peer debriefing, negative case analysis, member checks	Thematic coding of written artefacts and evaluation using rubrics. Comparison of written explanations for pre- and post-intervention and between experimental and comparison groups.
Qualitative data investigating experience of stakeholders during implementation of the TFA to determine mechanisms of action:				
2a) What do students perceive as the supporting aspects of TFA for learning science in terms of the epistemological, ontological and social/affective dimensions?	Grade 8-10 students in 2014 and 2015	Semi-structured clinical interviews	Prolonged engagement, persistent observation, peer debriefing, negative case analysis, member checks	Thematic coding of interviews, comparison between pre- and post-intervention.

b) What main features and benefits do other teachers observe during implementation of the TFA in terms of how it supports multidimensional conceptual change?	Teachers, Learning Support Aides, Acting Principal, Parents	Semi-structured clinical interviews, open-ended interviews, unsolicited comments	Prolonged engagement, persistent observation, peer debriefing, member checks	Thematic coding of interviews
Quantitative and qualitative data for individual students analysed:				
3. What can be learned about a multidimensional conceptual change approach from analysis of individual students' progress in learning with the TFA throughout the two years of the study?	Grade 8 students in 2014, Grade 9 students in 2014 and Grade 10 students in 2015	Semi-structured student interviews, pre and post-test diagnostic instruments, students' pictorial, written explanations, other student artefacts.	Prolonged engagement, persistent observation, peer debriefing, negative case analysis, member checks	Thematic coding, triangulation between interviews and video/audio lesson data, comparison between pre- and post-intervention. (grounded theory?)
Qualitative data from teacher's experiences:				
4. What were the affordances and limitations of the TFA in supporting me to implement a multidimensional approach to conceptual change?	Teacher researcher	Reflective journal, video and audio recordings of lessons	Prolonged engagement, persistent observation.	Thematic coding of reflections, audio and video transcripts of lessons and triangulation between these sources.

This is the sequence of typical TFA lessons. First, in order to challenge common alternative conceptions about this topic (Posner et al., 1982), demonstrations were developed. Before watching the demonstration, students were asked to predict what would happen in small groups and then discussed their predictions as a whole class. When the experiment was carried out, they were often surprised to find that their predictions were not correct. To explain what happened in the experiment, students were asked again to use the concepts that they had learned in previous lessons and discuss in their small groups and then present their ideas to the whole class. I then facilitated the whole class discussion. This part of the lesson is similar to the “Predict-Discuss-Explain-Observe-Discuss-Explain (PDEODE) teaching strategy (Coştu, Ayas, & Niaz, 2012; Savander-Ranne & Kolari, 2003) based on the Predict-Observe-Explain (POE) framework. Once they finished the group discussion, students then started filling out the TFA worksheets individually with group discussion as necessary. The structure of the TFA lessons, including the steps found in the TFA worksheets, are presented in *Table 2.1*.

After completing the worksheet, students evaluated their work, based on the rubric called Levels Mountain (LM) (Newberry et al., 2005) (Appendix B), in terms of how successfully their explanations address cause and effect and use scientific language. I then collected students’ TFA sheets at the end of the lesson. Some students asked to be able to complete a more comprehensive answer and bring it the next day. These were marked, feedback was given on how to give a higher-level answer as evaluated on the LM and any errors corrected and returned, usually the following day. Two forms of the TFA worksheets are available (Newberry, 2006; Newberry et al., 2011) (see Appendix B), one for answering questions explaining “how” something happens and one for use when explaining “why” something happens. These worksheets provide a sequence of steps to scaffold students’ production of explanations.

All of the TFA worksheets produced by the students were scanned, after grading, and kept for analysis. Lessons were recorded either on video or audio using Audacity™ software and transcribed. A journal which detailed observations and teacher reflections on the lessons was also kept.

3.3 The Lessons

Students in the experimental groups from Grades 8-10 studied a variety of topics using the TFA. Class 8E in 2014 completed 18 TFA lessons and 9E in 2014 completed 19 TFA lessons in the first year of the study. Class 8E in 2015 completed 23 TFA lessons, 9E in 2015 completed 18 TFA lessons and 10E completed 19 TFA lessons in the second year of the

study. I did not want to overuse the TFA in any particular topic at the risk of students becoming bored with its use. Therefore, between 3- 7 TFA lessons were presented per topic.

As I became more aware of students' alternative conceptions in the second year of the study and also became more proficient at developing appropriate TFA questions, I was able to refine and add to questions from the previous year. Since space is limited, the following seven topics were chosen to illustrate the implementation and results of teaching using the TFA: Physical sciences - thermal physics, Newtonian physics, electricity and energy; Biology – genetics and natural selection; and Chemistry - kinetic/particle theory of matter.

3.3.1 Thermal physics

Students experience heat in many contexts in their daily lives and hence they develop conceptual frameworks in order to explain and understand these phenomena which involve many alternative beliefs that are very resistant to change (Erickson, 1979). Some of the most widespread beliefs are that heat and cold are substances which flow from one place to another, that heat rises, that metals are intrinsically colder than other materials at room temperature, that temperature is a measure of heat and that temperature always increases when a substance is heated (Clough & Driver, 1985; Erickson, 1979; E. L. Lewis & Lin, 1994).

Many students appear to hold a 'Caloric' view of heat and heat transfer rather than one based on the kinetic theory of matter (KTM) (Carlton, 2000; Clough & Driver, 1985). This attachment to the Caloric Model, which historically linked temperature change with the amount of the material substance, caloric, it contained, demonstrates the matter-base ontological understanding that is most frequently held, rather than the process-based ontological understanding which relates particle movement and excitation with increased energy of a material (Slota et al., 1995). The matter-based ontological framework has been found to persist up until at least 16 years of age (Clough & Driver, 1985). In fact, students often complete courses in thermal physics without undergoing statistically significant conceptual change (Carlton, 2000; Thomaz, Malaquias, Valente, & Antunes, 1995) and even some adults who would be considered experts had difficulty applying the thermodynamic concepts in everyday situations (E. L. Lewis & Lin, 1994). Surprisingly then, the concept of thermal equilibrium, a cornerstone in understanding thermal energy transfer using the kinetic model, is addressed in a cursory manner in many textbooks (Thomaz et al., 1995).

During teaching of the thermal physics topic, students in both the experimental and comparison groups, 9E in 2014 and 9E in 2015, completed 12 lessons over three weeks in the topic of thermal physics. This links with the Australian Curriculum content descriptor, ACSSU182. As part of these 12 lessons the experimental group completed the six TFA

questions described in *Table 3.6*, each question being answered during one 50-minute period.

Table 3.6

Thermal Physics TFA Lessons

Lesson Topics	Guiding Questions
Thermal Equilibrium	Explain how the temperature changes when ‘hot’ (77°C) water is mixed with ‘cold’ (19°C) water.
Conduction	Explain why the drawing pins fell off the metal rods sooner than the glass rod when heated on the other ends.
Melting Ice	Explain why ice on the metal plate melted faster than on the ceramic plate
Convection	Explain how a whole room can heat up if a radiator is in the corner. How does double glazing help to keep the room warm?
Latent Heat	Explain why the temperature of water increases as we heat it from 0°C to 100°C but then stays at 100°C.
Heating a paper cup	Explain why a paper cup with water in it does not burn when placed over a Bunsen burner.

In 2015, Class 9E completed an extra TFA lesson about heat capacity. In 2014, Class 9E completed a question about latent heat of fusion rather than vaporisation.

3.3.2 Newtonian Physics.

Alternative conceptions of force and motion have been extensively studied (Clement, 1982; Finegold & Gorsky, 1988; Gunstone, 1987; I. A. Halloun & Hestenes, 1985; McCloskey, 1983; Watts & Zylbersztajn, 1981). The most common alternative conceptions are as follows: If there is motion, there must be a force acting; this leads to the impetus concept which suggests that, if an object is thrown, the force applied continues to be exerted even after letting go; equating position with velocity or velocity with acceleration; objects with greater mass fall faster; objects with a greater mass or the most active agent exerts a greater force- the dominance theory.

Students in Classes 10E and 10C studied Newton’s laws over a 23-lesson period in Semester 1 of the second year of this study. This links with the Australian Curriculum content descriptor, ACSSU229. Both groups watched videos, carried out experiments and completed question sets and problems from their text-books. Students were expected to solve simple mathematical problems involving calculations of such concepts as force and acceleration, velocity and momentum. In addition, students from Class 10E used the TFA to answer six questions related to Newton’s laws. The lesson topics and questions are found in *Table 3.7*.

Table 3.7

Summary of TFA Lessons on Newton's Laws

Lesson Topics	Guiding Questions
Newton's 1 st law: Inertia	Explain why paper can be pulled (quickly) from under a large beaker of water without the beaker moving
Newton's 2 nd law	Explain what will happen (and why) when a heavy car (4kg) attached to a light car (1kg) with a rubber band is stretched and released.
Newton's 3 rd law	What happens when you step off a skateboard and why?
Newton's 3 rd law and momentum	Why is it important to have a crumple zone on the front of your car?
Newton's 1 st , 2 nd and 3 rd laws	Explain why a car towing another car speeds up even though the force of car 1 on car 2 is the same as the force of car 2 on car 1.
Newton's 1 st , 2 nd and 3 rd laws	Explain why two balls of mass 1kg and 2kg thrown from a cliff at the same velocity hit the ground at the same place and the same time.

3.3.3 Electricity concepts.

Six different models of current, which are common amongst students, have been identified (Mélioui, Brassard, Levasseur, & Lavoie, 2007; Millar, 2006; Millar & Hames, 2002): the conservation model, the scientifically accepted model; the attenuation model, the current wears down as it goes around the circuit; the consumption model, different components of a circuit use up the current; the sharing model, current is shared equally between different parts of the circuit; the clashing currents model, positive and negative charges flow from either ends of the battery; the proximity model, a component closer to the battery gets a greater share of the current.

The topic of electricity, including the concepts of voltage, current, resistance in parallel and series circuits, was taught to Grade 9 students over 10 lessons at the end of semester 2 in 2014 and 2015. This links with the Australian Curriculum content descriptor, ACSSU182. Students were encouraged to use a water analogy to understand these concepts as well as Kirchhoff's laws. The experimental groups, Class 9E in 2014, completed three TFA lessons while Class 9E in 2015 completed four TFA lessons. These lessons are shown in *Table 3.8 and 3.9*. The TFA lessons given to Class 9E in 2015 were modified as a result of feedback from students of 9E in 2014, who found the TFA lessons challenging and insufficient to build understanding. Students of the comparison classes, 9C in 2014 and 9C in 2015, also completed lessons on these concepts in the topic of electricity and carried out similar experimental tasks without using the TFA to answer these questions.

Table 3.8

TFA Electricity Lessons Given to 9E in 2014

Lesson Topics	Guiding Questions
Voltage, current and resistance concepts	Explain how a simple series circuit with two lights in it works. (Use an analogy to explain and use the words voltage, current and resistance.)
Conservation of energy (Kirchhoff's 2 nd law)	Explain how (and why) a series circuit with two light bulbs is different in brightness from a parallel circuit with two bulbs.
Conservation of charge and energy (Kirchhoff's 1 st and 2 nd laws)	In a complex circuit with both series and parallel elements explain what each voltmeter and ammeter will read and why.

Table 3.9

TFA Electricity Lessons Given to Class 9E in 2015

Lesson Topics	Guiding Questions
Voltage, current and resistance concepts	Explain how a simple series circuit with two lights in it works. (Use an analogy to explain and use the words voltage, current and resistance.)
Conservation of energy (Kirchhoff's 2 nd law)	Explain why two lamps in series are dimmer than two lamps in parallel when the voltage of the battery is the same.
Conservation of charge (Kirchhoff's 1 st law)	Explain how a variable resistor in parallel with a lamp affects current in the circuit.
Conservation of charge and energy (Kirchhoff's 1 st and 2 nd laws)	Explain the reading on the ammeters in a series circuit with two 3 ohm resistors, a circuit with two 3 ohm resistors in parallel and the same circuit when the switch is open in the second loop.

3.3.4 Energy concepts.

Like many terms which are used in everyday conversation, students hold many alternative views of what energy is, based on their daily experiences. Watts (1983) identified seven different frameworks that students use when they are talking about energy. These include a belief that it is mostly living things that have energy; that certain things possess energy as if it were a material substance or produce energy when acted upon; that energy is created when something moves; that energy flows like a fluid and makes things work and is active for a short time before disappearing (Gilbert & Pope, 1986; Gilbert & Watts, 2008; Watts, 1983). High school science teaching has been largely ineffective in enabling students to transfer their alternative conceptions into more complex and scientifically acceptable conceptions (Driver, Rushworth, Squires, & Wood-Robinson, 2005).

Students hold these alternative conceptions and hence they often have difficulty understanding concepts such as energy degradation, transformation and conservation (Driver & Warrington, 1985). Analysis of the TIMSS data led Liu and McKeough (2005) to develop

a series of progressions that students move through in order to obtain a scientific understanding of energy. These progressions begin with an understanding that energy is something that gives the ability to do work, followed by the ability to distinguish different sources and forms of energy, understanding energy transfer, understanding that energy degradation means transfer of energy to less useful forms, and finally comprehending that energy is conserved. The topic of conservation of energy is often only addressed superficially in high school and in ways that do not aid the integration of learning across these progressions (Linn & Eylon, 2006).

At the end of semester 1 of the second year of the study a nine-lesson unit introducing energy concepts, including forms of energy, transformation of energy, degradation of energy and conservation of energy, was delivered to two Grade 8 classes, one of which was taught using the TFA (8E in 2015) while the other acted as a comparison group (8C in 2015). This links with the Australian Curriculum content descriptor, ACSSU155. A summary of the four TFA lessons on energy is found in *Table 3.10*.

Table 3.10

Summary of TFA Lessons Given to 8E Students Studying Energy Concepts

Lesson Topics	Guiding Questions
Forms of energy and energy transformation	Explain how a cheezel™ can be used to heat water.
Forms of energy and energy transformation	Explain how electricity is formed in a coal fired power station.
Energy transformation and degradation	What happens when a bike rider at the top of the hill lifts his feet off the pedals? Why? (There is a horizontal section at the bottom of the hill.)
Energy conservation	A car is driving along and hits a wall. It comes to a stop. Explain how the law of conservation of energy is obeyed in this situation.

3.3.5 Genetics

Genetics has consistently been found to be a very difficult topic for students to achieve conceptual understanding and change and they struggle with the linguistic difficulties posed because of the large number of unfamiliar specific scientific terms (Bahar, Johnstone, & Hansell, 1999; Hackling & Treagust, 1984; Johnstone & Mahmoud, 1980). One reason that students find genetics difficult is that it requires thinking on macro, micro, sub-micro and symbolic levels (Johnstone, 1991).

Students also tend to see genes as particles or sections of a chromosome rather than as the process by which data in the form of a base sequence is read and results in the production of a protein (Venville & Treagust, 1998). In terms of the categories of ontological understanding of the world described by Chi et al. (1994), genes belong to process-based

ontology: genes are copied by the *procedure* of mitosis, passed to offspring by the *procedure* of meiosis. Both these processes are *events* that occur at a specific time. The reading of the genes involves a *constraint-based interaction* where recessive genes are not read if dominant ones are present (Tsui & Treagust, 2004a). However, textbooks and teacher talk often uses the analogy of genes as particles on a chromosome (Tsui & Treagust, 2004a) A focus on Mendelian genetics in high school leads to a matter-based ontology rather than a process-based one. Mendelian genetics should be taught in the context of reading of genes to produce proteins that result in certain effects within chemical processes in the body.

As well as this conceptual change that must take place on the ontological level, students also hold many alternative conceptions in terms of their epistemological understanding. For instance students believe that specific types of cells only contain the genetic code that they need to do their job, that mitosis is not associated with growth (Hackling & Treagust, 1984); they have limited understanding of the structure and location of genes (J. Lewis, Leach, & Wood-Robinson, 2000a) or are unaware that cell division in mitosis involved copying of chromosomes (J. Lewis, Leach, & Wood-Robinson, 2000b).

Tsui and Treagust (2010) identify six different types of reasoning which students must master in order to gain a scientific understanding of genetics (adapted from Hickey, Wolfe and Kindfield (2000) and reproduced in Figure 3.1).

		Domain-general dimension of reasoning (Novice ← → Expert)		
		Cause-to-effect reasoning	Effect-to-cause reasoning	Process reasoning
Domain-specific dimension of reasoning (simple ← → complex)	Between-generations	Monohybrid inheritance: Mapping genotype to phenotype (Type II)	Monohybrid inheritance: Mapping phenotype to genotype (Type IV)	Punnett squares (input/output reasoning): Meiosis process (event reasoning) Mitosis process ^a (Type VI)
	Within-generations	Mapping genotype to phenotype (Type I)	Mapping phenotype to genotype (Type III)	Mapping information in DNA base sequence (genotype) to amino acid sequence in protein synthesis (phenotype) ^b (Type V)

Figure 3.1. Six Reasoning types tested in the SRG (Tsui & Treagust, 2010)

Students in Grade 10 completed a unit on Introductory Genetics in Semester 2 of the second year of this study. All Grade 10 students completed a series of 20 lessons on genetics involving questions and problem sets found in their text-book. This links with the Australian Curriculum content descriptor, ACSSU184. The experimental group, 10E, used the TFA to explain the answers to seven genetics questions. I designed a teaching programme which addressed the six reasoning types described in Figure 3.1. A summary of the TFA lessons on genetics is found in *Table 3.11*.

Table 3.11

Summary of TFA Lessons Given to 10E on Genetics

Lesson Topics	Guiding Questions (Reasoning Type)
DNA as a code bearer from cell to cell	What characteristics of DNA allow it to copy itself and transmit the information carried from cell to cell as new cells are made? Students used string and pegs to model DNA replication (V).
Identifying the amino acid sequence from the DNA base sequence	Explain how the cells in your iris know to produce melanin (V).
Meiosis reasoning– different chromosomes may carry different alleles. Formation of gametes	One of the homologous chromosomes has the gene for skin colour red and one for green. The cell containing these homologous chromosomes undergoes meiosis. Four sperms are formed. Explain how this happens and how many sperm carry the gene for red skin colour (VI).
Identifying genotype from phenotype in a monohybrid cross	If the gene for brown eye colour (B) is dominant over the gene for blue eye colour, (b) explain why two brown-eyed parents can have a blue eyed child (IV).
Co-dominance Identifying genotype from phenotype	‘Jose Luis (blood group ‘O’) marries Antonia (blood group ‘A’). They would like to know which blood groups their children might have. Antonia’s father was blood group ‘B’: (a) Can you say which blood groups Jose Luis and Antonia’s children might have? (b) What is the probability in each case?’ (IV) (Banet & Ayuso, 2003)
Using Punnet squares/ meiosis reasoning	The coat colour characteristic in cats is co-dominant, sex-linked. Can a male cat be tortoiseshell in colour? (VI)
Using Punnet squares/ meiosis reasoning	Students were given a pedigree and had to use their Punnett squares to work out if the characteristic was dominant/recessive/sex-linked.(VI)

3.3.6 Natural selection

The topic of natural selection is also a topic that students find conceptually challenging (Clough & Wood-Robinson, 1985). A number of non-scientific ontological frameworks are observed amongst high school students, for instance: teleological understanding of adaption and change as being part of a plan or having a purpose; the Lamarckian concept of change because of a driving need, anthropomorphic explanations which explain that an animal understands the need for change and therefore works to change itself (Clough & Wood-Robinson, 1985, 2010).

As students learn more about the processes of natural selection, a variety of alternative conceptions become apparent in students' epistemological understanding. Banet and Ayuso (2003) produced a comprehensive list of alternative conceptions in genetics and natural selection. Students, for instance, believe that mutations are always harmful and negative (Cho, Kahle, & Nordland, 1985), adaptations occur in all individuals of a population (Bishop & Anderson, 1990), students don't relate understanding of genetics to the source of variation within a population or the transmission of characteristics to the next generation (Clough & Wood-Robinson, 1985).

The topic of natural selection was taught to Grade 10 students at the end of Semester 2 in the second year of this study. This links with the Australian Curriculum content descriptor, ACSSU185. Both the experimental group, 10E, and the comparison group, 10C, used the text-book, an online simulation of natural selection in pepper moths and videos to learn about natural selection. Three TFA lessons were given as part of a seven lesson unit on natural selection to students of the experimental group, 10E. These TFA lessons are summarised in *Table 3.12*.

Table 3.12

TFA Lessons on Natural Selection Given to Class 10E

Lesson Topics	Guiding Questions
Mechanism of natural selection – increase in predation	Explain how natural selection works using the example of the pepper moth.
Natural selection – change of food source	Explain how iguanas from South America adapted to life on the Galapagos islands using the ideas of natural selection.
Natural selection and co-evolution	Cheetahs (large African cats) are able to run faster than 100 km per hour when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could run only 30 km per hour? (Nehm & Reilly, 2007)

3.3.7 Kinetic and particle theory of matter

Alternative conceptions in the KTM were discussed in 3.3.1. Students' alternative conceptions about the particle theory of matter have also been extensively studied (Garnett, Garnett, & Hackling, 1995). Some commonly held alternative conceptions include: Atoms expand when heated, they can be seen under a microscope, there is no space between particles or there is a lot of space between particles in a liquid, gas molecules are orderly, melting and boiling break covalent bonds, air escapes when things boil, bubbles in boiling water are made up of air, hydrogen or oxygen, when liquids evaporate there is a decrease in mass (Andersson, 1990; Gabel, Samuel, & Hunn, 1987; Gilbert, Osborne, & Fensham, 1982; Novick & Nussbaum, 1978, 1981).

Kinetic and particle theory of matter was taught as two consecutive units in the second semester of the first year of the study to 8E in 2014 and in the second year of the study to 8E in 2015 over a total of 14 lessons. This links with the Australian Curriculum content descriptor, ACSSU151 & 152. On the basis of what I had learned about students' alternative conceptions in the first year of the study, I modified and expanded the number of TFA questions in the second year. The sequence of TFA lessons for this topic is found in *Table 3.13*. Extra TFA topics given to 8E in 2015 are shown in italics.

Table 3.13

TFA Lessons on Kinetic and Particle Theories of Matter

Lesson Topics	Guiding Questions
Particles move faster when heated and take up more space.	Explain how an empty flask with a tube coming out of it can be made to blow bubbles in water.
Diffusion in gases	Explain how the smell of a candle travels from one end of the room to the other. Which travels faster, a gas in a vacuum or one with air present? Why?
Gases take up much more volumes than liquids	Explain how the particle and kinetic theories of matter can explain what happens when things heat up and change state. (<i>A can with a small amount of water, heated, inverted into cold water. Can crumples. Explain why the can implodes.</i>)
<i>Liquids cannot be compressed. They transfer pressure.</i>	<i>Two syringes filled with water and attached by a rubber hose. Students try to compress the water. TF question: Explain why we use brake fluid in our car's brakes.</i>
Density	Explain how Archimedes was able to tell that the crown was not made of pure gold.
<i>Conservation of mass</i>	<i>Mass of acetone in a flask before and after heating. TF question: Explain what happens to the particles in a liquid when they evaporate</i>
Dissolving	What happens when a salt is dissolved in water? How do we know this isn't a chemical change?
Atomic nature of matter	How and why are pure helium and pure carbon different from one another?
Atoms rearrange when reactions happen	(Using molymod™ kits) Explain what happens when oxygen and hydrogen molecules combine. How do we know this is a chemical reaction?
Conservation of matter	How and why do we write a balanced equation for the reaction between hydrogen and oxygen (Molymod™ kits)

3.4 Instruments for Conceptual Understanding

Various instruments were sought that could be used to measure the extent of students' conceptual change in each topic as a result of learning with the TFA (see *Table 3.14*). Students' results were used to answer Research Question 1a. These instruments allowed students to choose between common alternative conceptions and scientific explanations. Although there are many tests to measure conceptual understanding for a variety of topics in

the literature, not all tests were of an appropriate level of difficulty for the grade level of the students in this study or did not contain appropriate questions probing the content being addressed. The tests, which were finally chosen as appropriate, are described below and were administered to students before learning in the topic commenced. There were two purposes for this pre-test: to provide a baseline result to assess change in students' conceptions after teaching using the TFA, and to determine the range of alternative conceptions which the students held in order to design appropriate learning experiences which would challenge these conceptions.

Table 3.14

Instruments used to measure conceptual change

Topic (No of items)	Instrument	Cronbach's Alpha	Source
Thermal Energy (26)	Thermal Concept Evaluation (TCE)	0.72 (N=100)	(Yeo & Zadnik, 2001)
Newton's Laws (29)	Force Concept Inventory (FCI)	0.72 (N=53)	(Hestenes et al., 1992)
Electricity (10)	Evidence Based Practice in Science Education (Set 2) (EPSE-Set2)	0.83 (N=148)	(Millar, 2002)
Energy (17)	Energy Concept Assessment (ECA)	0.71 (N=58)	(Neumann, Viering, Boone, & Fischer, 2013)
Genetics (11)	Scientific Reasoning in Genetics (SRG)	0.70 (N=172)	(Tsui & Treagust, 2010)
Natural Selection (20)	Concept Inventory of Natural Selection (CINS)	0.79 (N=50)	(D. L. Anderson, Fisher, & Norman, 2002)
Natural Selection	Open Response Instrument (Cheetahs and Natural Selection) (ORI)	n/a	(Nehm & Reilly, 2007)
Kinetic and Particle Theory of Matter (20)	Evidence Based Practice in Science Education (Set 8) (EPSE-Set 8)	0.73 (N=53)	(Millar, 2002)

Immediately following the teaching period, students were given the appropriate instrument as a post-test in order to assess conceptual change and to determine those alternative conceptions that persisted in students' understanding. Students were not informed of the correct answers after completing the pre- or post-tests. They were told their scores on each component. In some cases, students were also given the instrument after a prolonged period of approximately six months to determine whether the conceptual change that had taken place over the teaching period had persisted and to evaluate whether there were particular alternative conceptions that returned to prominence over time. No further teaching of the topic occurred during this six-month period.

3.4.1 The Thermal Concept Evaluation (TCE) instrument

The Thermal Concept Evaluation (TCE) is an instrument developed and tested by Yeo and Zadnik, (2001), which consists of 26 multiple-choice items designed to assess students' understanding and alternative conceptions in this topic, by presenting everyday scenarios and asking students to choose between a scientific explanation and various common alternative explanations of those observations. The TCE was found to have construct validity and has been successfully used to investigate students' alternative conceptions in thermal physics and as a pre-/post-test to determine the extent of conceptual change (Baser, 2006; Chu, Treagust, Yeo, & Zadnik, 2012; Yeo & Zadnik, 2001).

The TCE was administered to 9E in 2014 as a pre- and post-test and again after six months as a delayed post-test. The TCE was also administered to 9C in 2014 as a post-test after finishing the unit on thermal physics and as a pre- and post-test by 9E in 2015 and 9C in 2015. The internal consistency of the TCE results was satisfactory (Cronbach's alpha =0.72, $N=100$).

3.4.2 The Force Concept Inventory (FCI)

The Force Concept Inventory (FCI) was developed by Hestenes, Wells and Swackhamer (1992) for use as a diagnostic tool to determine the level of conceptual understanding of Newton's Laws amongst students of senior high school and university. It consists of 29 multiple-choice items, which present contexts followed by a choice between "common sense" alternative conceptions and the scientific explanation in the areas of Newton's first, second and third laws, superposition, types of forces and kinematics. The authors identify the two most persistent alternative conceptions amongst students as "the impetus concept of motion" and "the conflict concept of interaction" (Hestenes et al., 1992).

The FCI has been widely used by researchers (Bayraktar, 2009; Caballero et al., 2012b; Hake, 1998; Savinainen & Scott, 2002b) and its total score results have been validated and found to be remarkably reliable (Savinainen & Scott, 2002a), particularly as a measure of how well students understand the Newton force concept (Hestenes & Halloun, 1995; Lasry, Rosenfield, Dedic, Dahan, & Reshef, 2011). However, the consistency of individual items has been questioned (Lasry et al., 2011) and there has been some concern over the validity and interpretation of the FCI (Huffman & Heller, 1995).

Hestenes et. al. (1992) suggest that a score of at least 60% is required to begin to effectively solve problems in Newtonian physics, while Halloun and Hestenes (1995) consider a score of 85% or above indicates that a student has attained mastery of Newtonian concepts.

In the second year of the study, students in 10E and 10C were given the FCI as a pre-test and then as a post-test immediately after completing a course on Newtonian physics. Students in 10E were also given the FCI as a delayed post-test six months after studying Newton's Laws, without further instruction. The internal consistency of the FCI results was satisfactory (Cronbach's $\alpha = 0.72$, $N=53$).

3.4.3 Evidenced-Based Practice in Science Education (EPSE) Set 2

The Evidence Based Practice in Science Education Network was a collaboration between researchers at the Universities of York, Leeds, Southampton and King's College London to develop question sets which probed students' commonly held conceptions in a variety of topics in order to measure the effectiveness of classroom teaching practice at Key Stage 2, 3 and 4 (Middle School and High School level). The EPSE Set 2 (Millar, 2002; Millar & Hames, 2002) is a 10-item test; the first eight questions are two-tiered and students choose between common alternative conceptions and the scientific conception followed by a choice of explanations. Both tiers must be correct for the student to be marked correct. Question nine has three parts describing students' understanding about current in different parts of a series circuit. All three parts must be correct to gain a mark. Question ten is a single question which allows students to choose between four multiple-choice alternatives.

EPSE Set 2 responses allow a choice between the six different models of current which are common amongst students (Métoui et al., 2007; Millar, 2006; Millar & Hames, 2002), described in Section 3.3.3. Students' choices within the EPSE Set 2 make the underlying model that they hold evident. Millar and Hames (2002) and Maichle (1981) found that the most popular alternative model amongst Grade 9 students was the attenuation model.

Students' understanding of electrical current was tested using the EPSE Set 2 and administered as pre- and post-tests to 9E in 2014, 9E in 2015 and 9C in 2015. The internal consistency of the EPSE Set 2 test results was good (Cronbach's $\alpha = 0.83$, $N=148$).

3.4.4 The Energy Concept Assessment (ECA)

The Energy Concept Assessment (ECA) was developed and validated with extensive testing by Neumann, Viering, Boone and Fischer (2013) in order to investigate learning progression of students across Years 6-10 in terms of understanding of the four main characteristics of energy (Duit, 1986): forms and sources, energy transformation and degradation and energy conservation. It consists of multiple-choice questions which present a context with a diagram, for instance a hydroelectric dam and power station. Four choices, made up of common alternative explanations and a scientifically accurate explanation, are given to the students. In addition to the initial contextual information and question, some items are also

given between one and three additional pieces of information in order to gradually reduce the complexity of the question. It was found (Neumann et al., 2013) that the test had good validity and that students had the least difficulty understanding forms and sources of energy, followed by transformation of energy. Even students of higher grades had considerable difficulty understanding the concepts of energy degradation and conservation.

From Neumann et. al.'s list of questions and additional information I chose 17 items: five of which addressed forms and sources of energy, four of which addressed the concept of transformation of energy, four of which addressed degradation of energy and four of which addressed conservation of energy. Within each of these categories I left at least one item at the highest complexity without any additional information, an item where one extra piece of information was added, an item with two pieces of extra information, and an item with three extra pieces of information (see Appendix D).

In Semester 1 of the second year of the study, students in 8E were given the ECA as a pre-test before learning about energy. They were then taught using the TFA and given the ECA as a post-test and a delayed post-test, six months after the teaching period. The students of the comparison group, 8C, were given the ECA as a post-test. The internal consistency of the ECA results was satisfactory (Cronbach's $\alpha = 0.71$, $N=58$). The correct answers to the ECA were not revealed to the students after completing the pre- or post-tests.

3.4.5 The Scientific Reasoning in Genetics instrument (SRG)

Tsui and Treagust (2010) developed a two-tiered diagnostic instrument in order to investigate scientific reasoning amongst secondary students in genetics (SRG). The instrument was designed for use as a pre- and post-test to evaluate students' understanding of genetics and to determine the efficacy of teaching methods. Two-tiered tests allow a greater analysis of students' alternative conceptions (Treagust, 1988). An answer is not deemed to be correct unless both tiers, the answer and the reason, are answered correctly.

The SRG is a 12 item two-tiered test found to be a reliable instrument to test genetics reasoning (Tsui & Treagust, 2010) based on the six reasoning types of Figure 3.1 and containing genetics scenarios with multiple-choice answers combined with multiple-choice reasons that correspond to common alternative conceptions. There is a pre- and post-test form of the SRG. The content of the questions in both forms is essentially the same with variations in the scenarios presented. It was discovered after giving the post-test that one of the questions, question 10, did not provide any correct answers, so this question and the corresponding question in the pre-test were removed from the test results. The pre-test was given to both 10E and 10C before teaching. The post-test was given to both groups directly

after teaching of the unit was complete. The internal consistency of the SRG test results was satisfactory (Cronbach's alpha =0.70, N=172).

3.4.6 Concept Inventory of Natural Selection (CINS)

The CINS (D. L. Anderson et al., 2002) is a 20 item test which consists of various scenarios followed by multiple-choice questions based on those scenarios and provides a choice between scientific and common alternative conceptions. It was developed for testing undergraduate university students' understanding of evolution and the process of natural selection. The test is based on five essential facts and three inferences of Mayr (1982) which lead to the following ten concepts that form the basis of understanding of natural selection: biotic potential, stable populations, limited natural resources, limited survival, variation within a population, variation inherited, differential survival, change in populations, origin of variation, and origin of species (D. L. Anderson et al., 2002). The concepts that university students had the most difficulties with and hence held the greatest proportion of alternative conceptions were: the fact that variations occur randomly, change in the proportion of alleles in a population over time result in change within that population, and evolution of new species (D. L. Anderson, 2003).

The CINS has been used by several researchers to evaluate conceptual understanding and change in natural selection (D. L. Anderson et al., 2002; Andrews, Leonard, Colgrove, & Kalinowski, 2011; Nehm & Schonfeld, 2008). Nehm and Schonfeld's study suggested that, while the CINS is valid and reliable, it does not provide sufficient evidence of students' alternative conceptions. These objections were answered by Anderson, Fisher and Smith (2009).

Conceptual understanding of natural selection was measured using the CINS before and after teaching of the topic to Classes 10E and 10C. The internal consistency of the CINS test results was satisfactory (Cronbach's alpha =0.79, N=50).

3.4.7 Open Response Instrument – cheetahs and natural selection.

Nehm and Reilly (2007) developed an Open Response Instrument to measure students' conceptual understanding of natural selection as an alternative to the CINS and compared results from both tests. They suggest that the ORI gives a more accurate indication of how well students have understood the processes that occur for natural selection to take place. Studies suggest that this is a task which students find more difficult than completing the CINS (Nehm & Schonfeld, 2008).

The Open Response Instrument (ORI – cheetah) (Andrews et al., 2011) is a pen and paper task which asks students the following question: "Cheetahs (large African cats) are

able to run faster than 60 miles per hour when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could run only 20 miles per hour?" (Nehm & Reilly, 2007). Students' written explanations were graded according to the rubric of Andrews et al. (2011) designed specifically to evaluate answers to ORI- Cheetah with a maximum score of nine points. This rubric gives greater weight to three core concepts: the variation of phenotypes found within any population, genes and hence characteristics are passed on from parent to offspring, selective pressures result in some individuals having greater reproductive success due to the characteristics that they display. The three other concepts measured with this rubric were considered to be more advanced concepts and hence were given lower weighting.

In order to further determine students' understanding of the process of natural selection in terms of the ontological framework, Class 10E were given the ORI-Cheetah instrument as a post-test after completing the unit on Natural Selection.

3.4.8 Evidenced-Based Practice in Science Education (EPSE) Set 8

Validated conceptual tests for particle theory of matter concepts of an appropriate level for Grade 8 were not available. The Evidence-Based Practice in Science Education (EPSE) Set 8 (Millar, 2002; Millar & Hames, 2002) is a test which was developed in order to probe students' understanding of the particle model of matter in terms of changes of state (Q1), representations of particles in a gas (Q6) and linking of pictorial representations with ideas about physical and chemical change in elements, mixtures and compounds (Q7-10), a total of 20 items. Answers to questions 2-5 of Set 8 were excluded from both the pre- and post-test results because of difficulty in scoring and ambiguity of questions. The internal consistency of the EPSE (Set 8) results was satisfactory (Cronbach's $\alpha = 0.73$, $N=53$).

Question types vary from multiple-choice, multiple-choice combined with open-ended explanation provided by students, True/False and drawings by students. EPSE Set 8 was given to students of 8E in 2014, 8E in 2015 and 8C in 2015 as pre- and post-tests.

3.5 Evaluation of Written Explanations

In order to address Research Question 1b two frameworks were used to evaluate students' written explanations. At the end of each TFA lesson, students' work was evaluated using the Level's Mountain (LM). Since the LM framework is less well known and validated than the Claim, Evidence and Reasoning framework, both frameworks were used to determine the extent and characteristics of the change in student writing as a result of learning using the TFA.

3.5.1 The Level's Mountain

Students' written explanations were graded at the end of each lesson on the basis of a modified LM framework based on the Levels Mountain and Literacy Ladder rubrics developed by Newberry et al. (2005) to support students in visualising their progression in explaining scientific concepts (Appendix B). The 'paragraph' sections of student worksheets were categorised as follows: Level 1, simple description or inaccurate explanation; Level 2, description of what happens without explanation or limited explanation; Level 3, simple relationship between cause and effect; Level 4, extensive explanation of cause and effect accurately using scientific language; Level 5, successful application of concepts learned in a less familiar situation with elaborated explanation of cause and effect using scientific terminology. Examples of student writing at each level is found in *Table 3.15*.

Table 3.15

Examples of Writing Levels in answer to the TFA question: Explain why cars have crumple zones at the front.

Level	Example of student writing at this level
1	A car has a crumple zone which is designed to protect important parts in a car when it crashes. The crumple zone is also used to stop the energy in a collision.
2	Cars with a crumple zone reduces passenger's injury when it collides with an object, as the change of momentum is less (impulse). Upon impact the crumple zone increases the time before impact and before the collision comes to where the passengers would be. In the impact the passengers would fly forward because of inertia.
3	When there is a crumple zone in a car, it takes the force applied by the pole on the car which makes it have zero momentum, and extends it over a longer time, making the effect on the car smaller, which in turn puts less damage on the car and the passenger.
4	Cars have crumple zones on them to protect them. When two cars crash there is a huge amount of momentum. Impulse is the change in momentum and impulse is force x time. When the crumple zone is crumpled in a crash, the plastic and other materials give extra time before the momentum reaches the passenger. As impulse is force x time, the more time the crumple zone provides, the less force the passengers will experience.
5	Cars include crumple zones to reduce the effect of accidents. For example, if a 1000kg car driving at 30 m/s crashed into a pole this would cause a change in velocity from 30m/s to 0 m/s resulting in a big change in momentum. Because of this change in momentum there is a big impulse. In this case the cars change in momentum is -30,000kgm/s. The formula, Impulse=force x time, enables us to rearrange force to the subject to help us to see the impact on the car. $-30,000 = F \times 0.1s$. $F=300,000N$. This means that without crumple zones the force on the car is huge and dangerous for the passengers. Including crumple zones allow the time on the impulse to slow down and results in less force. For example, $30,000=F \times 10s$. Force = 3,000N. As you see crumple zones provide less destructive results.

3.5.2 The Claims, Evidence and Reasoning framework

Written explanations were also analysed using the simplified base explanation rubric of McNeill, Lizotte, Krajcik and Marx (2006) based on the framework for evaluating arguments developed by Toulmin (1958). This framework has been used by many researchers to evaluate written arguments in science. Studies have shown that students struggle to use appropriate evidence in their explanations (Sandoval, 2003), tending to present their personal ideas (Hogan & Maglienti, 2001). When they do provide evidence to support their claims, students frequently do not provide reasoning to explain how the evidence supports the claim (Jimenez-Aleixandre, Rodriguez, & Duschl, 2000) or link that reasoning to the underlying scientific theory or model (Lizotte, Harris, McNeill, Marx, & Krajcik, 2003). This rubric was modified to include assessment of whether the explanations were conceptually correct (McNeill & Krajcik, 2008) and evaluated the claims, evidence and reasoning (CER) presented by the students. Specific rubrics were produced for each TFA lesson that was evaluated. These rubrics are found in Appendix E.

3.6 Semi-structured Interviews

In order to answer Research Question 2a and b, evaluating the mechanisms by which the TFA resulted in bringing about changes in conceptual understanding, writing explanations and feelings of self-efficacy, students and teachers were selected to participate in interviews. The selection process was determined by students' results in terms of the quantitative data. As much as possible, students with a variety of levels of improvement or experiences were chosen. This choice was constrained by the fact that not all students were willing to participate in interviews.

Detailed semi-structured interviews about students' experiences learning with the TFA, attitudes to learning science and feelings of self-efficacy were carried out at the end of Semester 1 with 24 students from 8E in 2014 and with 23 students from 9E in 2014. At the end of Semester 2 in the first year of the study 15 students from 8E in 2014 and 15 students from 9E in 2014 were interviewed and encouraged to elaborate on their answers to the semi-structured interview questions. At the end of the second year of the study five students from 8E in 2015 and twelve students from 9E in 2015 were interviewed, seven individually and five as a group; and 16 students from 10E in 2015 were interviewed, four individually and twelve students in a large group interview while two of these students were interviewed for further clarification of issues that arose after analysis of the interviews at the beginning of the following year.

The final interviews given at the end of each year of the study lasted for 33 minutes on average, were recorded using Audacity™ audio software, and were then transcribed.

Students' names were replaced with pseudonyms for the participants' privacy. The questions used for semi-structured interviews after teaching the TFA are found in Appendix F.

3.7 Data Analysis

3.7.1 Analysis of pre- and post-test instruments

Individual questions on pre-/post-test instruments are based on common alternative conceptions held by students and changes between pre- and post-test results were used to determine the degree of conceptual change in the epistemological dimension, as students transfer their allegiance from alternative to scientific conceptions in specific areas. Participating students' answers to the pre- and post-test instruments were collected and the mean and standard deviations of the results were obtained. Results from the pre- and post-test (and delayed post-test where appropriate) from the experimental groups were compared using two-tailed paired t-tests using the online statistical package found at <http://vassarstats.net/index.html>. The results from the post-tests of comparison groups were also compared with those of the appropriate post-test from the experimental groups using independent two-tailed two-sample t-tests. Care was taken to ensure that consistent data sets were used by presenting comparing student results from those students who were present for both pre- and post-tests.

Where there was sufficient data from both experimental and comparisons groups, two-factor analysis of variance (ANOVA) test, with repeated measures as appropriate, were carried out. The results from multiple regression analyses were presented in place of the ANOVA tests as they provide a more detailed picture of the factors influencing learning.

Multiple regression analyses were used to test which factors most influenced post-test results. Theobald and Freeman (2014) suggest that when evaluating the effect of an intervention on student post-test scores, other factors such as previous learning and differing abilities between members of classes can falsely produce results which indicate that the intervention has resulted in a statistically significant difference between classes. For this reason, they suggest using a multiple regression analysis using centred data (the value for each student is determined by subtracting the mean value from each student's raw results) from other tests to ensure that the effect is as a result of the treatment rather than these other factors. Students' NAPLAN scores for numeracy and reading were available and hence these were used as standardised measures of students' abilities in these areas, together with the pre-test results, and compared with post-test results. NAPLAN results had a range of 250 points and therefore students' results were centred and then divided by 10 in order to make comparisons with the effect of pre-test scores more meaningful. The relationship between

post-test scores and the various factors tested may be represented according to equation (example from comparison of TCE results)

Post-test score = $\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k$ where

- β_0 is the expected TCE post-score with an average pre-score, NAPLAN reading and numeracy results of those who did not receive the treatment.
- β_1 is the expected increase in the TCE post-score for each additional 10 points on the NAPLAN Numeracy test.
- β_2 is the expected increase in the TCE post-score for each additional 10 points on the NAPLAN Reading test.
- β_3 is the expected increase in the TCE post-score for each additional point on the students' pre-score.
- β_4 is the expected increase in the TCE post-score for students who were taught using the TF approach relative to students who experienced the TFA intervention.
- β_5 is the expected increase in TCE post-score if gender is male rather than female

For each item in the pre- and post-tests the percentage of students choosing each alternative was determined and summarised in terms of scientific and alternative conceptions. If appropriate, data were also grouped in conceptual areas and the means and standard deviations determined and results compared using two-tailed, paired t-tests.

In cases where students were tested for conceptual understanding before and after learning, it was appropriate to compare the size of the difference between these two measures using the Cohen's effect size (d) (J Cohen, 1969; Rosenthal, 1994). This is an effective measure for quantifying the effect of the teaching which has taken place (Coe, 2002) and is thought to allow comparison of the effect across studies (Nakagawa & Cuthill, 2007; J. R. Thomas, Salazar, & Landers, 1991). As a more accurate measure of Effect Size I used the pooled standard deviation to calculate this value (Becker, 2000; Rosnow & Rosenthal, 1996). The formula used was $d = (M_1 - M_2) / \sigma_{\text{pooled}}$, where $\sigma_{\text{pooled}} = \sqrt{[(\sigma_1^2) + (\sigma_2^2) / 2]}$ and M_1 and M_2 are the means for each test. A small effect size is considered to correspond to a value of $d < 0.2$, medium effect size $0.2 < d < 0.8$, large effect size $d > 0.8$ (J. Cohen, 1988)

The Hake's normalised gain measure has been used extensively in analysing the FCI to determine the gain in post-test scores over pre-test scores compared to the maximum possible gain (Hake, 1998, 2002).

$$\langle g \rangle = \frac{\langle S_{\text{post}} \rangle - \langle S_{\text{pre}} \rangle}{100\% - \langle S_{\text{pre}} \rangle}$$

where $\langle S_{pre} \rangle$ and $\langle S_{post} \rangle$ are the mean of the pre and post test results. Hake classified the normalised gain as follows: low gain, $\langle g \rangle < 0.3$; medium gain $0.3 < \langle g \rangle < 0.7$; high gain $\langle g \rangle > 0.7$.

Pre- and post-tests were also analysed in terms of ontological conceptual categories, where appropriate. For instance, answers to EPSE 2 can be analysed in terms of a variety of underlying ontological frameworks, including the scientific conservation framework (Millar & Hames, 2002). Similarly, the FCI questions can be grouped and analysed in terms of students' overall understanding of Newton's 1st, 2nd, 3rd laws and kinds of forces (Hestenes et al., 1992), and the ECA questions can also be grouped to determine students' understanding of forms of energy, transformation, degradation and conservation of energy (Neumann et al., 2013). Likewise, the SRG questions can be organised by reasoning type to give an indication of the degree to which students have progressed from a matter-based to a process-based understanding of genetics (Tsui & Treagust, 2010). The CINS questions provide answers based on a Lamarckian framework as well as a Darwinian framework and so can be used to determine the degree of ontological transfer (D. L. Anderson et al., 2002). Finally, the ORI was used as a measure of the degree to which students had adopted an evolutionary ontological framework (Andrews et al., 2011). Certain sections of the EPSE 8 also indicate representational understanding of particles in mixtures, compounds and elements as well as representational changes of the arrangement of particles in different states. Change in these factors indicate an ontological shift towards a kinetic particle model of matter.

3.7.2 Analysis of written representations

Students' written explanations in the Paragraph section of the TFA were initially marked using the LM modified rubric described in Section 3.5.1. A modified rubric was used rather than the original LM, which contains one more category related to how well students integrated more than one scientific model in their answer. Since not all TFA questions gave the opportunity for students to do this, this category was removed to enable comparison of student writing between different TFA lessons. In some cases, marking using the LM was found to be quite subjective and therefore students' work was analysed several times in order to determine a set of marking criteria for the specific topic which specified expectations for attaining each level and until grading of student work was consistent. Mean and standard deviations were determined for each lesson, two-tailed paired t-tests and Cohen Effect sizes were calculated between writing from the first TFA lesson and one of the final TFA lessons to determine the degree of change in level of written explanations. When investigating the changes over the whole year of learning using the LM rubric, in some cases it was necessary to estimate marks for a small number of students based on levels achieved. Only those

students who had been present for all lessons or were absent for a maximum of one lesson were included.

In order to use a more commonly recognised rubric for assessing scientific writing the CER Rubrics described in Section 3.5.2 were developed and applied to students' writing in the TFA Paragraphs obtained at the beginning of teaching with the TFA and towards the end of teaching using the TFA. In order to obtain the maximum number of matched scripts possible TFA lessons were chosen where the majority of students were present. The mean, standard deviation, 95% Confidence Intervals, two-tailed, paired t-tests and Cohen effect sizes were calculated to determine the degree of change occurring over the one-year period of teaching.

3.7.3 Analysis of qualitative data

Analysis of qualitative data proceeded according to a grounded theory framework (Bryman, 2012; Glaser & Strauss, 1967). In order to answer Research Questions 2-4, and to triangulate interview data from audio recording of interviews with students and teachers during and after teaching with the TFA with video and audio recordings of lessons and students artefacts, these were transcribed and were coded for themes using nVivo™ software.

The initial coding was open-ended (Strauss & Corbin, 1990), in that, students' explanations of their experiences learning using the TFA were coded by type or category as they arose. As coding progressed it became clear that there were a number of categories of response, or concepts arising (Bryman, 2012). For instance, several students mentioned that the demonstrations made them surprised and think differently about what was happening and this was coded under: Cognitive conflict made students think differently/more deeply.

In order to probe these categories further, data were obtained from interviews of students at the end of the second year of implementation, both individually and in small group interviews to determine whether other concepts would arise. Interviews were thematically coded three times in order to consistently establish concept categories. Since no more categories arose, it may be assumed that theoretical saturation had been reached (Bryman, 2012). Comparison between concepts obtained generated a number of common categories that answered the research questions. For instance: Scaffolding of understanding by the TFA process was considered to be a very important reason for students having greater understanding of concepts.

Having determined aspects of the TFA that students believed supported their learning, different perspectives were sought by interviewing Learning Support Aides, teacher colleagues and parents and provided triangulation of other data. A similar coding process

was followed as outlined above in order to determine categories of concepts that answered this question. Comparison was also made between these and the student responses.

The categories that arose through these selective and focused coding processes (Charmaz, 2006) could be further categorised in terms of the epistemological, ontological social and affective aspects of learning (Duit et al., 2008). Students in interviews referred to all three aspects, although the epistemological and social/affective aspects were most evident. Although some students mentioned aspects of ontological change as a result of completing a number of lessons that built upon the underlying model, further probing of the ontological aspect of conceptual change was carried out through coding of lesson transcripts in order to determine how ontological change was addressed. Once again selective and focused coding processes led to a number of categories describing teacher/student dialogue that supported ontological conceptual change.

The third research question arose as a result of analysis of both the quantitative and qualitative data that revealed some students for whom the TFA seemed to be outstandingly efficacious for their learning and some for whom limited improvement in conceptual understanding was achieved. In order to probe these instances, further interviews with a sample of those students were carried out, coded and the narratives searched for rich description of their TFA learning experience. Comparison between these students' experiences, along with triangulation with lesson transcripts, video and audio recordings, student artefacts and pre-/post-test data, led to several hypotheses being formed about possible causes for greater or less success of learning with the TFA.

The fourth and final research question was answered through analysis of reflective journal entries and triangulation with transcripts of lessons. Once again, as categories arose from coding for themes, these themes were further probed by further reflection about the process.

3.8 Validity and Reliability

Data were obtained by myself, as a participant-observer. This opened up the possibility for introduction of bias in the evaluation of the data collected and in manipulation of events. To overcome this problem, raw data were checked and evaluated by others, including my doctoral supervisors and regular member checks were carried out with participants to clarify ambiguous or contradictory statements.

Another source of bias may be found in the power relationship between myself, as teacher, and the students. This may result in students being reluctant to honestly evaluate the TFA and express their feelings of self-efficacy. In order to overcome this problem, it was

made plain to students that there would be no repercussions for their honest responses in interviews. One way of addressing this issue was to encourage students to be co-researchers or stakeholders, that is, they were told that we were working together to find out whether the TFA is a useful approach to support learning.

During individual interviews with students, many students enthusiastically participated, presenting their opinions with little prompting and describing their experiences. Some students, however, were more reticent and the interviewer found it necessary to encourage them to elaborate on very short answers. Where the students' meaning was unclear, she asked for clarification or repeated what she had understood from the students in order to check that she had correctly comprehended the students' response. Students generally seemed to feel free to answer questions honestly, openly explaining negative as well as positive experiences. As the project progressed, the researcher became more adept at supporting students in elaborating their answers and was less likely to ask leading questions. Carrying out several group interviews also gave students more confidence to openly express their ideas. These acted as triangulation with individual student interview responses. Similarly, the interviews with teachers who were frequently present in the class provided further triangulation of the students' and my perceptions. The fact that one of the staff was an experienced science teacher and another an experienced primary school teacher meant that their observations were also informed by their own pedagogical knowledge. They were also present in many other classes, other than the experimental class and therefore were able to contrast these experiences.

Greater reliability of the results was obtained by triangulation between the quantitative and qualitative data (Mathison, 1988). This process of triangulation increases the internal validity of the conclusions drawn.

3.9 Ethical Considerations

Approval for the research in this thesis was obtained from the Human Research Ethics Committee (Project Number: SMEC-53-13) to collect research data from 9th December, 2013 to 8th December 2017. Approval established conformity with the NHMRC National Statement on Ethical Conduct in Human Research.

In order to consider the privacy and views of the parents and of the children involved in the study, each parent and their child was sent a consent form outlining the research and how the data from the research would be used. They were encouraged to contact me for clarification of any point. Since I was also the teacher of these classes, students and parents may have felt obligated to participate. It was made clear to them that they were not obliged to participate in providing data or completing the interviews and that

they could withdraw at any time. This was reiterated several times throughout the process because the disparity of power between myself and the students may have resulted in the students feeling that they had to participate despite reassurance to the contrary. Several students did in fact choose not to participate and their results have been excluded from the study. Two students who did not participate in the 9E in 2014 experimental class chose to participate in 10E in 2015. As students became more comfortable with the research process and became more assured that their individual work would not be identified in any way when presented to an outside audience, these students became more willing to participate.

Informed consent to use interview data from other teachers was obtained. Throughout the process the teachers of the comparison classes have also remained informed of the progress of the project and they have been supported in preparing appropriate materials and experimental demonstrations to align with those that the experimental classes were receiving. The teachers of the comparison classes frequently met with me for discussions about content of pre- and post-tests, planning for units of work and other assessment tasks. I was concerned that these teachers not feel that their practice was being undervalued. I also provided professional development to all staff in the school on theoretical and practical aspects of the TFA. I also provided professional development about effective feedback and formative assessment.

Anonymity was guaranteed to students, teachers and the school. Names were coded and identifying features removed from the data during data preparation and entry and students, teachers or the school will not be identified in the reporting of the data. Access to the data gathered will be limited to myself and my supervisors.

At several points throughout the research process, following data analysis, summaries of results have been provided to students, parents and the school principal. Feedback will also be provided to the school principal and teachers involved in the form of a report, as well as to any parents who are interested in the results.

Chapter 4. Improvement in Conceptual Understanding and Written Explanations

In order to determine the effectiveness of teaching using the TFA, this strategy was used to teach a broad range of topics to Grade 8-10 students, including topics from chemistry, physics and biology. Pre- and post-test results of conceptual tests comparing students in the experimental and comparison groups were administered and analysed to determine the degree of epistemological and ontological change that occurred. The first nine sections of this chapter present quantitative data for each topic answering Research Question 1a: *To what extent does the Thinking Frames Approach build scientific understanding of concepts and lead to epistemological and ontological conceptual change?* Since the TFA also provides a “writing to learn by learning to write” strategy, the change in students’ ability to write coherent causal explanations was also determined. These results are presented in answer to Research Question 1b: *To what extent does teaching using the Thinking Frames Approach enable Grade 8-10 students to give coherent scientific explanations using written text?* The final section draws conclusions from the evidence presented.

4.1 Summary of Conceptual Test Results

This section discusses the extent of students’ conceptual change as a result of learning using the TFA, in the topics of physics (thermal physics, Newtonian physics, electricity and energy), biology (genetics and natural selection), and chemistry (kinetic and particle theory of matter). In order to assess students’ conceptual understanding, some previously validated instruments were used, obtained from the literature and described in Chapter 3. These instruments were administered as pre- and post-tests. The results encompass data from Grades 8, 9 and 10. The experimental group in each case was taught by me, using the TFA, while the other class in each year learned the same material and acted as comparison. A summary of all results obtained in both years of the study are presented, followed by a closer analysis of each individual topic. Multiple regression analyses of data from students of the experimental and comparison groups in 2015 are presented in order to determine the factors that had the greatest effect on students’ conceptual change for each topic.

In the first year of this study, conceptual change as a result of teaching using the TFA was measured in the topics of kinetic and particle theory of matter in Grade 8, and thermal physics and electrical current in Grade 9 through the administration of concept tests (EPSE 8, TCE and EPSE 2). The mean and standard deviations of the pre- and post-test scores for the experimental groups from the first year of implementation, 2014, are presented in Table 4.1. Paired t-tests between students’ pre- and post-test results in all three tests indicated that

these Grade 8 and 9 students had achieved a statistically significant improvement in their conceptual understanding. During the first year of the study, pre- and post-test data for the comparison groups were not consistently collected.

Table 4.1

Conceptual Gains of the Experimental Group Students in 2014

Topic (Assessment Instrument)	Experimental Group		
	Pre-test M (SD)	Post-test M (SD)	t-test (p) pre vs. post
Grade 8 Particle Model of Matter (EPSE 8)	50.4 (24.3)	76.3 (17.7)	8.08 (<0.0001)**
Grade 9 Thermal Physics (TCE)	25.3 (10.5)	45.7 (15.1)	8.5 (<0.0001)**
Grade 9 Electrical Current (EPSE 2)	27.0 (21.6)	49.6 (31.1)	3.17 (0.004)**

** $p < 0.01$

In the second year the study was expanded to include the topic of energy concepts for Grade 8 and three more topics for Grade 10: Newton's laws, genetics and natural selection. In total, 2 topics from Grade 8, 2 topics from Grade 9 and 3 topics from Grade 10 were included. In addition to the increase in the number of topics addressed, the conceptual tests were administered to comparison group students to understand the overall effects of teaching using the TFA. Pre- and post-test results for these seven topics obtained from both experimental and comparison classes are presented in *Table 4.2*. Paired t-test results showed that students of the experimental classes taught using the TFA gained significantly in their epistemological conceptual understanding of all topics ($p < 0.01$). The students from the comparison groups, on the other hand, did not significantly transfer their epistemological conceptual understanding from their previously held alternative conceptions to more scientific ones, except in the topics of electricity in Grade 9 and genetics in Grade 10.

Comparison of the post-test results between the experimental and comparison groups was made using independent t-tests. These showed that students of the experimental groups had statistically significant improvement in conceptual understanding in the epistemological dimension after learning with the TFA in the topics of energy, thermal physics, Newton's laws, genetics and natural selection and the particle model of matter. Comparison between the experimental and comparison groups in the topic of electrical currents was more ambiguous. Although the experimental group's result was higher, it was not significantly different from that of the comparison group as measured by an independent t-test. The results obtained from individual topics are discussed in more detail below.

Table 4.2

Summary of Conceptual Change Data in 2015

Topic (Assessment Instrument) [No. of TFA lessons]	Experimental Group			Comparison Group			t-test (<i>p</i>) Exp vs. Comp post-tests
	Pre-test M (SD)	Post-test M (SD)	t-test (<i>p</i>) pre vs. post	Pre-test M (SD)	Post-test M (SD)	t-test (<i>p</i>) pre vs. post	
Grade 8 Energy (ECA) [4]	44.3 (13.8)	59.1 (18.0)	3.86 (0.001)**		42.1 (17.1)		3.04 (0.004)**
Grade 8 Particle Model of Matter (EPSE8) [10]	52.9 (19.0)	74.4 (12.6)	6.59 (<0.0001)**		53.6 (15.1)		4.40 (0.0001)**
Grade 9 Thermal Physics (TCE) [7]	28.8 (10.7)	55.1 (15.0)	11.0 (<0.0001)**	32.9 (10.2)	30.2 (10.6)	-1.1 (0.38)	6.50 (<0.0001)**
Grade 9 Electrical Current (EPSE2) [4]	16.7 (16.2)	58.6 (25.6)	5.94 (<0.0001)**	19.5 (18.3)	47.1 (25.7)	4.07 (0.0006)**	1.33 (0.19)
Grade 10 Newton's Laws (FCI) [6]	26.3 (10.2)	41.5 (14.5)	6.89 (<0.0001)**	24.3 (10.4)	25.3 (8.5)	0.42 (0.68)	4.75 (<0.0001)**
Grade 10 Genetics (SRG) [7]	20.5 (17.4)	54.9 (18.8)	9.37 (<0.0001)**	12.1 (12.9)	39.7 (15.6)	9.06 (<0.0001)**	3.20 (0.002)**
Grade 10 Natural Selection (CINS) [3]	43.3 (14.5)	60.2 (18.5)	4.78 (<0.0001)**	38.6 (12.9)	32.2 (13.1)	-1.36 (0.19)	5.53 (<0.0001)**

**
 $p < 0.01$

4.2 Conceptual Understanding of Energy Concepts

A unit introducing energy concepts was delivered to two Grade 8 classes in 2015, the experimental class (8E) and the comparison group (8C). The Energy Concept Assessment (ECA) (Neumann et al., 2013) was given as a pre-test to 8E and post-tests to both classes. The experimental group, Class 8E (n=19), showed a statistically significant improvement in understanding of energy concepts moving from a class mean of 44% to 59% correct (Table 4.2). The comparison group, Class 8C (n=20), had a post-test score mean of 42%, showing that the TFA group, Class 8E, had developed a significantly greater understanding of scientific concepts about energy after learning through the TFA, as measured by an independent, two-tailed t-test. The Cohen effect size between pre- and post-tests for Class 8E was high ($d=0.94$) suggesting that the TFA had a considerable, positive effect on student understanding. An effect size above 0.4 is above average for educational research (Hattie, 2009).

For the conceptual categories of energy concept, forms of energy and transformation of energy, the experimental group students showed statistically significant improvement in understanding, as shown in *Table 4.3*. They also showed improvement in understanding of degradation of energy. However, no significant change was found in the category of energy conservation. This suggests that students did not significantly transfer their allegiance to a conservation ontological model of energy, although steps were taken towards adopting this model through greater understanding of transformation and degradation of energy. It should be noted that Neumann et al.'s (2013) study showed that students of Grade 10 found the concepts of energy degradation and conservation particularly difficult. It is therefore noteworthy for Grade 8 students to score reasonably well in difficult conceptual sub-categories, including energy conservation and degradation, and to be able to sustain their understanding for several months as shown in the delayed post-test.

Table 4.3

Energy Concept Assessment Results Including Conceptual Groups

Concept Category [No. of items]	Experimental Group (8E)			Comparison Group (8C)	t-test (<i>p</i>)
	Pre-Test M% (<i>SD</i>)	Post-Test M% (<i>SD</i>)	Delayed Post M% (<i>SD</i>)	Post-Test M% (<i>SD</i>)	(8E pre vs. post)
Forms & Sources [5]	58 (24)	74 (28)	75 (24)	62 (20)	3.03 (0.007)**
Transformation [4]	29 (23)	54 (30)	50 (22)	36 (23)	3.17 (0.01)*
Conservation [4]	36 (23)	40 (25)	38 (28)	26 (25)	0.51 (0.48)
Degradation [4]	49 (26)	65 (27)	62 (28)	49 (15)	1.94 (0.069)
Total [17]	44 (14)	59 (18)	57 (19)	42 (17)	3.86 (0.001)**

* $p < 0.05$, ** $p < 0.01$

4.3 Conceptual Understanding of the Particle Model of Matter

The particle and kinetic theory of matter topic was taught to the Grade 8 experimental group students in 2014 and then again in 2015. Another Grade 8 class served as the comparison group in 2015. Students' conceptual understanding was measured with and Evidence Based Practice in Science Education – Set 8 (EPSE 8) (Millar, 2002). The comparison class in 2015 was given the EPSE 8 as a post-test only, although the teacher had used the test the previous year. Post test scores were relatively high as this was an age appropriate test.

For the first year of implementation of the TFA, the students in the experimental group (8E in 2014) improved their performance in the EPSE 8 test, showing a statistically significant increase from 50% to 76% (*Table 4.1*, $n=23$, $d=1.22$). Similarly, students in Class 8E in 2015 (*Table 4.2*, $n=19$) significantly improved their mean EPSE 8 scores (52% to 73%, $d=1.32$). The comparison group, Class 8C 2015, achieved a mean post-test EPSE 8 score ($n=18$) of 54%, which was considerably lower than either the Class 8E in 2014 or Class 8E in 2015 post-test scores. Independent t-test comparison between data from 8E in 2015 and 8C in 2015 for EPSE 8 was significantly different with a large effect size of 1.40.

Analysis of results from 8E and 8C in 2015 in terms of the conceptual categories found in the EPSE 8 tests are displayed in *Table 4.4*. Students of the experimental group showed statistically significant improvement in ability to correctly identify pictorial representations of changes of state, physical and chemical changes of elements, molecules and mixtures. They were also more able to represent the arrangement of particles in gases with appropriate drawings. After learning using the TFA, they correctly distinguished between elements, molecules and mixtures and their physical changes from pictorial representations, significantly more so than the students of the comparison group. This

evidence, together with their representations of particles in a gas, suggests that an ontological shift had occurred towards adoption of a kinetic/particle model of matter.

Table 4.4.

EPSE 8 Results from 2015 in Terms of Conceptual Categories

Conceptual Category (Assessment Instrument)	Experimental Group (8E)			Comparison Group (8C)	t-test (<i>p</i>) 8E vs. 8C post-tests
	Pre-test M (SD)	Post-test M (SD)	t-test (<i>p</i>)	Post test M (SD)	
Change of state (EPSE 8)	64.7 (36.5)	86.8 (25.2)	2.25 (0.039)*	77.8 (30.8)	0.94 (0.35)
Particles in a gas (EPSE 8)	50.0 (43.3)	82.4 (35.1)	2.68 (0.016)*	61.1 (43.9)	1.57 (0.13)
Representations of atoms/molecules (EPSE 8)	50.0 (18.6)	69.7 (16.7)	5.93 (<0.0001)**	45.6 (17.9)	4.12 (0.0002)**

* $p < 0.05$, ** $p < 0.01$

4.4 Conceptual Understanding of Thermal Physics

The thermal physics topic was taught in Grade 9 classes. Students' conceptual understanding in this topic was evaluated using the Thermal Concept Evaluation (TCE) instrument (Yeo & Zadnik, 2001) for both experimental and comparison groups for 2014 and 2015. As shown in Tables 4.1 and 4.2, the students in the experimental group for 2014 ($n=28$) and 2015 ($n=21$) showed a statistically significant improvement in their performance in the TCE test (25% to 46% for 2014, and 29% to 55% for 2015). The Cohen's effect size between pre- and post-test results for the first year experimental group was $d=1.57$, and for the second year experimental group was $d=2.04$, which are considered very large effects (Cohen, 1969). The conceptual gain for Class 9E in 2014 was sustained over the six months following the initial teaching period ($M=47.7\%$, $SD=17.7\%$) and was not significantly different from the post-test mean. This was despite the fact that no further teaching of thermal physics took place during this time. It should be noted that the TCE was developed for use with senior high school and university students. The TFA group attained post-test scores which were similar or higher than those obtained by Grade 10-12 students in Yeo and Zadnik's study (2001).

Interestingly, in four conceptual categories of thermal physics (heat transfer & temperature changes, boiling, heat conductivity & equilibrium, and melting & freezing), students of 9E in 2014 maintained their understanding over a six-month period in three conceptual categories while melting and freezing category showed some decline (see Table 4.5). Students of 9E in 2014 completed a TFA question about melting and latent heat of fusion, discussing latent heat of vaporisation. In the final TFA lesson they further addressed the concept of latent heat of vaporisation. In comparison, 9E in 2015 briefly discussed

melting but completed their TFA question on latent heat of vaporisation which was further reinforced in the final TFA lesson. The significantly higher gains in the concept area of boiling by 9E in 2015 in post-test scores (*Table 4.6*) compared to those of 9E in 2014 are consistent with their deeper engagement with the concept of latent heat of vaporisation rather than fusion.

In contrast to the great conceptual gains of experimental group students, the students in the comparison group did not seem to undergo significant conceptual change. This was despite having obtained similar pre-test scores and being taught the same concepts using many of the same demonstrations and experiments as the experimental group. They obtained an average post-test score of 30% in 2015 and 26% in 2014.

Table 4.5

Comparison of TCE Conceptual Group Means 9E in 2014

Conceptual categories	Grade 9 Experimental Group in 2014				
	Pre-test M (SD)	Post-test M (SD)	Delayed post M (SD)	t-test (<i>p</i>) pre vs. post	t-test (<i>p</i>) post vs. delayed
Heat transfer & temperature changes	33 (19)	58 (20)	59 (22)	7.69 (<0.0001)**	0.12 (0.92)
Boiling	24 (28)	44 (39)	56 (26)	2.76 (0.010)*	1.22 (0.23)
Heat conductivity & equilibrium	13 (14)	34 (27)	46 (31)	4.65 (<0.0001)**	1.29 (0.06)
Melting and freezing	35 (35)	57 (24)	37 (25)	2.75 (0.011)*	-2.75 (0.011)*

* $p < 0.05$; ** $p < 0.01$

Table 4.6

Comparison of TCE Conceptual Group Means 9E in 2015

Conceptual categories	Grade 9 Experimental Group in 2015		
	Pre-test M (SD)	Post-test M (SD)	t-test (<i>p</i>) pre vs. post
Heat transfer and temperature changes	38 (23)	62 (23)	4.31 (0.0003)**
Boiling	38 (6.6)	83 (2.7)	4.93 (<0.0001)**
Heat conductivity and equilibrium	15 (16)	40 (18)	4.71 (0.0001)**
Melting and freezing	43 (17)	51 (18)	0.72 (0.48)

** $p < 0.01$

Overall, these results support the observation that teaching thermal physics using the TFA to Grade 9 students results in a statistically significant and sustained increase in conceptual understanding as compared to students taught using more traditional methods. This effect

was observed over a two-year teaching period with two different cohorts, which indicates that the improvement observed is not just a function of a particular cohort's attitude, interactions or abilities but can be seen as a more generalised phenomenon.

4.5 Conceptual Understanding of Electrical Current

A unit introducing series and parallel circuits and current, voltage and resistance was taught using the TFA to both Class 9E in 2014 (n=28) and Class 9E in 2015 (n=22). Students' understanding of electrical current was tested using the Evidence-Based Practice in Science Education – Set 2 (EPSE 2) (Millar, 2002; Millar & Hames, 2002) and administered as pre- and post-tests. The comparison group, Class 9C in 2015 (n=23), also completed these pre- and post-tests and the results are displayed in *Tables 4.1* and *4.2*. In all cases students showed a statistically significant improvement in conceptual understanding in the epistemological dimension when pre- and post-test results were compared, whether they were in the experimental or comparison groups.

Comparison of EPSE 2 post-test between Class 9E in 2015 and 9C in 2015 displayed no significant difference, which may be in part a function of the small number of items (10) in this test. In EPSE 2, Class 9E in 2015 results showed a much higher Cohen's effect size ($d=1.98$) than the comparison group ($d=1.24$). Class 9E in 2015 also showed a much higher effect size than that of Class 9E in 2014 ($d=0.88$). This may be as a result of 9E in 2015 having completed more TFA questions and those questions having been modified on the basis of the previous year's experience to include a question focusing on current and Kirchhoff's 1st law.

An analysis of the alternative conceptions of students of 9E in 2015, in terms of ontological frameworks (Section 3.3.3), is found in *Table 4.7* and showed a statistically significant transfer from the attenuation model and an inconsistent model to the scientific conservation model. Some students, however, transferred from other alternate models to a sharing model. Overall, the most popular alternative conception remained the attenuation model. Despite being replaced with the conservation model after teaching by a significant number of students, persisted as the most plausible explanation for 20% of students.

Table 4.7

EPSE 2 Results: Percentage of Students Holding Various Ontological Models (9E in 2015)

Model	Pre-test M (SD)	Post-test M (SD)	t-test (<i>p</i>) pre vs. post	Cohen's <i>d</i>
Conservation	17 (16)	59 (26)	5.94 (<0.0001)**	1.96
Attenuation	47 (23)	22 (24)	-3.93 (0.0004)**	-1.05
Consumption	3 (6)	0 (0)	-2.03 (0.06)	-0.63
Sharing	0.5 (2)	9 (12)	3.07 (0.006)**	0.98
Clashing currents	4 (6)	0 (0)	-3.29 (0.004)**	-1.01
Proximity	3 (6)	1 (4)	-1.28 (0.21)	-0.40
Inconsistent	25 (26)	10 (14)	-3.49 (0.002)**	-0.76

** $p < 0.01$

4.6 Conceptual Understanding of Newtonian Physics

Students in Classes 10E and 10C were introduced to Newtonian physics during Semester 1 of the second year of implementing the TFA. Apart from one new student to the class, all students of Class 10E had experienced learning with the TFA as Class 9E in 2014. The comparison group, Class 10C, was the same cohort as Class 9C in 2014, taught by the same teacher.

Conceptual understanding was measured using the Force Concept Inventory (FCI) (Hestenes et al., 1992). Students in 10E ($n=30$) and 10C ($n=23$) were given the FCI as a pre-test and then as a post-test immediately after completing a course on Newtonian physics. Mean and standard deviation results from the FCI tests are presented in *Table 4.2*, along with t-test comparisons. The means of the FCI pre-tests from both 10E and 10C were not different from guessing the correct answers. The TFA group, 10E, showed substantial improvement in conceptual understanding in the epistemological dimension over the teaching period, with a statistically significant increase in mean score from 26.3% to 41.5%. This improvement has a Cohen's effect size of $d=1.21$, whereas the comparison group, 10C, did not improve.

A delayed FCI post-test was administered to the experimental group, 10E ($n=29$, $M=43.3\%$, $SD=15.7$), 6 months after the teaching period. The results were not significantly different to the post-test results even though no further teaching was given on this topic. The Cohen's effect size remained very high ($d=1.28$). It has often been noted that sustaining conceptual change in students is problematic, as students tend to return to their alternative conceptions over time (Duit & Treagust, 2003). Students' results in delayed post-tests in all three physics topics, energy, thermal energy and Newton's laws across Grades 8-10, suggest the efficacy of the TFA approach in supporting long-term conceptual change.

Three students held a university ‘entry-level’ understanding of Newtonian physics (>60%) directly after the teaching period, while four students had attained this level in the delayed post-test. Although these scores are lower than those reported in other investigations (Caballero et al., 2012b; Hestenes et al., 1992; Savinainen & Scott, 2002b) it must be noted that these studies involved students who were physics majors in senior high school or university while the 10E students were a mixed ability class completing a compulsory general science course.

Certain ideas appeared to be unaffected by the teaching students had received, such as the idea that the impetus given to an object continues on after the two objects are in contact (pre-test M=56%, post-test M=54%, delayed post-test M=46%). Similarly, 32% of students believed that the effect of an impetus given to an object wore off over time and this remained remarkably fixed as an idea in post-tests and delayed post-tests. These results are consistent with Hestenes et al.’s (1992) observations that the “impetus concept of motion” and the “conflict concept of interaction” are some of the most persistent alternative conceptions.

Newtonian concepts can be grouped into six categories (Hestenes et al., 1992) and the mean percentage of students who correctly responded to the items from the FCI grouped by four of these categories can be seen in *Table 4.8*. The areas of kinematics and superposition were not investigated using the TFA and hence have been removed.

The adoption of understanding of Newton’s 1st, 2nd and 3rd laws as ontological frameworks for understanding motion can be determined by examining the change in means between pre- and post-test results for the percentage of students transferring their commitments to the scientific model. *Table 4.8* highlights normalised gains (see Section 3.7.1) (Hake, 1998, 2002) for experimental and comparison group students, showing some concepts and conceptual categories where there were medium and high gains between pre- and post-tests. Students taught with the TFA in 10E generally had much higher gains than those in 10C particularly in the categories of Newton’s first law, Newton’s third law and kinds of forces. Interestingly, the 10C class performed better in a couple of items, but their overall gains were extremely limited, suggesting conceptual change had occurred in certain epistemological beliefs although they did not undergo significant ontological change.

Some overall gain by students of 10E was observed in the areas of Newton’s first law and kinds of forces. However, the most pronounced gain was in understanding of Newton’s third law, which reduced slightly over time (*Table 4.8*). Students have been observed to have particular difficulty understanding Newton’s third law (Maloney, 1984; Terry & Jones, 1986). For example, in a study of 64 Grade 12 physics students, Yeo and

Zadnik (2000) reported pre- and post-test results for item 2 of the FCI, a question related to the third law, of 33% and 35% respectively whereas 10E achieved 3% and 53%, dropping slightly to 45% after 6 months.

Students in the experimental group, 10E, completed TFA tasks on Newton's three laws. They had some exposure to different types of forces but did not complete a TFA lesson specifically addressing types of forces whereas they did complete a TFA lesson addressing why acceleration due to gravity was independent of weight. Students of the experimental group showed high normalised gain on items 1 and 3, addressing this concept, compared to the comparison group. No significant increase in conceptual understanding was seen in the area of Newton's second law. In fact, for some items students' results indicated that they had become more confused about this topic (e.g., items 7 and 24). This may have been due to the persistence of the impetus concept of motion for most students.

There are some items that tested similar concepts where students displayed widely varying results, possibly because the wording of the questions was of a higher difficulty level than appropriate for this age group. For instance, students showed a very limited understanding of passive contact force in item 9, while displaying a moderate gain in understanding in the same topic in item 12. It must be noted that this test was designed to determine understanding of physics majors in senior high school or university.

Overall, considering the mixed ability of the class, the gains in conceptual understanding in the topics of energy, electrical currents, thermal energy and Newton's laws and the persistence of those gains in both thermal physics and Newtonian physics are very pleasing. These results seem to indicate the efficacy of the TFA in supporting sustained epistemological and ontological conceptual change in these physics topics.

Table 4.8

Students' Responses on FCI Items (Percentage Correct) and Hake's Normalised Gain <g>

Item No.	Correct response	10E					10C		
		pre-test	post-test	delayed post	normalised gain (pre vs post)	normalised gain (pre vs delay)	pre-test	post-test	normalised gain (pre vs post)
<i>Newton's First Law</i>		27.1	47.1	48.3	0.27	0.29	27.2	31.5	0.06
4	First law with no force	30.0	73.3	72.4	0.62*	0.61*	56.5	87.0**	0.70**
6	First law with no force	33.3	40.0	44.8	0.10	0.17	17.4	13.0	-0.05
10	First law with no force	53.3	76.7	86.2	0.50*	0.70**	52.2	65.2	0.27
26	First law, velocity, direction constant	30.0	36.7	27.6	0.10	-0.03	21.7	21.7	0
8	First law, speed constant	30.0	36.7	44.8	0.10	0.21	13.0	8.7	-0.05
27	First law, speed constant	43.3	83.3	55.2	0.71**	0.21	34.8	39.1	0.07
18	First law with cancelling forces	0	16.7	34.5	0.17	0.35*	13.0	13.0	0
28	First law with cancelling forces	26.7	13.0	20.7	-0.18	-0.08	8.7	4.3	-0.05
<i>Newton's Second Law</i>		28.3	22.5	27.6	-0.08	-0.01	23.9	20.7	-0.04
6	Second Law Impulsive force	33.3	40.0	44.8	0.10	0.17	17.4	13.0	-0.05
7	Second Law Impulsive force	33.3	10.0	13.8	-0.35	-0.29	39.1	26.1	-0.21
24	Second law constant acceleration	30.0	20.0	27.6	-0.14	-0.03	21.7	17.4	-0.06
25	Second law constant acceleration	16.7	20.0	24.1	0.04	0.09	17.4	26.1	0.11

<i>Newton's Third Law</i>		11.7	53.3	47.4	0.47*	0.40*	5.4	8.7	0.03
2	Third law for impulsive forces	3.3	53.0	44.8	0.52*	0.43*	13.0	8.7	-0.05
11	Third law for impulsive forces	13.3	60.0	55.2	0.54*	0.48*	0	4.4	0.04
13	Third law for continuous forces	10.0	50.0	37.9	0.44*	0.31*	4.3	4.4	0
14	Third law for continuous forces	20.0	50.0	51.7	0.38*	0.40*	4.3	17.4	0.14
<i>Kinds of Force</i>		25.8	39.7	42.8	0.19	0.23	24.6	23.6	-0.01
9	Passive contact force/gravitation	0	10	13.8	0.1	0.14	17.4	8.7	-0.11
12	Passive contact force/gravitation	13.3	43.3	41.4	0.35*	0.32*	43.5	56.5	0.23
15	Impulsive contact force	40	23.3	48.3	-0.28	0.14	21.7	43.5	0.28
29	Friction opposes motion	50	47	48.3	-0.07	-0.03	30.4	39.1	0.13
22	Air resistance/gravitation	23.3	20	34.5	-0.04	0.15	21.7	17.4	-0.06
5	Air pressure/gravitation	13.3	6.67	34.5	-0.08	0.24	13.0	0	-0.15
17	Gravitation	26.7	40	31	0.18	0.06	34.8	30.4	-0.07
18	Gravitation	0	16.7	34.5	0.17	0.35*	13.0	13.0	0
1	Acceleration independent of weight	43.3	96.7	93.1	0.94**	0.88**	8.7	17.4	0.10
3	Acceleration independent of weight	23.3	83.3	44.8	0.78**	0.28	21.7	4.4	-0.22
16	Parabolic trajectory	60	60	51.7	0	-0.21	52.2	47.8	-0.09
23	Parabolic trajectory	16.7	30	37.9	0.16	0.25	17.4	4.4	-0.16

**High $\langle g \rangle > 0.7$, *Medium $0.3 < \langle g \rangle < 0.7$, Low $\langle g \rangle < 0.3$ (Hake, 1998)

4.7 Conceptual Understanding of Genetics

Students in Year 10 completed a unit on Introductory Genetics in Semester 2. The concepts were new to most students and both the experimental and comparison classes were given the 11 item Scientific Reasoning in Genetics (SRG) pre-test (Tsui & Treagust, 2010). The 11 item second two-tiered SRG post-test was given to students of both classes at the end of the teaching period. Results from the pre-tests and post-tests are shown in *Table 4.2*.

An independent sample t-test comparing the pre-test results of Class 10E (n=26, M=21%) and Class 10C (n=27, M=12%) indicated that they were significantly different at a 95% significance level. This result was surprising as on all other measures the two classes were not significantly different, as discussed in Chapter 3. Both groups showed statistically significant improvement in understanding of genetics concepts; the mean result for Class 10C students improved from 12% to 40% while Class 10E students improved from a mean of 21% to 55%. Results from a 2x2 two factor ANOVA analysis with repeated measures on the SRG revealed that there was a significant difference between SRG scores from students learning using the TFA and the comparison group [$F(1,52)=10.0, p<0.01$]. There was also a statistically significant increase between pre-and post-test results overall [$F(1,53)=169.33, p<0.0001$]. However, there was no significant interaction between being in the TFA group or not and improvement between the pre- and post-tests [$F(1,51)=1.79, p=0.19$]. Both groups showed a very high Cohen's effect size ($d = 1.9$) when comparing pre- and post-test results.

In order to understand the conceptual growth that occurred amongst Grade 10 students in more detail, the 11 questions of the SRG were divided into six reasoning types as shown in Figure 3.1 (Tsui & Treagust, 2010). A comparison of the results for correct answers on each reasoning type can be seen in *Table 4.9*. Students of the experimental group, 10E, showed statistically significant increase in all reasoning types while students of the comparison group did not show significant improvement in questions of reasoning types IV and V. This suggests that learning using the TFA may support higher order thinking and understanding of the underlying molecular basis of inheritance (see Figure 3.1).

Table 4.9

Analysis of SRG Results According to Reasoning Types

Reasoning Type	Experimental Group			Comparison Group		
	Pre -est M (SD)	Post-test M (SD)	t-test (<i>p</i>) pre vs. post	Pre-test M (SD)	Post-test M (SD)	t-test (<i>p</i>) pre vs. post
I	27 (45)	92 (27)	6.87 (<0.0001)**	19 (40)	93 (27)	8.62 (<0.0001)**
II	19 (29)	40 (28)	3.35 (0.003)**	9 (20)	28 (25)	3.41 (0.0002)**
III	21 (35)	79 (32)	8.04 (<0.0001)**	15 (27)	70 (37)	6.81 (<0.0001)**
IV	27 (35)	54 (31)	3.03 (0.006)**	15 (27)	26 (35)	1.65 (0.11)
V	27 (35)	52 (36)	2.82 (0.009)**	15 (27)	31 (31)	2.55 (0.017)
VI	4 (14)	31 (38)	3.89 (0.0007)**	2 (10)	17 (28)	3.31 (0.003)**

** $p < 0.01$

Although both 10E and 10C showed significant gains in conceptual understanding of genetics concepts, the students who learned using the TFA had, on average, a greater understanding of the more complex relationships between phenotype and genotype within and between generations. They also had a greater ability to recognise the molecular basis of genetic traits, meiosis and mitosis. Reasoning types V and VI in particular require the adoption of process-based reasoning (Tsui & Treagust, 2010) and the experimental group's improvement in these two reasoning types suggest that students had undergone an ontological category shift (Chi, 1992) from material based to process based understanding.

4.8 Conceptual Understanding of Natural Selection

Natural selection and evolution were taught to students of Grade 10 in the second year of the study. Students in the experimental class (10E, $n=26$) were taught using the TFA while the other class (10C, $n=18$) was used as a comparison group. Conceptual understanding was measured before and after teaching using the Concept Inventory of Natural Selection (CINS) (D. L. Anderson et al., 2002) and are presented in *Table 4.2*.

Students in 10E displayed a statistically significant improvement in conceptual understanding of natural selection in the epistemological dimension with a pre-test mean result of 43.3% and a post-test mean result of 60.2%. Comparison of post-test results between experimental and comparison groups show a significantly greater conceptual understanding for Class 10E than Class 10C, who showed no significant improvement on their pre-test mean scores (32.2%). The Cohen effect size, $d=1.02$, for the experimental group, 10E, showed a high effect for teaching natural selection using the TFA.

Anderson et al. (2002) identified scientific and alternative conceptions from student responses to the CINS. *Table 4.10* shows change in the scientific responses given by students of 10E between pre- and post-tests as a percentage of the group. Many of the scientific

concepts increased in status. For example, most students understood after teaching that not all members of a population survive to reproduce (pre-test 46%, post-test 78%). Likewise, the percentage of students who understood that populations undergo natural variations while sharing many common characteristics increased (pre-test 70%, post-test 82%). An increase in the percentage of students who understood that new species originate as a result of the principles of natural selection was observed (pre-test 30%, post-test 56%), while the percentage of students who thought that speciation is driven by a need to change decreased from 68% to 44%. However, these high scores for this alternative concept reveal that the Lamarckian view of change remained remarkably persistent amongst many students. The TFA lessons on Natural Selection together with those related to Genetics particularly addressed the topics of limited survival, natural resources, variation within a population, inheritance of variation, change in a population, origin of species and origin of variation. As seen in *Table 4.10*, students of 10E displayed increased scientific reasoning in each of these areas. Anderson, Fischer and Smith (2009) suggest that a score of 80% or higher for the CINS indicates that a student has a good understanding of Natural Selection. Of the 26 students in 10E, 7 students obtained a post-test score of 80% or above, with the highest score being 95%.

Table 4.10

Analysis of Responses Given by 10E to the CINS by Category

Topic	% of students with scientific conception	
	Pre-test	Post-Test
Biotic Potential	68	74
Population Stability	70	74
Natural Resources	54	60
Limited Survival	46	78
Variation within a population	70	82
Variation is inherited	50	62
Differential survival	42	42
Change in a population	12	36
Origin of species	30	56
Origin of variation	18	44

4.8.1 Open Response Instrument results

In order to address Nehm and Schonfield's (2008) criticisms of the CINS, that suggest that it does not provide sufficient evidence of students' coherent understanding of the ontological model underpinning natural selection, students also completed an alternative instrument developed by Nehm and Reilly (2007). At the end of the unit students wrote responses to the Open Response Instrument (ORI – cheetah) (n=19) explaining how cheetahs have evolved to

be able to run at 100 km/h from ancestors that could only run at 30km/h. This was graded according to the rubric of Andrews et al. (2011). Students of Class 10E displayed a high degree of coherent conceptual understanding of the natural selection model (M=5.68, SD=1.8, Maximum points=9), particularly of the core concepts identified by Andrews et al. (Phenotypic variation exists in populations: M=1.42, SD=0.61; Selective pressures result in differential rates of reproduction: M=1.79, SD=0.42; Traits are inherited by offspring through genes: M=1.42, SD=0.77; Maximum points =2). Students were less likely to refer to those concepts identified as displaying more advanced understanding (Andrews et al., 2011) (Variation is a result of mutations: M=0.21, Proportions of phenotypes change because of differential reproduction: M=0.51; Selection over many generations results in change in a population: M=0.32; Maximum grade=1). Use of these more advanced concepts require transfer from an ontological category based on a sequential process, due the action of an agent, to an emergent process which is a response to a number of factors (Chi et al., 2012). For many students who perform less well this emergent process category is a missing schema.

These results from Class 10E compared very favourably with those obtained from a large study of students studying natural selection at 77 colleges and universities in Introductory Biology courses (Andrews et al., 2011). Mean score for post-tests completed by these university students for the ORI-cheetah was 3.22, SD=0.85. Considering that the students of 10E were a mixed ability class, this result indicates the power of the TFA to support ontological conceptual change and explanatory writing in this topic.

In summary, learning with the TFA resulted in very high Cohen's effect sizes and statistically significant transfer of understanding from alternative concepts scientific ones in both biology topics. There was also evidence that students had adopted scientific ontological models. For example, after learning using the TFA, at least half of students displayed a shift towards understanding of natural selection as an emergent process, recognising that there were phenotypical variations within a population, that selection pressures led to differential rates of reproduction resulting in a change in the proportion of phenotypes.

4.9 Multiple Regression Analyses of Data

Multiple regression analyses were carried out to determine the factors that most influence students' performance on each post-test and the results are presented in *Table 4.11*.

Table 4.11

Multiple Regression Analyses of Conceptual Test Data for 2015

Topic		β_0	β_1	β_2	β_3	β_4	β_5
			NAPLAN Numeracy	NAPLAN Reading	Pre-test	Treatment group	Gender
Grade 8 Energy	Regression coefficients	41.075	0.440	1.550		14.802	4.213
	Standardised regression coefficients		0.148	0.406		0.377	0.107
Grade 8 Particle Model of Matter	Regression coefficients	56.382	1.270	-0.650		17.68	-2.63
	Standardised regression coefficients		0.482	-0.194		0.499	-0.073
Grade 9 Thermal Physics	Regression coefficients	30.399	0.520	0.080	0.596	28.993	-3.306
	Standardised regression coefficients		0.184	0.031	0.370	0.813	-0.093
Grade 9 Electrical Currents	Regression coefficients	45.983	1.970	-0.380	-0.102	17.689	0.345
	Standardised regression coefficients		0.506	-0.100	-0.066	0.342	0.007
Grade 10 Newton's Laws	Regression coefficients	22.748	0.650	0.220	0.184	14.504	9.834
	Standardised regression coefficients		0.312	0.093	0.132	0.495	0.329
Grade 10 Genetics	Regression coefficients	42.276	1.530	0.640	0.186	10.324	-0.533
	Standardised regression coefficients		0.537	0.216	0.017	0.265	-0.013
Grade 10 Natural Selection	Regression coefficients	34.182	0.430	0.260	0.760	23.144	6.072
	Standardised regression coefficients		0.153	0.082	0.102	0.559	0.147

The factors tested were NAPLAN Numeracy and Reading results (centred and divided by 10), pre-test results (centred), treatment group (1= TFA group, 0= comparison group) and gender (male=1, female=0) and their relationship with students' post-test results. In the case of the energy (ECA) and the particle model of matter (EPSE 8) topics, pre-test results were not included as they were not available for the comparison groups.

Across different science topics, being in the treatment group (experimental group) played a statistically significant role in determining the post-test results. For example, for the Grade 9 thermal physics topic, a multiple regression analysis of experimental and comparison group data [$R^2 = 0.71$, $F(5,29)=13.87$, $p<0.001$] indicated that the greatest contribution to TCE post-test results was whether a student was learning using the TFA or not ($\beta=0.81$, $p<0.0001$). Pre-test scores also had a statistically significant but more limited effect on TCE post-test results ($\beta=0.37$, $p=0.009$). NAPLAN test scores and gender had no significant influence over the students' post-test performance. The effect on post-test scores from being in the treatment group compared to the comparison group, all other measures such as NAPLAN results and pre-test scores being equal, was an additional 29 percentage points on the TCE test.

On the other hand, for the Grade 9 electricity topic, the results of the multiple regression analysis of experimental and comparison group data [$R^2 = 0.25$, $F(5,32)=2.13$, $p=0.087$] were more ambivalent and indicated that NAPLAN numeracy results had a statistically significant influence on post-test results ($\beta=0.51$, $p=0.010$), while being in the treatment group also had some effect on post-test scores at a 95% significance level ($\beta=0.34$, $p=0.047$). NAPLAN reading, pre-test scores and gender had no significant effects on students' post-test results.

A similar phenomenon was observed for Grade 10 students as well. For the topic of Newton's laws [$R^2 = 0.68$, $F(5,43)=18.44$, $p<0.0001$], the greatest influence on post-test results was whether students were in the treatment group or not ($\beta=0.50$, $p<0.001$) followed by gender ($\beta=0.33$, $p=0.005$). The topic of Newton's laws was the only one for which gender showed a moderate correlation ($r=0.492$), boys scoring 10 percent higher on the FCI test than girls, all other factors being equal. NAPLAN numeracy scores also had a positive influence on post test scores ($\beta=0.31$, $p=0.023$). For the topic of Newton's laws, when all other factors are equal, a student in the TFA group would be expected to obtain a post-test score 14.5 percent higher than a similar student in the comparison group. In the topic of natural selection [$R^2 = 0.50$, $F(5,31)=6.17$, $p=0.0004$], a student in the TFA group would be expected to obtain a post-test score 23 percent higher than a similar student in the comparison group. The only statistically significant influence on post-test scores for natural selection was being in the TFA group or not ($\beta=0.56$, $p<0.001$).

On the other hand, the results of the multiple regression analysis for the genetics topic [$R^2 = 0.63$, $F(5,39)=13.4$, $p<0.0001$] indicated that NAPLAN Numeracy scores had a statistically significant effect on post-test results ($\beta =0.54$, $p=0.002$) as did, to a lesser extent, being in the treatment group ($\beta =0.27$, $p=0.012$). NAPLAN reading, pre-test scores and gender had no significant influence. When all other factors are equal, a student in the TFA group would be expected to obtain a post-test score 10.3 percent higher than a similar student in the comparison group

Regression analyses of the topics taught to Grade 8 students also indicated that learning using the TFA was a statistically significant factor in students' post-test scores. For instance in the energy topic [$R^2 = 0.50$, $F(4,31)=7.85$, $p=0.0002$], the only statistically significant contributions to post-test scores were from NAPLAN reading results ($\beta =0.41$, $p=0.010$) and whether the student was in the TFA group ($\beta=0.38$, $p=0.009$). When all other factors are equal, a student in the TFA group would be expected to obtain a post-test score 14.8 percent higher than a similar student in the comparison group. Similarly the multiple regression analysis of the EPSE 8 test results [$R^2 = 0.49$, $F(4,27)=6.40$, $p=0.001$] in the topic of the kinetic particle model of matter indicated that the most statistically significant effect on post-test results was whether a student was in the treatment group ($\beta=0.50$, $p=0.002$) giving a student a post-test score 18 percent higher than a similar student in the comparison group. A students' NAPLAN numeracy score also had a significant effect on post-test score ($\beta=0.48$, $p=0.01$).

4.10 Development of Students' Written Explanations

In order to answer Research Question 1b, students' written explanations from the paragraph section of the TFA worksheets were graded on the basis of a modified 'Levels Mountain' (LM) framework developed by Newberry et al. (2005) and described in Section 3.8. Development of students' written explanations over the period of teaching using the TFA was evaluated by Grade level. Written explanations were also analysed using six Claim, Evidence, Reasoning (CER) rubrics developed for written responses to specific TFA questions given to students in grades 8-10 which are found in Appendix G. A maximum of two marks each were awarded for identifying claims, evidence that supported those claims and reasoning based on the scientific model.

In order to compare results from the same set of students over one year, in the case where one mark was missing from the data set for a lesson, a conservative estimate was made for that student's explanation based on their previous work. Results for TFA lessons where the majority of students were present were used. A maximum of one estimate was made per lesson. Those TFA lessons containing estimates are in italics. Only examples of

students' written explanations will be presented for Grade 9 and 10 because of space limitations.

4.10.1 Development of students' written explanations in Grade 8

Trends in students' written explanations over two semesters. Students in Class 8E in 2015 studied a variety of topics using the TFA. In Semester 1, they completed units on cells, body systems and energy, and in Semester 2, they completed a unit on the particle and kinetic theories of matter. LM means from TFA lessons completed by a majority of the students are presented in *Table 4.12*. Only those students who completed at least 6 of the 7 lessons were included.

Table 4.12

Evaluation of Grade 8 Students' Written Explanations Using the LM (n=17)

Lesson No.	Topic	Guiding Question	LM M (SD)
TFA1	Biology (cells)	Why are cells so small?	2.50 (1.29)
TFA2	Biology (cells)	Why do different cell in the body have different structures?	2.88 (0.63)
TFA7	Biology (plants)	How and why do plants move?	3.68 (1.00)
TFA9	Physics (energy)	How can a cheezel™ be made to heat water?	3.62 (0.49)
TFA11	Physics (energy)	What happens when a bike rider takes his feet off the pedals at the top of a hill? Why?	3.74 (0.59)
TFA14	Chemistry (particle theory)	How does the smell of a candle travels from one end of the room to the other?	3.50 (0.43)
TFA18	Chemistry (density)	How did Archimedes solve the problem of whether the crown was made of gold?	3.44 (0.71)
t-test (<i>p</i>) TFA1 vs. 11			4.44 (0.0004)**
Cohen's <i>d</i>			1.23

** $p < 0.01$

The seven TFA lessons presented in *Table 4.12* addressed several different topics, cells, plant biology, energy transformation and conservation and the particle and kinetic theory of matter, which makes comparison problematic. However, the level of difficulty of each question was quite similar and appropriate for the grade level. The mean score obtained by students based on the LM framework showed a statistically significant increase when comparing the first TFA lesson to those following. The concepts addressed in each TFA lesson were relatively unfamiliar to students. For example, the ideas of cell size and surface to volume ratio, addressed in TFA1, and the concepts of energy transformation and conservation, addressed in TFA 11, were both unfamiliar concepts for students.

Conservation of Energy is generally the least well understood concept in the topic of energy (Neumann et al., 2013) .

Comparison between TFA1 and 11 was made since the results from TFA1 and 11 were from all 17 students and contained no estimates. The mean LM score for TFA 11 was 3.74, indicating that most students had successfully linked cause and effect, using scientific language and were beginning to elaborate their answers. Analysis of students’ writing from TFA11 showed a statistically significant improvement compared to TFA1 ($M=2.50$). In TFA1 some students were successful in linking cause and effect but many still gave a description of what they had observed rather than explaining how surface area to volume ratio affected rate of absorption of nutrients. Limited use of scientific language was also observed in answers to TFA1. The mean gain in level between TFA1 and 11 was between 0.66 and 1.55 with a 95% confidence. This gain corresponds to a high effect size ($d=1.23$). A plateau in LM scores is observed from TFA7 onwards as the majority of students recognised that more than a description was required. As they became familiar with the TFA process they became more adept at writing elaborated causal explanations.

Results from applying the CER rubric to evaluate students’ written explanations for TFA1 and 11 are found in *Table 4.13* and support the evaluation made using the LM framework. Only those students who completed both tasks were included. Although there was no significant change in students’ correct use of claims, there was a statistically significant increase in correct use of evidence, and there was an increase in the level of reasoning. The difference in total scores was also statistically significant and the effect size for the increase in total score was high ($d=0.92$).

Table 4.13

Evaluation of Grade 8 Students’ Written Explanations Using CER Rubric (n= 17)

	TFA 1 M (SD)	TFA 11 M (SD)	t-test (p)	95% CI (difference of means)	Cohen’s d
Claim	1.29 (0.85)	1.24 (0.44)	-0.29 (0.78)		
Evidence	0.65 (0.70)	1.65 (0.61)	4.76 (0.0002)**	[0.55, 1.45]	1.52
Reasoning	0.47 (0.62)	1.00 (0.61)	2.73 (0.015)*	[0.12, 0.94]	0.86
Total	2.41 (1.77)	3.88 (1.41)	3.23 (0.005)**	[0.51, 2.43]	0.92

* $p<0.05$, ** $p<0.01$

4.10.2 Development in written explanations of students in Grade 9

Trends in writing levels over two semesters. Students in the experimental Grade 9 classes in 2014 and 2015 used the TFA to learn a variety of topics: atomic structure and bonding, ecosystems, thermal energy and electricity. In order to give a snapshot of the

development of students' written explanations, data from TFA lessons where most students (n=26) were present were analysed. Data describing the mean levels as determined using the LM framework for Class 9E in 2014 and Class 9E in 2015 written explanations are presented in *Table 4.14*. Similar to students of Grade 8, Grade 9 students began the year by writing descriptions rather than causal explanations of phenomena (TFA1 and 3, LM mean < 3). However, over the year a statistically significant improvement was observed as students became aware of the importance of presenting a causal argument (TFA 12 and 14, M=3.81).

Table 4.14

Evaluation of Grade 9 Students' Written Explanations Using LM (n=26)

Lesson No	Topic	Guiding Question	LM M (SD)
TFA1	Chemistry (atomic structure)	How do we know about the structure of the atom using the models of the atom and the evidence for them?	2.48 (0.91)
TFA3	Chemistry (atomic structure)	How are objects dated using C-14 radioactivity?	2.92 (0.97)
TFA6	Biology (ecosystems)	Why do scientists believe that animals like jellyfish will take over the oceans?	3.87 (0.90)
TFA10	Physics (thermal energy)	Why are metals better conductors of thermal energy than glass?	3.42 (0.81)
TFA12	Physics (thermal energy)	How can a small radiator be used to heat a whole room?	3.81 (0.84)
TFA14	Physics (thermal energy)	Why does a paper cup on a Bunsen burner burns immediately while one with water in it does not burn?	3.81 (0.83)
t-test (<i>p</i>) TFA1 vs 14			6.40 (<0.0001)**
Cohen's <i>d</i>			1.53

***p*<0.01

Students found certain topics easier to write explanations about. For example, most students wrote elaborated causal explanations using scientific language to explain why scientists believe that simple organisms like jellyfish will take over the oceans (TFA6, M=3.87) after watching a documentary about the effects of overfishing. Many of the concepts related to food chains and webs were familiar to students. The concepts within the thermal energy topic, however, were quite unfamiliar to students and they held many alternative conceptions about thermal energy at the beginning of the unit (TFA10) which resulted in a slight decrease in mean LM scores. However, they were mostly able to write elaborated causal explanations for thermal physics phenomena presented in TFA 10, 12 and 14. The statistically significant improvement in ability to link cause and effect and use scientific language over the year of implementation can be seen when comparing the mean level for

TFA1 ($M=2.48$) with that of TFA14 ($M=3.81$). Both these questions were of a similar level of difficulty. A plateau effect similar to that observed with Grade 8 students was seen towards the end of the year, as students became more confident in writing elaborated causal explanations.

In order to see the change between TFA1 and TFA14 for all Grade 9 students in the experimental classes (9E from both 2014 and 2015), another t-test was run with data from 46 students who completed both lessons. (Table 4.15) The analysis reveals a statistically significant improvement in production of elaborated, causal answers using scientific vocabulary and a very large Cohen effect size.

Table 4.15

Improvement in All Grade 9 Students' Written Explanations Using LM (n=46)

	TFA 1 M (SD)	TFA 14 M (SD)	t-test (p) TFA1 vs 14	Cohen's d
LM	2.33 (0.92)	3.56 (0.90)	8.42 (<0.0001)**	1.35

** $p < 0.01$

Similar comparison between written explanations for TFA1 and TFA14 was conducted using the CER rubric (Table 4.16). Statistically significant improvement was observed in all three areas: production of a comprehensive claim, selection of appropriate evidence and reasoning with correctly linked claim and evidence using scientific principles. Once again, the effect size over the 9-month period learning using the TFA was very high ($d=1.41$).

Table 4.16

Improvement in All Grade 9 Students' Written Explanations Using CER Rubric (n=46)

	TFA 1 M (SD)	TFA 14 M (SD)	t-test (p)	95% CI (difference of means)	Cohen's d
Claim	1.09 (0.76)	1.61 (0.61)	4.23 (0.0001)**	[0.27, 0.77]	0.76
Evidence	0.46 (0.66)	1.28 (0.58)	6.38 (<0.0001)**	[0.57, 1.08]	1.33
Reasoning	0.09 (0.28)	0.72 (0.62)	8.04 (<0.0001)**	[0.47, 0.79]	1.31
Total	1.63 (1.34)	3.61 (1.47)	8.32 (<0.0001)**	[1.50, 2.46]	1.41

** $p < 0.01$

The initial Reasoning score for Grade 9 (TFA1) was particularly low ($M=0.09$) compared to that of the initial Reasoning score for Grade 8 students ($M=0.47$). Teachers' observations of the Grade 8 cohort indicated that, on the whole, this cohort tended to more conscientiously complete tasks compared to the Grade 9 cohorts. This may have resulted in a higher initial mean score. It should also be noted that concepts covered in TFA lessons in Grade 9 were

more challenging and required a higher level of reasoning than those topics addressed in Grade 10.

Comparison of 9E and 9C in 2014 written explanations in an extended examination question. Students of both 9E in 2014 and 9C in 2014 were examined on the work covered during semester 2, ten days after completing teaching on thermal physics. The results from the extended answer question on thermal physics can be seen in *Table 4.17*. The experimental group obtained a higher mean score on the extended question than the mean of the comparison group and this difference was statistically significant. While students constructed their written answers to TFA questions in class within their small group, students produced their own written explanations, unaided, within the examination context.

Table 4.17

End of Semester Exam Results

	9E in 2014 (n=28) M% (SD)	9C in 2014 (n=29) M% (SD)	t-test (<i>p</i>) 9E vs 9C
Extended answer question	48.9 (31.9)	17.2 (15.6)	4.79 (<0.0001)**

***p*<0.01

The extended examination question was based on TFA14. Both 9E and 9C had been shown this experiment. While 9E constructed explanations of their observations using the TFA, 9C had been given an opportunity to discuss their observations with the teacher without the use of the TFA. The answers given by 9E students were noticeably more detailed and several students produced complex explanations linking the scientific models learned throughout the topic on thermal physics with the observations in this experiment. One teacher marked all the students and these marks were checked and corroborated by the second teacher. A further analysis of both the 9E in 2014 and 9C in 2014 answers to the extended exam question using the CER rubric also showed that students who had learned using the TFA showed a significantly greater use of claim, evidence and reasoning (*Table 4.18*) than those students in the comparison group.

Examples of students' written explanations. Students' written explanations generally increased in the use of scientific concepts as opposed to their previously held alternative conceptions and in their ability to explain their observations in terms of those conceptions. The high average levels attained by both 9E in 2014 and 9E 2015 on TFA questions 10, 12 and 14 are consistent with their significantly higher post-test scores on the TCE compared to their pre-test results (*Tables 4.1 and 4.2*).

Table 4.18

Comparison of 9E in 2014 and 9C in 2014 Extended Exam Question Using CER Rubric.

	9E in 2014 (n=28) M (SD)	9C in 2014 (n=29) M (SD)	t-test (<i>p</i>) 9E vs 9C	95% CI (difference of means)	Cohen's <i>d</i>
Claim	1.25 (0.75)	0.55 (0.57)	3.96 (0.0002)**	[0.34, 1.05]	1.05
Evidence	1.36 (0.68)	0.66 (0.55)	4.29 (<0.0001)**	[0.37, 1.03]	1.13
Reasoning	0.50 (0.75)	0.17 (0.38)	2.10 (0.04)*	[0.02, 0.64]	0.55
Total	3.11 (1.87)	1.38 (1.21)	4.15 (0.00012)**	[0.90, 2.56]	1.10

* $p < 0.05$, ** $p < 0.01$

TFA 14, in particular, gave opportunities for students to write explanations of questions that linked several concepts from previous lessons. Some of the paragraphs in these lessons scored a LM level 5 as the explanations were not only scientifically accurate, using appropriate vocabulary, but they were also well-organised and displayed an ability to synthesise a variety of thermal concepts in a clear explanation. The increased elaboration of ideas, use of reasoning to explain the link between evidence and their claims and use of scientific vocabulary in written explanations can be seen in the following examples:

At the beginning of the year Willa's answer to TFA1 on how and why understanding of atomic structure had changed gave a description of two different models of the atom together with a description of Rutherford's experiment. This explanation was given a level 2 on the LM framework because she did not link the experimental observations that led to the development of each model. Similarly, in terms of the CER rubric (Appendix G) she made claims that the model for the atom had changed and she provided details of Rutherford's experiment as evidence for that claim but she made no attempt to link the evidence provided with the claim to explain the change in understanding of atomic structure.

Willa (TFA1): Firstly, Dalton believed that atoms were indivisible and very small but then he found that they could be split. Then Thomson's theory was that an atom was like a cake with the electrons being the pieces of fruit and the rest of the cake being positive. Finally, Rutherford conducted an experiment where he fired positively charged alpha particles at a gold sheet and recorded where they went with a sensor. Some ricocheted off of the sheet but most went through to the other side. (LM 2; Claim 1, Evidence 1, Reasoning 0)

By the middle of the second semester, however, Willa was able to produce much more elaborated causal explanations. Her explanation for TFA14 of why a paper cup without water in it burst into flames over a Bunsen burner, while a cup with water in it did not,

successfully linked the concepts of thermal energy transfer, thermal heat capacity and latent heat of vaporisation to explain that the cup did not reach ignition temperature when it contained water. Although she displayed a limited understanding of thermal equilibrium, this linking of cause and effect, together with correct usage of other scientific vocabulary in a cohesive argument earned her a level 5 in the LM framework. Willa achieved an average score on the post-test TCE of 54%. However, her written explanation displays considerable conceptual growth in the topic of thermal physics.

Willa (TFA14): When a cup filled with water is heated by a Bunsen burner, thermal energy from the Bunsen burner is transferred to the paper cup through both radiation and conduction. The cup heats the water through conduction, and convection means that the water is heated [throughout]. Water has a high thermal heat capacity, and because of the water and the cup's contact thermal equilibrium keeps the cup and the water's temperature rising together slowly. When their temperature reaches 100°C, the thermal energy is used for latent heat of vaporisation. The cup cannot light on fire because of thermal equilibrium and until the water is all evaporated the cup will not be able to reach its ignition temperature. (LM 2; Claim 2, Evidence 2, Reasoning 2)

Similarly, evaluation using the CER rubric showed that Willa provided an accurate and complete claim that the ignition temperature of the cup would not be reached until all of the water had boiled away. She provided evidence for her argument: the water and the cup's temperature rises slowly, contact between the cup and the water transfers heat and the temperature of the water does not go over 100°C and she linked evidence with her claims to produce an argument explaining that the slow rise in temperature is due to the high thermal heat capacity of water and the reason that the water doesn't go over 100°C is due to the energy being used to change the state of the water.

Eliza (9E in 2014) was a student who was greatly lacking in confidence in her scientific ability at the beginning of Grade 9. She often complained that she didn't understand anything. At the beginning of the year she wrote an explanation of how carbon-14 can be used to find out how old something is but simply wrote a description of the process of decay with some alternative conceptions such as that no more C-14 is present after a half-life:

Eliza (TF3): A flower with carbon 12 atoms and carbon 14 atoms. Carbon 14 atoms are radioactive which means they have a half-life. When they decay, they are transformed into nitrogen atoms. After the half-life process happens the

flower shows that there is no more C14 left but only N-14. (LM 1; Claim 1, Evidence 0, Reasoning 0)

By the second semester when Grade 9 students were studying thermal physics she was writing complex paragraphs using scientific language and competently explaining cause and effect. She achieved a much higher score on the TCE post-test (62%) than her previous results would have indicated. In her explanation of why ice on a metal plate melts more quickly than ice on a ceramic plate (TFA11) she recognised that ceramics are poor conductors of thermal energy while metals are good conductors and therefore that the metal plate was able to rapidly and continuously conduct heat from the environment into the ice cube causing it to melt rapidly. She used some scientific language and elaborated her causal explanation although she could have added an explanation of why metals are good conductors while ceramics are not:

Eliza (TFA11): The ice on the metal plate melted faster than the ceramic, because the metal is a faster and better heat conductor. It transfers thermal energy to the ice cube and then regains thermal energy from the environment and spreads it quickly to keep converting energy to the ice cube, causing the ice cube to receive constant thermal energy and melt fast. Whereas the ceramic plate is a slow conductor of energy and when the ice cube is placed in the middle, thermal energy is converted into it from the plate, but due to the fact that the ceramic is a slow conductor, the rest of the thermal energy from the plate doesn't reach the ice cube quickly, causing it to melt slower. (LM 4.5; Claim 2, Evidence 2, Reasoning 1)

4.10.3 Development in students' written explanations in Year 10

Trends in students' written explanations. Class 10E in 2015 used the TFA to learn about Newton's laws in Semester 1 and genetics and natural selection in Semester 2. These students had all (except for one) participated in the TFA research in the previous year so were very familiar with the process. Students' written explanations from TFA questions were analysed using the LM framework and these results are presented in *Table 4.19* (n=17).

Unlike the results from students of Grades 8 and 9, students' level of written explanations varied throughout the year and did not plateau. Students appear to have found it more difficult to write scientific explanations about some topics compared to others. For example, the topic of chemical bonding was only addressed once using the TFA (TFA8) and consequently students didn't have opportunities to practise explaining using the scientific model and vocabulary (M=2.91).

Table 4.19

Evaluation of Grade 10 Students' Written Explanations Using LM (n=17)

Lesson No	Topic	Guiding Question	LM M (SD)
TFA1	Physics (motion)	Newton's 1 st law: Why does the beaker full of water stay still when the paper is pulled out quickly while an empty beaker moves with the paper?	3.12 (0.96)
TFA2	Physics (motion)	Newton's 2 nd law: Explain what will happen (and why) when a 4kg car and a 1 kg car are attached with a stretched rubber band and released.	3.71 (1.12)
TFA3	Physics (motion)	Newton's 3 rd law: Explain what happens and why when someone steps off a skateboard.	2.94 (0.70)
TFA4	Physics (motion)	Impulse: Crumple zones Explain why cars have crumple zones and airbags	3.35 (0.98)
TFA5	Physics (motion)	Towing a car: Explain why a car towing another car accelerates even though the force on car 1 on car 2 is the same as the force of car 2 on car 1.	3.18 (1.38)
TFA8	Chemistry (bonding)	Predict how nitrogen and hydrogen will bond, and how strontium and bromine will bond.	2.91 (0.87)
TFA15	Biology (genetics)	Using a pedigree to determine the kind of inheritance of a characteristic	3.59 (1.27)
TFA16	Biology (natural selection)	Explain how natural selection works using the example of pepper moths	2.88 (1.11)
TFA17	Biology (natural selection)	Explain how the iguanas of the Galapagos islands, originally from South. America have become the way they are.	3.65 (0.58)
t-test (<i>p</i>) TFA1 vs 17			2.55 (0.02)*
Cohen's <i>d</i>			0.67

* $p < 0.05$, ** $p < 0.01$

The Newtonian physics topic presented considerable conceptual challenges for the students. As discussed by Halloun and Hestenes (1985) students commonly hold a wide range of alternative conceptions about the topic which are very resistant to change. Also, in order to explain many of these concepts some level of engagement with the relevant equations is required to explain some of the observations more fully, especially when explaining the last three topics presented as TFA exercises. The topic of crumple zones in cars requires an understanding of impulse and change of momentum, while understanding of projectile motion required students to be able to understand the vector nature of motion and manipulate the equations for force. These questions assume an ability to think mathematically with which many of the students struggled.

Despite these challenges students generally grappled with producing detailed explanatory written paragraphs answering these questions. As can be seen in *Table 4.19*, the average level of students' explanations was mostly at or above LM level 3, indicating that students produced paragraphs that engaged with the question and linked cause and effect in

their answers. Many students also successfully used scientific vocabulary in their explanations.

Students found writing explanations of phenomena best explained using Newton's 3rd law particularly challenging (*Table 4.19*, TFA3, $M=2.94$), although students did show an improvement when asked to explain the difficult concept of applying Newton's third law to determine whether there is an unbalanced net force acting on an object (TFA5, $M=3.18$). This is consistent with observations of other researchers that students have particular problems applying Newton's 3rd law (Yeo & Zadnik, 2000, 2001). Results from the FCI presented in *Table 4.8* indicate that many students did, however, successfully adopt conceptual Newton's 3rd law as an explanatory ontological framework, as discussed in Section 4.6.

As students progressed through a topic using the TFA, they generally began to gain facility in using scientific vocabulary correctly and applying the underlying model to new phenomena more confidently. For example, TFA15 asked students to apply all that they had learned over a series of seven TFA lessons on genetics in order to determine the type of inheritance (autosomal dominant/recessive, sex-linked dominant/recessive) on the basis of a pedigree given to students (*Table 4.19*, $M=3.60$). Despite many students finding this task challenging, most students were able to successfully make the appropriate claim that the characteristic was neither sex-linked dominant nor recessive and that there was not enough evidence to discriminate between autosomal dominant or recessive (*Table 4.20*, Claim=1.67). Most students were able to give at least one piece of evidence from the pedigree to support their argument (Evidence=1.00) and many were able to successfully link their claim about the characteristic not being sex-linked to the specific evidence (Reasoning=0.52).

TFA Lesson 16 introduced the unfamiliar topic of natural selection to students and this lack of familiarity with the underlying emergent ontological category and the appropriate vocabulary led to an initial drop in mean LM score (*Table 4.19*, $M=2.88$). As Chi et al. (2012) note, supporting a category shift in the topic of natural selection is particularly difficult because students have a missing schema based on emergent processes and so are unable to transfer their conceptual understanding to this schema. Many students were able to link some causes of change in distribution of characteristics in a population due to a change in the environment but elaborated explanations of causal factors were generally limited as was the correct use of appropriate scientific vocabulary. After receiving feedback on their written explanations, the following TFA Lesson 17 allowed students to write more elaborated, causal explanations of the effects of natural selection on the iguanas of those islands correctly using scientific vocabulary (*Table 4.19*, $M=3.65$).

Comparison of students' writing in terms of claim, evidence and reasoning over the two-year period that Class 9E in 2014 and Class 10E in 2015 learned using the TFA (Table 4.20), revealed that, while there was a statistically significant overall improvement in students' written explanations during this period (TFA1, $M=2.05$, TFA 15, $M=3.19$), the improvement was most pronounced over the first year of implementation (TFA1 $M=2.05$, TFA14, $M=3.52$). The lower scores in the second year of implementation amongst these Grade 10 students may be a function of the considerably greater level of conceptual difficulty of the topics addressed compared to those of Grade 9. The effect size, however, remained high ($d=0.72$). The most significant improvement in student writing was seen to be in making appropriate and comprehensive claims (1.67), the majority of students were able to provide at least one correct piece of evidence and many were able to use appropriate reasoning to link claim with that evidence (0.52).

Table 4.20.

Improvement in Students' Mean Written Explanations (2014 and 2015) Using CER Rubric (n=21)

	9E in 2014		10E in 2015		t-test (p) TFA1 (9E) vs TFA15 (10E)	95% CI (difference of means)	Cohen's d
	TFA 1 M (SD)	TFA 14 M (SD)	TFA 5 M (SD)	TFA 15 M (SD)			
Claim	1.24 (0.70)	1.67 (0.58)	1.43 (0.60)	1.67 (0.66)	2.90 (0.009)**	[0.11, 0.74]	0.63
Evidence	0.67 (0.73)	1.29 (0.64)	1.10 (0.77)	1.00 (0.89)	1.32 (0.19)	[-0.26, 0.84]	0.41
Reasoning	0.14 (0.36)	0.57 (0.75)	0.67 (0.86)	0.52 (0.60)	2.49 (0.018)*	[0.07, 0.69]	0.77
Total	2.05 (1.40)	3.52 (1.60)	3.19 (1.99)	3.19 (1.75)	3.36 (0.003)**	[0.73, 1.85]	0.72

* $p < 0.05$ ** $p < 0.01$

Examples of students' written explanations in Genetics. Students in 10E completed seven TFA exercises related to genetics (Table 4.21). TFA9 was an introduction to DNA structure while TFA10 addressed the Type V question described by Tsui and Treagust (2010)– “Mapping information in DNA base sequence to amino acid sequence in protein synthesis” (Table 1, p1077). TFA11 was a Type VI question addressing meiosis processing. TFA12 and 13 were Type IV questions which involved mapping of phenotypes to genotypes between generations. TFA14 and 15 were a combination of type IV and type VI questions which involved Punnet squares to determine possible inheritance, dominant, recessive, sex-linked, from phenotype data in a pedigree in order to determine genotype and involved the synthesis of learning from earlier exercises.

Despite the fact that all of the questions posed were towards the more complex, expert end of the continuum proposed by Tsui and Treagust (2010), students displayed a high level of engagement with the questions, generally producing explanations which related cause and effect and effectively using scientific vocabulary. Many wrote persuasive paragraphs showing sophisticated understanding of the concepts. Results from analysis of students' writing in the seven TFA lessons in the genetics topic are found in *Table 4.21* (n=15). Difficulty levels rose towards the end of the unit as students grappled with applying their understanding to fresh contexts (*Table 4.21*). On average they achieved a LM level of greater than three, indicating that they were successfully addressing the question and writing explanations using appropriate scientific vocabulary, rather than simple descriptions. Answering these questions required the use of process-based reasoning (Types V and VI), suggesting that conceptual change in the ontological dimension was occurring.

Table 4.21

Evaluation of Grade 10E Students' Written Explanations of Genetics Using LM (n=15)

Lesson No	Lesson Topic (Reasoning Type)	LM M (SD)
TFA9	DNA as a code bearer from cell to cell (V)	3.07 (0.92)
TFA10	Identifying the amino acid sequence from the DNA base sequence (V)	3.17 (0.75)
TFA11	Meiosis reasoning– different chromosomes may carry different alleles. Formation of gametes (VI)	3.33 (0.70)
TFA12	Identifying genotype from phenotype in a monohybrid cross (IV)	3.23 (0.50)
TFA13	Co-dominance Identifying genotype from phenotype (IV)	3.10 (0.85)
TFA14	Using Punnet squares/ meiosis reasoning (VI)	3.63 (0.58)
TFA15	Using Punnet squares/ meiosis reasoning and pedigrees (VI)	3.46 (1.08)

** $p < 0.01$

Several of the students who generally displayed lower achievement in their studies showed considerable improvement in their ability to explain genetic concepts over the teaching period. Rebecca, a student who had below average NAPLAN scores, began the unit by explaining how DNA is copied by nucleotides pairing up. However, she failed to explain how DNA acts as a code carrier.

Rebecca (TFA9): The structure of DNA is so important and powerful because in the end the cells/DNA form our characteristic and create us! The beauty and power of the necessary structure of our DNA is that when the bases separate and a new nucleotide comes in they form together (C to G, A to T). This is what makes DNA able to copy itself and carry information.” (LM 3; Claim 2, Evidence 1, Reasoning 0)

At the end of the unit, however, she produced a sophisticated explanation of her logic in determining the type of inheritance exemplified by the pedigree given and using appropriate

scientific language. She correctly claims that the characteristic cannot be sex-linked and that there is insufficient evidence for concluding that it is autosomal dominant or recessive. She provides evidence for both these claims from the specific generations within the pedigree and uses Punnett squares to defend her claims using evidence from the pedigree.

Rebecca (TFA15): The inheritance that the genetic family tree cannot be is sex-linked dominant and sex-linked recessive. Using Punnett square method, it becomes clear and rather obvious that if it was sex-linked dominant for lines I and II, then the offspring (girls) would have the disease, and the boys would not. However, in the diagram one boy and one girl is affected. Using Punnett squares [which she correctly produced] also to prove that it is not sex-linked recessive the boys have to carry [have] the disease – however – one boy doesn't, which proves this theory incorrect. There is however, no proof as to whether there is either autosomal recessive or autosomal dominant. There is no proof – only a 50/50 chance that it could be either. In order to prove that it could be either – two parents who don't have the disease need to produce a child with the disease (this process shows that it is recessive not dominant. (LM 5, Claim 2, Evidence 2, Reasoning 2)

Overall, despite the conceptual complexity of these topics, students were able, on the whole, to write elaborated causal explanations linking evidence with claims. These skills showed significant improvement as students used the TFA throughout the topic.

4.11 Conclusion

Analysis of pre and post test data for experimental and comparison groups in Grades 8-10 across a variety of topics revealed that students' learning using the TFA showed a statistically significant transfer of their alternative conceptions, based on their epistemological understanding of concepts, to scientific ones. Delayed post-tests showed that this gain was sustained over a six-month period. Further analysis of ontological categories within the conceptual tests shows that many students had made ontological category shifts towards a process-based understanding of phenomena. Evaluation of students' written explanations across these three grade levels using both the LM framework and the CER rubric indicates that students had developed significantly greater skills in presenting their scientific explanations over the study period. Many had adopted the scientific model and were able to use it to reason using evidence to support a claim. A comparison of students' written explanations between the experimental and the comparison group revealed significantly greater use of claim, evidence and reasoning after students learned with the TFA.

Chapter 5. Students', Teachers' and Parents' Evaluation of the TFA

In order to understand the significant growth in conceptual understanding attained by students in the epistemological and ontological dimensions, the perspective of students and teachers was sought on the mechanism of this change. As a result of coding of interviews, a number of categories arose which could be further categorised as addressing epistemological, ontological, social and/or affective aspects of conceptual change. The students' voice addressing the reasons they believed the TFA to be effective is presented in answer to Research Questions, 2a: *What do students perceive as the supporting aspects of TFA for learning science in terms of the epistemological, ontological and social/affective dimensions?* The observations of teachers acting as learning support aides within the experimental classroom, some parents and the acting principal corroborate many of the students' perceptions. Their viewpoint is presented in answer to Research Question 2b: *What main features and benefits do other teachers observe during implementation of the TFA in terms of how it supports multidimensional conceptual change?*

5.1 Students' Evaluation of the TFA Lessons

This section addresses Research Question 2a. Students' interview responses, obtained after learning with the TFA, are presented in relation to the features of the TFA that helped them learn science and undergo conceptual change (see *Table 5.1*). These themes were determined through iterative coding, as described in Section 3.7.3. Results are presented from interviews with Grade 8 students of 8E in 2014 and 2015 (n=16), and Grade 9 students of 9E in 2014 and 2015 (n=27). As the students of 9E in 2014 continued to study using the TFA in 10E, 10E responses are not included so as not to duplicate results. The responses are categorised in terms of structural features of the TFA, engagement with the underlying ontological model, social organisation of the TFA, and evidence of changes in student characteristics, such as self-efficacy, intentionality, epistemic motivation, mastery goals and positive activating emotions. These categories may be grouped in terms of the dimensions of conceptual change: epistemological, ontological and social-affective. It was evident that cognitive and social aspects of learning with the TFA influenced students' affective characteristics and these in turn influenced cognitive aspects.

Table 5.1

Categorisation of students' interview responses (n = 43)

Aspect that aided understanding of specific concepts	Grade 9 (n=27)		Grade 8 (n=16)	
	Frequency	No of students	Frequency	No of students
Use of multiple representations:	67	21	71	16
Transferring mental pictures into a drawing	33	14	28	15
Formation of a mental picture of the model	23	13	32	14
Writing the explanation in their own words supported understanding	11	9	11	8
Steps within TFA lessons support construction of understanding:	48	14	50	16
The combination of steps of the TFA scaffolded construction of understanding	32	14	29	15
Keywords aided in knowing how to use the scientific vocabulary correctly	13	10	14	10
Teacher questioning supported student construction of understanding	3	2	3	3
PDEODE aspect supported student conceptual change:	19	9	7	6
PDEODE aspect helped students understand	12	9	5	5
Cognitive conflict encountered in PDEODE made students think differently/ more deeply	7	6	2	2
Engagement with the ontological model:	56	19	34	13
Deeper understanding of the overall theory/model	36	13	27	11
Individual TF lessons building a more detailed explanatory model – deepening understanding of connections	20	12	7	6
Group work benefits:	82	21	43	15
Peer explanations were helpful for understanding	31	18	10	9
Hearing multiple views presented in group discussions	23	13	12	9
Consensus gained through discussion aided understanding and writing	15	9	11	7
More confident to ask questions and more opportunities to express ideas	13	10	10	8
Feedback benefited students:	47	21	27	15
Feedback enabled students to correct alternative conceptions/improve explanations	33	21	14	13
Levels mountain encouraged self-assessment	14	10	13	12
Increased intentionality and engagement:	287	24	164	15
Evidence of mastery goals developing	79	22	29	9
Greater intentionality evident	78	25	29	13
From negative to positive activating emotions	35	22	21	10
Motivated to study science in Grade 11/12	24	24	7	7
Epistemic motivation avoiding closure	24	17	20	8
Forced to be intentional in deeper engagement	24	16	18	9
Science lessons became more interesting	23	15	29	12

Increased belief that they can ‘do’ science	10	9	4	4
TFA question was relevant to daily life	6	6	5	4
Peripheral persuasion to be intentional	6	5	2	2
The concepts discussed in one TF were of manageable scope	2	2	0	0
Feelings of greater self-efficacy:	68	25	78	16
Increased confidence in understanding new concepts	28	15	35	14
Increased confidence in effectively writing explanations	28	19	23	14
Greater confidence in using scientific vocabulary correctly	5	4	12	9
Practice forming explanations multiple times gave greater fluency/ confidence	7	7	8	7

5.1.1 Support for epistemological aspects of conceptual change

In interviews, students talked about the benefits of the organisation of the TFA in relation to building conceptual understanding based on scientific concepts. Although, the change in understanding was supported by specific applications of the ontological model, the resultant change can be seen as lying within the epistemological dimension since students were addressing conceptual change of specific alternative conceptions within each TFA lesson. The most frequently cited aspect of the TFA, which supported students’ understanding, was the production of their own *multiple representations*. This was true for both Grade 8 and Grade 9 students. Fourteen students from Grade 9 and 16 students from Grade 8 mentioned that visualising sub-microscopic aspects based on the kinetic theory of matter and reproducing those mental models as drawings increased their understanding of concepts in topics like thermal physics. Students also expressed that they were more able to form internal *representations* of the scientific model as a result of the TFA process (Grade 9:13, Grade 8: 14). They also felt that producing written explanations in their own words strengthened their conceptual understanding (Grade 9:9; Grade 8:8) and a total of sixteen students noted that having to explain and defend their ideas verbally (see further discussion of small group benefits) to peers helped them to refine and expand their conceptual understanding. Overall, production of multiple forms of representations in order to explain their observations appeared to strengthen the students’ understanding of the scientific concept. For instance, Will spoke about the way in which the TFA lessons enabled him to form an internal representation, which was then consolidated as he transferred this to a visual mode of representation.

Will: Some of the topics I didn’t quite wrap my head around until we did the thinking frames and then someone tells me how it’s done and there’s the

spark and then I'm able to visualise it, able to understand it and then drawing the pictures concretises it I suppose.

The next most frequently mentioned feature of the TFA lessons was *the step-by-step nature of the TFA* and how the procedures provided metacognitive prompts for their thinking and understanding (Grade 9:14, Grade 8:15). They spoke of the way in which each of the steps built on the previous step to incrementally support them in both their understanding and explanations of the phenomenon. Several students commented that the parts of this extended process, such as identifying the keywords to use in the paragraph (Grade 9:10, Grade 8: 10), drawings and scaffolding their thoughts using dot-points, worked together to enable them to produce more detailed explanations. Those explanations remained in their minds for longer, enabling them to recall their ideas and responses when they encountered similar questions in tests.

Mathilda: It's like a step-by-step [process] so it's like piecing everything together so at the end, like the pictures and the dot points they help me.

Cathryn's experience exemplifies that of many students. She was not a very engaged science student at the beginning of the year; however, she apparently recognised the value of the TFA for her learning and as a consequence began to display increased intentionality in using the TFA strategies. When one student complained about how many TFA questions we were doing, Cathryn turned to her and asked, "*Don't you want to learn?*" When questioned about this in the interview at the end of the year, she notes the value of the metacognitive scaffolding:

Cathryn: I love them. I just think "What are you on about. They help!" We do the keywords and that really helps because then I know what kind of language I should be using in my explanation. The pictures help because visual descriptions of something really help me. And then when you have to do the dot points of the explanation that also helps because that's the basis [of the paragraph] which is good and makes it easier to write the explanation.

Another specific section that nine students of Grade 9 and six students of Grade 8 found helpful was *the PDEODE aspect of the TFA*. This involved a short demonstration at the beginning of the TFA lesson. The small group discussion before the demonstration allowed students to present their conceptions, many of them based on a non-scientific model. After observing the outcome of the demonstration, students' alternative conceptions were often shown to be unfruitful as explanations and new explanations were sought based on the scientific model. The cognitive conflict that students experienced during the PDEODE section led them to think differently or more deeply about the topic. Both Taylor and Willa

found the PDEODE aspect engaging and expressed that their ideas had been challenged. Taylor appears to have become more motivated to engage because of situational interest due to predicting.

Taylor: With predictions it actually gets people engaged. And even though we might be wrong it is good to be corrected and then it helps a lot.

Willa describes how the demonstrations and discussions made the scientific explanation more intelligible and plausible and hence gained in status. She particularly notes increased situational interest which improved her engagement due to the interesting TFA questions, the way in which the cognitive dissonance she experienced clarified her thinking and the importance of social construction. Elements of increased mastery goals and epistemic motivation are evident.

Willa: The questions are really interesting questions – like you want to know these things. And then the demonstrations are usually quite helpful as well because I don't know anything about these things and then there's a demonstration and I get some understanding and then the discussion is good too because you get to hear what other people think and you can build your understanding of how it works. And presenting to the class is good too because we see what other people think. You kind of form your own idea.

5.1.2 Support for ontological aspects of conceptual change

The following aspects of the TFA highlighted the way in which students were supported in moving from non-scientific to scientific ontological conceptual categories in each unit of work. Students commented on the way a series of TFA lessons within a unit built on each other to support deeper, more unified understanding of the scientific ontological model, specifically in the topic of thermal physics which had immediately preceded the Grade 9 interviews. These comments suggest the effectiveness of the TFA in changing students' ontological category of thermal energy from the matter-based 'Caloric' to the process-based Kinetic Theory of Matter (KTM) model.

Some students interviewed mentioned that they felt that they now possessed a much deeper understanding of the underlying model behind thermal energy transfer (Grade 9:13, Grade 8:11). The TFA allowed students to produce mental models as they answered specific questions, such as how conduction works, in terms of particles. Petrus spoke of the ways in which producing a visual representation using elements of the ontological model enabled him to understand and explain concepts.

Petrus: Over the course of the year, drawing stuff, especially the thermal physics and the electricity, it really helped when I was drawing it because then labelling it with arrows really helped. With the thermal energy it really helped me know how the particles of water would heat and move.

There was evidence that students now perceived the whole topic of thermal energy in terms of the movement and collision of particles. For example, Rachel referred to the way in which a number of TFA lessons built on each other by applying the KTM model in different contexts so that the students constructed a consistent understanding of the scientific model:

Rachel: When we were doing a thinking frame, it would be like one little topic, but the next lesson it would be something that linked on to that. So that if you could understand the topic from the lesson before, you would be able to understand the next day. It kind of all linked together. It made sense.

Matthew spoke of using the mental picture that he had developed of the movement of particles in order to solve unfamiliar problems related to states of matter.

Matthew: The liquids, solids and all that helps us to have a better idea and an image in our head that helps us deduce our answer away from those that aren't right.

5.1.3 Support for social aspects of conceptual change

Students overwhelmingly believed that the social aspects of the TFA supported their understanding and that the social aspect of the TFA positively impacted the affective aspects of learning. An important part of the TFA process was teacher-student discourse. Only five students explicitly mentioned that the questions that the teacher asked, as part of the TFA process, supported their understanding as they considered aspects that they may not have previously considered, although this may be because they saw this questioning as an integral part of the PDEODE process. When discussing this aspect, students mainly mentioned discussing their own ideas which suggests that teacher questioning was interactive/dialogic rather than authoritative. This aspect will be examined further in Chapter 7.

Thirty-six of the forty-three students interviewed mentioned the *benefits of working in small groups*. Students worked in small groups to predict the outcome of the demonstration and then to discuss and reach consensus as they developed pictorial and written explanations for their observations. Aspects of these heterogeneous small groups that they found helpful were: peer explanations or peer tutoring (Grade 9:18, Grade 8:9); hearing a multiplicity of explanations from other members of their small group (Grade 9:13, Grade 8,9); gaining consensus, or interthinking between members of the group on the best way to explain the phenomenon helped them to write better explanations and supported self-efficacy

(Grade 9:9, Grade 8:7); and having greater confidence to ask questions and having greater opportunities to air their views in the small group environment (Grade 9:10, Grade 8:8). For instance, Petrus found interthinking and hearing a variety of ideas and evaluating them within the small group context helpful. This enabled him to understand concepts and determine which explanation was the most consistent with his observations and the scientific model.

Petrus: In my group, at least, I find the discussion really helpful because we all put forward our ideas and how it works. And they really vary a lot so you get to think about which way or whose idea would work... It helps me understand when we discuss it in the group.

Several students who had previously expressed very low feelings of self-efficacy in science found that the small group environment allowed them to ask for support and put forward ideas. Jane appreciated the explanations provided by peers as they were simpler and she had the opportunity to hear concepts explained in a variety of ways.

Jane: A lot of my classmates tend to explain it easily and very simply which helps. But if say one of us doesn't understand then the others can explain it in different ways.

Millie felt more comfortable asking for help and expressing ideas within the small group context, allowing her to adopt mastery goals rather than performance goals.

Millie: I get more of a say and I can express my opinion more openly without feeling like, 'oh my goodness there are other people around me and I might get it wrong, what if I get it wrong!'

Eliza, a student who began Grade 9 with a very low self-concept in science, felt she was able to contribute to understanding in the small group discussions, showed improved belief in herself as able to 'do' science, and developed confidence to ask for further clarification.

Eliza: Everyone knows different things about everything. Sometimes I feel I help, I help in my group if they don't understand something. But then I feel if I don't understand something they help me as well.

The positive effect of a carefully chosen small group is exemplified by Josh's experience. Initially Josh, a very low-achieving, disengaged student was disappointed to be separated from his friend, Cameron. Both he and Cameron displayed very low motivation to learn or interest in science and preferred to spend time together discussing computer games. At first, he resisted engaging fully in TFA activities but over the second semester his written

explanations and grades improved dramatically. He attributed this improvement to his small group experience learning with the TFA.

Josh: Well last year I didn't pay attention in many classes. But this year I've started paying attention in every other class and I reckon getting separated from Cameron was actually a good decision. At first I was like 'Oh that's not very nice.' But now it has actually improved my grades in a lot of subjects. I reckon how you made the table order, seating thing [small group]. Like people... I'm not sure how you did it but it just seems to work.

In response to further questioning, he expressed how much he appreciated the other members of his new group and their support for his learning. Through the peripheral persuasion of being in a small group that encouraged him and working together with peers that he looked up to, he became more engaged and hence more intentional in use of metacognitive strategies. He had mastery avoidance goals at the beginning of Year 9, but by the end of Year 9 he was displaying a mastery approach goal.

Not only did the lower-achieving students appreciate the benefits from the small group interactions but also high-achieving students, like Will, observed the benefits to his own understanding and written explanation in explaining concepts in an appropriate way to those in their group who didn't understand.

Will: Sometimes talking through something that you are teaching someone else, you talk through the concept [and] you can actually find yourself having learned something or understanding it a bit better, knowing how it works.

Almost all students interviewed (36 students) mentioned the *benefit of rapid, constructive feedback (FT and FP)* as enabling them to know what elements of their explanations were not consistent with the scientific model and how to improve their explanations in the future. Students frequently expressed some of their previous alternative conceptions in their written paragraphs, and students commented that the feedback given on their individual paragraphs enabled them to correct those alternative conceptions and reach a deeper and more scientific understanding as a result. This aspect of the TFA contributed to the social construction of understanding.

Bahardir saw the feedback as a means to correct his written explanations and know how to express his ideas more scientifically. He displayed high levels of intentionality and his use of feedback is consistent with the development of mastery goals.

Bahardir: The feedback, I would say [is the most helpful]. It's like the most important part. And you [the teacher] specifically write feedback, like a

couple of sentences and it basically ... fixes everything that I said, [compared to] a teacher who writes “right” or “wrong”. So, you basically just helped us to get to the next step but we were actually the ones who did most of the thinking.

Likewise, Cathryn appreciated the scaffolding that the feedback provided in expanding and elaborating her explanations. She also was intentional in her learning and was adopting a mastery approach stance.

Cathryn: I read through it and then it is good because I know for next time what I should be focusing more on. So, if you said go into depth – like ‘why would the cup heat up’ – then I know for next time that I have to explain why one single thing might do something. It might be obvious but I still need to do it.

One of the strengths of the TFA is the rapid turn-around in which the teacher can give feedback. For instance, in most cases I was able to write detailed corrections and comments on thirty students’ work in one hour.

Students also recognised the value of self-assessing their written explanations and drawings using the LM framework (FR). Although some students expressed that they found this process challenging, many expressed that having to assess their work motivated them to improve their written explanations (Grade 9:10, Grade 8: 12). Jane, another student who had developed intentionality and was adopting mastery approach goals, used the Levels Mountain as a prompt to self-assess and regulate her written responses.

Jane: I find it helpful because self-assessment is good because you look back at it and you think ‘Have I done well at explaining it? If I haven’t done well could I go through and change some things?’ And it helps you to see if you understand the idea or not.

Students eagerly compared the level that the teacher assigned each completed TFA sheet and were eager to gain a higher score than their previous ones. They would often express excitement when they did reach a new level of achievement corresponding with a more detailed, scientific causal argument. This desire to improve their written responses in the eyes of the teacher and peers suggests that this feedback contributed to the social dimension of conceptual change by providing both a central and peripheral route to persuasion.

5.1.4 Support for the affective aspects of conceptual change

By far the most frequently coded aspect of the TFA was its *positive influence on students’ intentionality and engagement* (Grade 8:164, Grade 9:287). During interviews, students evidenced adoption of mastery approach goals (Grade 8:29, Grade 9:79) as they discussed

how they used the TFA in order to improve their understanding and writing. They particularly noted the productive use of feedback in order to reach higher levels on the LM. As a result, there was an increase in intentionality evident (Grade 8:78, Grade 9:29), as students described how they used various elements of the TFA lessons. They particularly noted the ways in which they more deeply engaged in production of drawings, productive discussion in small groups to build understanding, identification of keywords and dot-points in order to transfer their understanding from these sections into the paragraph section.

It appears that most students felt that they had become more intentional because the TFA gave them no other choice but to intentionally engage with the process (Grade 8:9 Grade 9:16). For instance, Patricia found the TFA motivated her to investigate concepts more deeply, compared to learning using a text-book. She suggested that using the TFA constrained her to be more intentional in understanding the concepts rather than regurgitating facts. She noted that she had been able to get away with superficial learning when answering questions from a text, yet the TFA increased her intentionality in her learning as they could not be completed to her satisfaction without deep engagement with conceptual understanding.

Patricia: But in the Thinking Frames you actually need to understand it to do the work well and so I think that to complete the work you actually need to understand it but when you are doing the o-book you don't have to, it's like your own personal choice whether you are choosing to understand it or whether you just want to get the answers and finish.

As students completed more of the TFA lessons throughout the year, some students would groan when they were told that they would be having a TFA lesson. I queried some of the students who had displayed this response in interviews. Warren's response is representative of the views of other students. He describes increased intentionality in learning as there was no other choice than to engage with the metacognitive steps of the TFA. As a result, he moved from a performance avoidance stance towards a mastery approach stance in his learning.

Warren: Every time we get a TFA [lesson] we know that it will be a stressful, hardworking lesson and that's really tiring. But it is definitely the most that we will learn. Because we have to work through the whole lesson and our brains don't stop and we have to write a whole lot. Usually in other lessons we get small breaks in our heads where we won't be using as many thought processes. It is a good thing to push us but our initial response would be 'oh no!' But it is definitely good.

It appears that the groans were because of the level of intentionality that would be required.

For a small number of students this intentionality increased due to peripheral routes of persuasion, usually related to their relationships with other group members which meant that they became more intentional in their learning than they would be otherwise (Grade 8:2, Grade 9:5). A number of students also expressed that they had replaced negative deactivating emotions such as boredom or anxiety with positive activating emotions (Grade 8, 10, Grade 9:22) related to science, such as excitement, enjoyment and enthusiasm.

An interesting development was the number of students who expressed an interest in finding out more about science topics outside of school, interest and pride in explaining ideas to parents and that, rather than being overwhelmed by finding that they held conceptions inconsistent with the scientific model, they were motivated to find out more about the scientific model. This is evidence of epistemic motivation that does not seek closure (Grade 8:20, Grade 9:24). Some students also expressed much greater belief in themselves as being 'good at science' or able to help others understand science where they had previously thought of learning science as out of their reach (Grade 8:4, Grade 9:9). Most of these aspects are illustrated in examples from students' interviews presented throughout this section.

Another important aspect frequently mentioned by all but two students was that the TFA gave them greater confidence in conceptual understanding (Grade 9:15, Grade 8:14), writing elaborated explanations (Grade 9:19, Grade 8:14) and using scientific vocabulary correctly (Grade 9:4, Grade 8:9). For instance, Petrus felt that he was considerably more confident in both understanding new concepts and writing scientific explanations as a result of learning using the TFA. He could self-regulate his writing by recognising the elements that were missing. He recognised that his previous explanations had mainly been descriptive and presented limited causality while the TFA had supported him in knowing how to write causal arguments using the appropriate scientific vocabulary. Prior to learning using the TFA Petrus had regularly produced very short explanations of one sentence to questions that required causal relationships to be assessed. By the end of the year, after learning using the TFA, Petrus regularly produced thoughtful, elaborated answers of one page in length, using examples and linking cause and effect and averaged a LM score of 4 - 5. He attributed his considerable increase in self-efficacy to the practice in producing explanations over the period and he clearly displayed improved epistemic motivation, as he is searching for understanding, self-regulation and intentionality in his learning.

Petrus: [Before my confidence was] 4 or 5 out of 10. I would have an idea in my head about how it works but it would be completely opposite. And then I'd

be just stumped. Now - maybe a 9 out of 10. Now I can change my way of thinking when learning about new ideas in science. If I was writing it, I could probably describe it and write a really simple explanation of how and why something happened but now I can use more examples and scientific words in my writing.

Robyn, an extremely shy and quiet student who prior to learning with the TFA had never participated in class discussions and displayed performance avoidance goals, began to raise her hand in order to contribute her ideas. During the interview at the end of the year she explained that multiple opportunities to practise using the TFA had given her the confidence to trust her own explanations because she now felt that she understood the concepts and this had led to adoption of mastery approach goals.

Robyn: [I began putting up my hand] because I felt more confident because I understood it because I had done a lot of thinking frames.

Similarly, Warren, who had not attended school in the previous two years because of anxiety associated with schooling, displayed a remarkable improvement in attitude towards school and science in particular. He expressed that he had felt very anxious at the beginning of the year because he had never studied science before and felt that he was a long way behind other students but by the end of the year he felt confident in understanding and writing science, which led to a greater interest in science and a reduction in negative deactivating emotions. He attributed this to the TFA and particularly to his small group experience.

Warren: I was more worried than interested [in science] because I had never learned science before. I felt that I was 2 or 3 years behind and would never catch up but I feel like now at the end of the year I am on the same pace as everyone else. So, it's made it a lot easier and interesting.

Finally, fifteen of the Grade 9 and twelve of the Grade 8 students stated that they had a greater personal interest in science and found science lessons more enjoyable and interesting since learning using the TFA. A total of ten students mentioned that the TFA questions related to daily life, which made learning more relevant and encouraged them to be more engaged. For example, Jane had held a negative deactivating emotion about science in the past (boredom) and would never have considered a career in science previously as she hadn't believed that she was 'good at it'. Learning using the TFA had led to a greater personal interest in science, self-concept as a 'good' science student and the development of a positive activating emotion (enjoyment) due to an increased feeling of self-efficacy.

Jane: I used to find science a bit boring but now I find that I really enjoy it and I've found that I'm actually good at it and might even consider having a career in it because that would be awesome!

Even for those students who didn't intend to continue studying science in senior high school and university, some expressed a greater interest in scientific concepts, excitement about participating in science lessons and a feeling of achievement in being able to understand and explain scientific concepts to others. Eliza exemplifies some of these important outcomes of learning with the TFA in terms of gains in scientific literacy and positive activating emotions about understanding science.

Eliza: Sometimes I come and I'm like why do I need to know this? I'm never going to become a scientist or anything. But after I've done it I feel it's really interesting to know, and one day if someone asks me about it I can be like I know this. And then I can tell everyone.

Related to the increased motivation and engagement in science lessons, students talked about their desire to continue studying sciences in upper years. In the five years that I had taught at this school, I had been disappointed about how few students went on to study sciences in Grades 11 and 12. On average, only 4-5 students out of 50 students in my Grade 10 classes would choose to study a science in Grade 11. From the first cohort of students who learned science using the TFA, however, 10 out of 29 students chose to study a science in Grade 11. In interviews, almost 90 percent of interviewed students in my Grade 9 TFA classes said that they would seriously consider studying a science in Grade 11 and 12. Grade 8 students were less sure about whether they wanted to study science in Grades 11 and 12, possibly because they didn't understand what studying science at that level entailed.

Some girls, like Jane, who had expressed lack of interest in science at the beginning of Grade 9 and had said that they didn't feel confident understanding concepts in science began to consider that science might be an option for them after learning with the TFA. For instance, when asked about studying science in Grade 11 or 12, Patricia described the changes that she had observed in her epistemic motivation, emotions – from negative deactivating to positive activating, and her adoption of mastery goals.:

Patricia: Yes, I think so, because I know a lot of the grade 11's and I look at what they are doing and it doesn't look that different. It looks harder but the methods of learning it are still the same. So that makes it a lot less scary. I am really interested in science. I think that it is really cool. I don't think that it hit me that everything is science until last year and so in the past year I have become a lot more interested in science and tried a lot harder in

science. I think that if something came on the TV about it I think that if I didn't really understand it, like if it was robotics for example, I'd look at it and if I didn't understand the physics behind it then I would go look it up or ask someone about it. Like I'm a lot more [proactive] about it.

The improvement in self-concept in science is evident and suggests that learning using the TFA built understanding and confidence and successfully encouraged some girls, who often do not go on to study chemistry and physics (Osborne et al., 2003), to consider further engaging with science in Grades 11 and 12.

5.1.5 Students' initial resistance to the TFA

Students had to think deeply and work consistently throughout the lesson in order to complete the whole TFA sheet satisfactorily. Student resistance did give me pause and make me think twice about whether implementing the TFA was beneficial at first. Some students expressed that initially they had found the TFA lessons difficult or couldn't see the point in learning science in this way but over time they had recognised the value of learning using the TFA. Gabrielle, for instance, told of her change in emotional response to science lessons from negative deactivating to positive active emotions as a result of learning with the TFA.

Gabrielle: At the beginning I would go, 'really, do I have to do these?' But I have grown to like them because they are better than other subjects. So I have started to look forward to science and pay more attention, because it's fun.

In the year following the completion of this study, three students from Grade 9 approached me to request that I ask their teachers to use the TFA as they realised how much they had learned using the TFA in the previous year. Ironically two of the students were students who had complained about doing so many TFA lessons in Grade 8. Comments such as these from students who had initially been resistant to learning with the TFA indicate the importance of persisting with this approach. Students took time to realise the benefits of the TFA to their understanding and writing. However, as students started to obtain improved post-test scores on conceptual tests, and gain in confidence in understanding, writing and remembering concepts over a longer term, they became advocates for the approach.

5.2 Teachers' and Parents' Evaluations of the TFA Lessons

To respond to Research Question 2b, five colleagues who observed the TFA lessons were interviewed. The following aspects of the TFA were highlighted. Their responses correspond to the students' responses: TFA scaffolded understanding and communication and increased confidence and engagement of students. Responses are organised in terms of each of the multidimensional aspects of conceptual change.

5.2.1 Support for epistemological aspects of conceptual change

The TFA scaffolds student understanding and writing. Teachers acting as learning support aides (LSA) who were present in many of my TFA classes spoke of the TFA as a “complete package” which allows students to systematically break down the question and utilise a variety of methods to represent their understanding. It resulted in the production of elaborated, higher order explanations. This agreed with the students’ assessment of the TFA. Mr Rogers spoke of the simplicity of the process which resulted in a logical progression from one type of representation to another.

Mr Rogers: If you follow the steps, which are really quite simple, then you progress from a to b to c. It’s just a very simple logical progression for them to follow and in practice in the classroom it works really well.

It was also noted by other teachers that students’ written explanations had improved substantially. This was confirmed by the analysis of students’ written explanations (section 4.2). Mr Malcolm, an experienced science teacher, acting as an LSA in my classroom, noted a marked improvement in students’ writing and attributed that improvement to a structured approach that supported the students in finding the most important points which linked cause and effect to form a coherent argument.

Mr Malcolm: The quality of the written answers was a cut above – than say something that you would see on a test. You find a lot of difficulty with the kids linking cause and effect into a coherent argument. You know they leave a step out or they mix the steps up. Probably what the TFA does is forces them to come up with the three or four or five vital points and it helps them not to leave any of the steps of the argument out. And it helps them to structure it into a good timeline.

5.2.2 Support for ontological aspects of conceptual change

Teachers also mentioned that the TFA was a method that genuinely supported teachers in implementing a constructivist teaching methodology. Although they did not specifically mention the students’ change in ontological categories, they did note that the students were constructing their understanding at a much deeper level than when learning by more traditional methods. The TFA process required students to engage more fully in imagining and applying that framework. They were motivated by the TFA to construct that deeper conceptual understanding otherwise they could not complete the lesson. This agreed with students’ observations that they had no choice but to adopt an intentional stance which led to greater mastery goals. Similar to the student’s responses, the teachers noted that students

became more aware of the alternative conceptions which reduced in status as they found a more plausible and fruitful scientific explanation.

Mr Malcolm: It is really student centred. Because you are really forcing them to get the ideas themselves, to collect the dot points and then put them into a coherent structure and a coherent understanding. I would say that it's one of the techniques that I have seen that lends itself to that really effectively, because you could see them doing it. It really forced them into getting the pieces of the puzzle and putting it into a picture. Yes, some did it better than others. It forced them to come up with a coherent picture of what was going on and, if they got it wrong, it was obvious for them that they were getting it wrong because it didn't answer the question. And it forced them to go back and not just leave it lame or to say, 'oh well, lessons over. I answered the questions. I didn't do 3,4 or 5. Whatever!' It forces them to come up with a solution and to construct a solution.

5.2.3 Support for social/affective aspects of conceptual change

Greater engagement in science lessons. Similar to the students' evaluations, the teachers spoke of the increased level of enthusiasm for science that they had observed. One teacher/parent spoke of the improvement that she had seen in her son's conceptual understanding of science which resulted in greater enthusiasm to investigate and learn more about scientific topics through increased epistemic motivation, and improved intentionality and ability to analyse, not just in science but also in maths.

Ms Sullivan: I think conceptually a few things clicked. I think that once he started to experience success – and also because maths and science are linked - he saw the relevance [of what he was learning]

The acting principal commented on the effects that she perceived the TFA was having in terms of the increased individual interest in science in the school as a whole.

Mrs Scott: There has been a notable lift in student interest and achievement in Science since the implementation of Thinking Frames in your class.

Ms Boots, an LSA who was frequently in classes supporting Carl, a student with complex additional needs, ASD, OCD, verbal and developmental delays and dyspraxia, expressed how much she personally enjoyed the lessons and how much she was learning from them. She noted that Carl was more engaged, was willing to contribute his ideas in class discussions and was enjoying science lessons.

Teachers who were present in lessons to support several students with high anxiety levels and ASD noted that students were calmer when learning with the TFA and needed less

support. They also appeared to be more confident. This effect seemed to be as a result of the supportive small group structure, which was also noted in student interviews, and the structured nature of the TFA process. The familiarity that students developed with this process reduced negative deactivating emotions and had a calming influence on those students with ASD.

Mr Malcolm: I found with the TFA, Fred [with high anxiety and ASD] always seemed to be very calm, always confident with what he was doing and I often questioned why I was there during those lessons because he didn't need my help. He was quite happy just doing it himself ... The fact was that there was enough structure there and you could see that once Xavier [ASD and cognitive delay] had done it enough that the routine became familiar.

The TFA appears to increase student confidence and interest in pursuing science. Finally, most of the teachers interviewed mentioned the higher levels of confidence in their ability to understand and write science that they saw in the students. This supported the same observation made by most students when interviewed. Those teachers frequently present in my classes noted that students who had not put forward their ideas in the past were putting up their hands and feeling confident to express their explanations in front of the whole class. The Acting Principal noted an increased interest in pursuing science as a result of implementing the TFA over the two-year period.

Mrs Scott: In my time as Acting Principal, students and parents reported increased student confidence in subject matter and a willingness to undertake Science subjects in Grades 11 & 12 where previously they had decided not to take Science. Notably, increasing numbers of young women expressed the desire to study Science and pursue a career in a Science field.

I was approached by several parents to comment on their children's improved attitudes towards and confidence in science. For example, Bryce was an unwilling student at the beginning of Grade 8, often avoiding completing work and not participating in any class discussions. In the second year of using the TFA Bryce began to interact well with his small group, sometimes producing quite sophisticated written answers. In particular, his participation in class discussions improved and he began to volunteer answers and often gave very thoughtful and insightful explanations. Bryce's father told me that Bryce had really changed in his attitude to science lessons. Bryce had told his father that he enjoyed them because the teacher really cared about whether they learned or not. I believe that this was as a result of learning with the TFA, particularly due to the level of feedback and interaction with the class, both as a whole and as individuals during TFA lessons.

The TFA supports the learning of students with additional needs. Several students with additional needs, including Autism Spectrum Disorder (ASD), cognitive delays and high anxiety levels, were present in the experimental classes. The teachers who were present were asked specifically about their perception of the TFA for these students. They said that the consistent structure of the TFA lesson was a benefit for students with ASD. They became familiar and comfortable with the process, the small groups also benefited them as they felt less anxious about asking questions or getting help and the students became more confident in being able to contribute to those discussions and write explanations.

Anxiety can be a negative activating or deactivating emotion and can be related to reduced conceptual change (Linnenbrink & Pintrich, 2003) The small groups also enabled students to observe how their peers were drawing their answers and answering their questions. It was noted that peers of students with additional needs willingly engaged with these students and broke the tasks down into simpler steps for them. Mr Rogers noted that the TFA was helpful for focusing attention of those students who found it hard to stay on task as there were visual prompts to help them to know what to do next. Mr Malcolm added that the initial drawing task was less threatening and more manageable for these students than beginning with writing. As students felt greater self-efficacy, the intensity of the negative deactivating emotions, such as anxiety, decreased.

Mr Rogers: I think that it has worked well due to its simplicity. A – it prevents minds from wandering but B – when they do wander it is easy for them to find their way back just by glancing at it.

Mr Malcolm: Carl [ASD with cognitive delays] would always either start with the terms or drawing the picture/ diagram. It was a non- threatening way to get the information down. You are not writing down all the information on a blank page that some kids might find daunting. There was a framework on which to begin putting down information and start joining the dots.

5.2.4 Student resistance to the TFA

As noted in the student interviews, teachers also noted that there was some resistance to TFA lessons. They likewise attributed this to the higher level of engagement and deeper thinking that was required during TFA lessons compared to more traditional lessons; however, they noted that the resistance was usually short-lived and, once the lesson was underway, students appeared to be positive and engaged in thoughtful discussion.

Mr Malcolm: There were the couple of groans at the start when you could see them thinking, ‘oh no, she’s making us do proper work, where we have to think. We can’t just cruise through’... And I always remember there was a kind of

bright bubbly level of noise and activity and discussion and, if there was any disengagement, it was just the usual kids taking a quick mental break.... My biggest bugbear with teaching science to senior students is trying to break through that outer crust of the superficial thinking, you know, just that factual stuff and get down into the deeper and more coherent expression of argument of cause and effect and explanation. And anything that does that is gold. And I think the TFA does that really well.

5.2.5. Possible cross-curricular uses for the TFA

Two teachers who were interviewed recognised the cross-curricular possibilities of the TFA. In fact, the deputy principal successfully used the approach in a modified form in her English literature class and to prepare Grade 12 students for a standardised reasoning test in order to help them produce more elaborated answers which addressed cause and effect. She claimed that she had seen an improvement in these and other external test results.

Mrs Scott: I would say there has also been a skill transfer to other subject areas - those students now writing well in Science are writing with more precision in English and humanities subjects. The marked improvement in the quality of their writing was enough for me to suggest the Head of Senior School adopt the approach to assist students in responding to the short answer section of the Australian Scholastic Test [Year 12 Australian Capital Territory Scaling test] paper.

5.3 Conclusion

The interview data collected from students, colleagues, learning support aides and parents indicated that the TFA successfully addressed all three dimensions of a conceptual change approach. Students stressed the social aspects of the approach in giving them greater opportunity to negotiate meaning in small groups. This, together with the cognitive conflict with their alternative conceptions and scaffolding of scientific understanding through the production of multiple representations resulted in increased self-efficacy. They also noted the effectiveness of feedback from the teacher and engagement with evaluating their own written explanations in enabling them to know how to further develop their explanations and understanding.

Deeper engagement with the ontological model occurred as they produced pictorial representations over multiple lessons which applied the model in different contexts. The observations of colleagues, learning support aides and teacher reflections corroborated the students' perceptions.

The positive influence of the TFA process on student characteristics in adoption of mastery goals, increased epistemic motivation and belief, development of personal interest and positive activating emotions was observed. The way in which the TFA forces students to intentionally engage with various meta-cognitive strategies was noted by both students and teachers. This intentionality resulted in improved outcomes, which in turn led to improved feelings of self-efficacy for students of all abilities.

Chapter 6. Three Case Studies

As suggested by Dole and Sinatra (1998), case studies of students with varying levels of engagement and conceptual change are sought in order to obtain a more fine-grained understanding of the conceptual change process in this situation using the TFA. This section answers Research Question 3: *What can be learned about a multidimensional conceptual change approach from analysis of individual students' progress in learning with the TFA throughout the two years of the study?* Three students' experiences are presented in depth. These students learned through the TFA over two years (9E in 2014 and 10E in 2015).

6.1 Identification of Focus Students

In order to further probe the effects of the TFA on individual students' learning, three focus students were chosen based on their normalised gains in conceptual tests in relation to their national standardised test scores. For each student the mean Hake's normalised gain was calculated comparing matched data for each of the five conceptual pre- and post-tests. The average normalised gain for each student over these five tests was then plotted against that student's centred NAPLAN Numeracy score from Grade 9 (Figure 6.1). It was assumed that the NAPLAN numeracy scores were an indication of students' reasoning abilities, although this is open to debate. However, students' NAPLAN numeracy and mean normalised gain showed a moderate positive correlation ($r=0.57$), indicating that students with higher NAPLAN Numeracy scores were more likely to have higher normalised gains on all conceptual test scores.

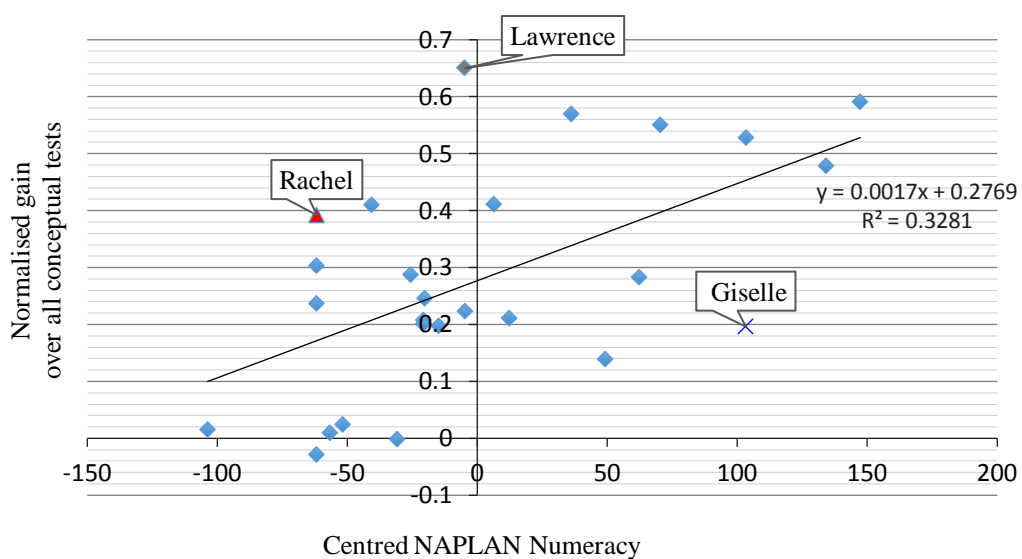


Figure 6.1 Average normalised gain over all conceptual tests versus centred NAPLAN numeracy results

If the line of best fit is taken to represent the expected interaction between student ability and the mean normalised gain that they obtained in all five conceptual tests over a two-year period, then Figure 6.1 reveals that within this class, there were students who obtained much higher than expected normalised gains in conceptual understanding after learning with the TFA. However, some students obtained lower than expected gains. The five lowest normalised gains were from students with low NAPLAN scores. Of these students two were students with many absences. These students' overall gains were commensurate with the gains of students with similar NAPLAN scores from 9/10C who did learn using the TFA. They also tended to achieve average conceptual gains in some topics but not in others. The electricity topic, in particular, seemed to have been difficult for these students and they adopted an alternative ontological framework which resulted in strong negative gains in this topic.

Results from Figure 6.1 were used to identify those students whose experience learning using the TFA may bring further clarity towards understanding how the TFA functions in supporting student learning. Three students were chosen to represent a variety of experiences learning with the TFA. Lawrence (Figure 6.1, green diamond) was an average student in this class, yet he obtained the highest mean normalised gain in conceptual tests. Rachel (Figure 6.1, red triangle) was a low-achieving student who greatly benefited from the TFA in terms of conceptual gain. Giselle (Figure 6.1, blue cross) was a high-achieving student whose normalised conceptual gain was much less than expected.

In order to put these results in context, the comparison class, 9C/10C, obtained an average of mean normalised gains, using matched data obtained in the second year of the study, of 0.14 (SD=1.3). The experimental group obtained a gain of averages using matched data from the same tests of 0.30 (SD=0.16), showing that most students of the experimental class showed a much higher average improvement in scores than the comparison class. A small number of students in the experimental group showed comparable gains to those in the comparison class.

6.2 Lawrence and the TFA

Lawrence was an enthusiastic student who was quite talkative. In class, he often had to be reminded to stay on task. He would frequently be involved in discussions with friends rather than listening to instructions. These discussions, however, were often centred around an aspect of the lesson topic in hand. He also asked a lot of questions and participated well in class discussions. Lawrence had a wide group of friends and was a keen participant in sports.

6.2.1 Lawrence's progression in conceptual understanding and written explanation

Lawrence showed a great improvement on conceptual tests with a very high normalised gain ($\langle g \rangle = 0.65$). While Lawrence's NAPLAN score was at the class average and he would have been expected to achieve a normalised gain of about 0.25, he had the greatest mean normalised gain of any student in his class. This suggests that he had experienced the highest level of conceptual change amongst all the students. As seen in *Table 6.1*, his conceptual understanding for the thermal physics topic was greatly improved from 23% to 50% and it was sustained after six months (54%). Lawrence also showed outstanding improvement in the topics of electricity, genetics and natural selection, achieving some of the highest results in each of these conceptual tests.

Table 6.1

Conceptual Test Results (pre-, post- and delayed post-tests) for Lawrence.

Conceptual Test	Pre-test (%)	Post-test (%)	Delayed post-test (%)	Normalised Gain $\langle g \rangle$
TCE (thermal physics)	23.1	50.0	53.8	0.35
EPSE Set 2 (electricity)	20.0	100.0		1.00
FCI (Newtonian physics)	48.3	69.0	55.2	0.40
SRG (genetics)	9.1	72.7		0.70
CINS (natural selection)	50.0	90.0		0.80

As a Grade 8 student, before learning with the TFA, Lawrence participated well in class discussions but he mostly wrote quite simple explanations and got low scores on higher order thinking questions. He gained a B grade at the end of Grade 8. During two years of TFA lessons, Lawrence's written explanations improved dramatically to include scientific keywords, causal explanations, and elaborations (*Table 6.2*). This improvement occurred over the first few TFA lessons and plateaued by TFA lesson 6. On introduction of new topics, such as Newton's laws, where concepts and vocabulary were unfamiliar, Lawrence's first attempts at writing explanations often contained alternative conceptions or lacked elaboration. However, on receiving feedback on how to express ideas he then assimilated these corrections and following TFA explanations showed increased levels of conceptual understanding and correct use of scientific language (see TFA 1 vs 2, 3 vs 4 and 16 vs 17 from 2015)

Table 6.2

Written explanations LM results for TFA lessons over 2014 and 2015 (Lawrence, Rachel and Giselle)

Lesson No	Topic	Guiding Question	Written Explanation LM		
			Lawrence	Rachel	Giselle
TFA1	Chem atomic structure	How do we know about the structure of the atom using the models of the atom?	1.5	1	4
TFA3	Chem atomic structure	How are objects dated using C-14 radioactivity?	3	3	4
TFA6	Bio ecosystems	Why do scientists believe that animals like jellyfish will take over the oceans?	4		3
TFA10	Physics thermal energy	Why are metals better conductors of thermal energy than glass?	4	4	3.5
TFA13	Physics thermal energy	Explain why the temperature of boiling water does not increase even though thermal energy is continually added.		4	4.5
TFA14	Physics thermal energy	Why does a paper cup on a Bunsen burner burns immediately while one with water in it does not?	4	4	3.5
TFA1	Physics motion	Why does the beaker full of water stay still when the paper is pulled out quickly while an empty beaker moves with the paper?	3	5	3.5
TFA2	Physics motion	Explain what will happen (and why) when a 4kg car and a 1 kg car are attached with a stretched rubber band and released.	3.5	4	5
TFA3	Physics motion	Explain what happens and why when someone steps off a skateboard.	2.5	3.5	3.5
TFA4	Physics motion	Explain why cars have crumple zones and airbags	3.5	5	5
TFA5	Physics motion	Explain why a car towing another car accelerates even though the force on car 1 on car 2 is the same as the force of car 2 on car 1.		3.5	5
TFA8	Chem bonding	Predict how nitrogen and hydrogen will bond, and how strontium and bromine will bond.	3.5	2.5	4
TFA11	Bio genetics	Explain the proportion of alleles in sperm after meiosis of a heterozygous individual	4	4	4
TFA15	Bio genetics	Using a pedigree to determine the kind of inheritance of a characteristic	3.5	5	5
TFA16	Bio natural selection	Explain how natural selection works using the example of pepper moths	3.5	4	2
TFA17	Bio natural selection	Explain how the iguanas of the Galapagos islands, originally from South America have become the way they are.	4	4	4

At the beginning of Grade 9, when his class began learning using the TFA, Lawrence produced annotated diagrams to explain his ideas but began by writing quite simple descriptions of what was observed rather than engaging in deeper explanations of cause and effect. In the first TFA exercise, students were asked to explain how we know about the structure of the atom. Figure 6.2 shows Lawrence's visualisation of Thomson's model of the atom and Rutherford's experiment. Although he showed one conclusion that Rutherford had come to as a result of this experiment, in his drawings, Lawrence wrote a very simple description in the paragraph section of the TFA:

Lawrence (TFA1): Though both Thompson's explanation and Rutherford's experiment and John Daltons conclusion that everything is made up of atoms. We know that an atom has mostly empty space but has all its positive charge in a nucleus. (LM 1.5; Claim 1, Evidence 0, Reasoning 0)

Lawrence did not engage with the question which required him to describe the original models of the atom and detail the experiments carried out which led to changes in the model. Interestingly he seemed to be unaware that his written explanation was inadequate as he graded his paragraph as a level 5 – a detailed and persuasive explanation of cause and effect using scientific language - as he said, 'I used some science vocabulary and I tried to use some persuasive writing'.

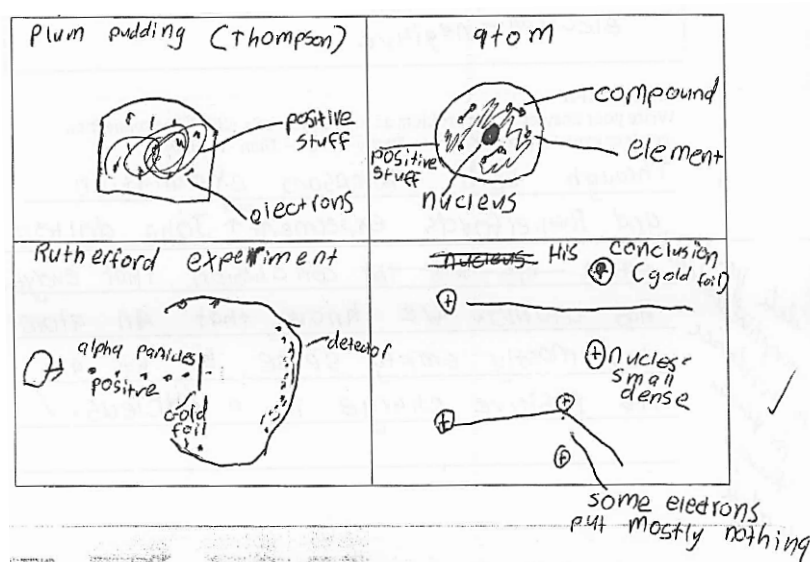


Figure 6.2 Lawrence's visualisation explaining how we know about the structure of the atom.

As Lawrence gained experience using the TFA over the first year of the study, although his drawings remained relatively basic, his written explanations began to improve and he began

to take care to address the TFA question, more consistently giving answers that related cause and effect and elaborated these ideas using scientific language. By TFA lesson 6 in 2014 (Table 6.2) he was achieving a LM 4 on most questions. In interviews he recalled the surprise that he felt when he only got a level 1 rather than the level 5 that he predicted for himself on this first TFA lesson. He said that this then caused him to really pay attention to his writing in terms of the elements described on the Levels Mountain as he was motivated to improve and get a higher level.

By the end of Grade 9, for instance, when answering TFA14, explaining why a paper cup filled with water does not burn, he produced quite a simple drawing which described the apparatus and contained a small number of written points explaining his ideas. His written explanation of this phenomenon, however, was far more detailed:

Lawrence (TFA14): A paper cup placed over a Bunsen burner flame will burn. Paper burns at 233°C, a Bunsen burner can reach 1100°C. When water is added to the cup, it won't burn. Water's boiling point is 100°C, which is far less than 233°C. The water in the cup acts as a 'heat sink', not letting the temperature pass 100°C because thermal energy converts it to water vapour. Therefore the paper will not burn. (LM 4; Claim 2, Evidence 2 Reasoning 1)

In his answer he refers to the ignition temperature of the cup, which he researched, and linked the fact that water's boiling point is 100°C with the idea that the paper cup can no longer reach its ignition temperature. He also indicated that the water absorbs the energy, meaning that the temperature was not able to go over 100°C and refers to the fact that the thermal energy at 100°C is being used to turn the water into vapour. He could, however, have elaborated his answer further by explicitly explaining the concepts of latent heat of vaporisation and thermal heat capacity of water.

In the second year of the study, at the beginning of Grade 10, Lawrence appeared to find more difficulty expressing causal relationships in the topic of Newton's laws but more effectively linked cause and effect in the genetics and natural selection units. He often did not have time to complete his written answers in class to his satisfaction. The TFA questions that he submitted in the Newton's laws topic were varied in quality, possibly because of being rushed to complete some of them. He appeared to spend most of the time in class verbally discussing his ideas and clarifying his answers. Focusing on the discussions and writing, to the detriment of his drawing, within the time constraints of the lesson may explain the limited scope of his drawings.

Toward the end of Grade 10, in the genetics unit, Lawrence used diagrams where necessary, for example Punnet squares and drawings of chromosomes; however, these

remained quite simple in nature. In the final natural selection unit, Lawrence produced limited or no visualisations but preferred to concentrate his efforts on writing key words, discussing with his small group, specifically Kyle, and writing the paragraph. His written explanations in the genetics and natural selection topics were more consistently explanatory, and, as he progressed in each of these topics, he became more confident in correctly identifying causal relationships and appropriate vocabulary. For instance, when answering the TFA question about how iguanas from the South American rainforests adapted to life on the Galapagos Islands, Lawrence wrote the following:

Lawrence (TFA17): Iguanas from South American rainforests ate leaves in rainforests. They are believed to have floated over to the Galapagos Islands on rafts, where the environment is quite different. This has led to natural selection of the species where helpful traits for the islands thrived (as there are different variations within the species), and are now in almost all of the iguanas. These traits allowed iguanas to learn to swim, to find moss [seaweed] deeper in the water, as well as physical traits like shorter snouts, sharper teeth to eat moss better. These traits made the iguanas stronger and breed more, thus making it more and more common throughout the generations. (LM 4; Claim 2, Evidence 2, Reasoning 2)

It can be seen in this paragraph that by the end of two years' learning using the TFA and practising writing detailed explanations of concepts, Lawrence had become much more adept at breaking down his ideas into steps and elaborating those ideas, linking cause and effect. He recognised that changes are as a result of environmental pressures and the interaction of these with the natural genetic variation in a population which results in selection of certain beneficial characteristics through more successful reproduction. However, he still struggled to express himself clearly and persuasively sometimes. Despite this, the improvement in transfer from alternative to scientific conceptions can be seen from the results he obtained in conceptual tests (*Table 6.1*).

6.2.2 Lawrence's small group interactions

Lawrence greatly benefited from the small group interaction during the TFA. Initially, he found working in a small group frustrating because certain members were not focused. When he was moved to a different group to be with his friend, Kyle, his relationship with Kyle appeared to provide peripheral persuasion that led to greater engagement, intentionality and adoption of both high performance and mastery goals.

Lawrence: I guess me and Kyle were talking about it [electricity] but I don't think that we were talking about it as a group. When the girls were in our group it

was hard because they were so quiet. We kind of split off into two sections. [The new group] was better because Kyle was in it. We [Kyle and Lawrence] would show each other what we had, to see how we could improve each other. I was trying to be really competitive with Kyle.

Kyle was a high-achieving student who exhibited a need for cognition as well as mastery approach goals and was confident in expressing his understanding and explaining to Lawrence. He obtained some of the highest post-test scores in all of the conceptual inventories with an average normalised gain of 0.53. Lawrence was willing to contribute his ideas and work together with Kyle to produce detailed responses. Lawrence admired Kyle and was in a friendly competition with him to improve his work, once he became aware of the errors and alternative conceptions that he was holding. The visibility of these alternative conceptions, through the PDEODE section of the lessons and as a result of his extensive discussions with Kyle and the feedback he received (see below), appear to have played an important role in Lawrence's achievements.

6.2.3 Lawrence's use of multiple representations

When asked about his conceptual gains, Lawrence noted drawing his ideas, particularly in topics such as thermal energy which required visualisation on a sub-microscopic level, was most helpful. In later topics he said that, rather than physically making the drawings, the aspect that was helpful was imagining a picture in his head. It seems that even though he did not draw elaborate diagrams, he used the 'visualise' section of the worksheet to form a mental image of the process and then transferred this internal representation directly into dot points and a paragraph.

Lawrence: Definitely drawing diagrams and I guess writing longer answers [were helpful] so I guess that sums up thinking frames. It has really helped me with writing long answers as I initially started at kind of a 2 but now I'm averaging 4 or 5 [on the LM].

He also noted the importance of collecting and writing key words, which he then knew how to use in his paragraph. Writing these seemed to help him to determine the most important ideas that he would use in his explanation and he would cross-check between the paragraph and these key words at the end of the TFA process. Thus the TFA increased his awareness of metacognitive strategies and helped him to build skills in self-regulation as he more intentionally engaged with the process.

Lawrence: Also I like the key words section. So I write the key words and then use them in my paragraph. Usually it is kind of like a check for me. Once I've

written my paragraph I go back and think, 'Have I written all of these key words?'

The production of multiple representations: identification of useful vocabulary, visualisation (both mental pictures and drawings), verbal explanations and the written explanations, worked together in order to help Lawrence gain deeper conceptual understanding. The 'productive constraints' (Tytler & Prain, 2013) that each of these representational forms placed on Lawrence's thinking resulted in a deeper engagement with the concepts involved and production of elaborated, higher order written explanations.

6.2.4 Lawrence's evaluation of the feedback

It was interesting to note that he appeared to be challenged by the feedback and the LM level that he was given on each TFA worksheet. He said that previously he had not been shown how to write scientifically and that he began by writing as he would in English. As he received more feedback he began to be aware of how to put together a good scientific explanation using the correct scientific vocabulary and linking cause and effect.

Adoption of mastery goals, influenced by the initial peripheral persuasion of competition with Kyle, seems to have led to a greater intentionality which, in turn, led to greater self-regulation and a more productive use of feedback. When asked about the process of giving a level for his work and the feedback that he received, he said that initially he had felt negative activating emotion, embarrassment, when he got a much lower level than he expected which, because of his high performance approach goals, motivated him to intentionally engage with the metacognitive strategies of the TFA process to determine what was wrong with his writing and fix it. This led to his recognising that the metacognitive step of providing a causal explanation was missing, which then led to his actively assimilating the feedback and adopting greater self-regulation of his written explanations in later TFA lessons. Thus, as a result of this process, he developed enhanced mastery approach goals over the two years of the study.

Lawrence: I think that I'm one of those people who when they don't do well, they're obviously a bit sad to start with and they have to try really hard because they want to do well. So at the start I thought [LM level] 2 was pathetic and I could do better and I was a bit ashamed because I wrote myself as a 5 straight up and I had to get into the higher [levels] ... realising that I was at a 2 I had to try really hard to make it a lot better. So initially you [the teacher] said like, 'Why is this sentence here?' so obviously I know why it is there but I obviously didn't explain. I explained how it happened but not why. So again I needed to focus on the why. So that's what pulls me up.

In summary, it appears from Lawrence's interviews and interactions within the class that there were several factors that contributed to the outstanding level of conceptual change that Lawrence underwent. His high performance approach goals initially motivated him to intentionally seek ways to improve his written explanations in terms of the LM. This led to his actively engaging in the TFA process as he visualised his ideas in multiple modes; adopted self-regulation strategies and actively assimilated feedback. Lawrence's highly social nature, coupled with the peripheral persuasion due to his friendship with Kyle, and his desire to achieve as well as Kyle did, meant that he engaged constructively in small group discussions with Kyle and then later with the whole group, in order to socially construct his understanding of concepts. This is an example of the positive way that high performance goals can lead to the development of mastery goals and increase intentionality.

At the end of Grade 10 Lawrence said that he wanted to study environmental science at university and he chose to continue with science in Grade 11, studying Biology. He wanted to study Physics as well but could not because of a timetable clash.

6.3 Rachel and the TFA

Students of lower average ability as measured by the NAPLAN numeracy results achieved more polarised mean normalised conceptual gains. A group of these students achieved very limited mean gains of less than 0.05, while another group achieved gains of between 0.24 and 0.41. Rachel's results are indicated by the red triangles in Figure 6.1 and show that Rachel achieved much higher post-test scores and a greater normalised gain in all tests than expected considering her relatively low NAPLAN results ($\langle g \rangle = 0.39$), which were in the lowest one-third of the class.

Rachel was a quiet, diligent student who displayed feelings of very low self-efficacy in science prior to this study. During Grade 8, before entering this study, Rachel was in my class and she always completed work thoroughly and in a timely manner. She gained a B grade for her work because of her diligence and because she took care to address marking criteria on assignments. She tried to meet her parents' expectations of hard work and her main motivation was performance goals of pleasing them. She mainly used shallow processing strategies, such as memorisation or focused on completing superficial tasks, such as presenting work in the right format for assignments, rather than deeply engaging in metacognitive strategies. As a result, she generally got lower grades on tests that involved higher order thinking questions or interpretation of data. She did not participate in class discussions, never volunteering answers or explanations and reluctantly answering direct questions, often with an 'I don't know'. Although she completed tasks as thoroughly as possible she frequently expressed a lack of confidence in understanding concepts and had

negative emotions about science and school. Rachel had a wide circle of friends, worked on weekends and some evenings and was interested in training as a hairdresser. From her perspective, science had a low utility value for her life goals.

6.3.1 Rachel's progression in conceptual understanding and written explanation

The improvement in conceptual understanding that Rachel achieved is seen by comparison of Rachel's pre- and post-test results in *Table 6.3*. The conceptual gains achieved in the Thermal Concept Evaluation (38.5% to 69.2%) were sustained over a six-month period as shown by her delayed post-test results (61.5%) and her results put her in the top 25% of the class. Although Rachel began with a very limited understanding of force concepts as shown in the FCI pre-test results (6.9%), at the end of the unit, she had gained some understanding (24.1%), which appeared to improve over the following six-month period (37.9%) despite no further teaching on the topic. Likewise, Rachel showed considerable improvement in conceptual understanding of genetics (27.3% to 54.5%). In the topic of natural selection, she achieved a surprisingly high mark on the pre-test (75%) which increased to 85% on the post-test, putting her amongst the top 3 students in the class in that topic. She obtained moderate normalised conceptual gains in all conceptual tests except for the FCI, although her delayed post-test results for this topic showed a surprising improvement over those of the original post-test.

Table 6.3

Conceptual Test Results (pre-, post- and delayed post-tests) for Rachel.

Conceptual Test	Pre-test (%)	Post-test (%)	Delayed post-test (%)	Normalised Gain <g>
TCE (thermal physics)	38.5	69.2	61.5	0.50
EPSE Set 2 (electricity)	30.0	70.0		0.50
FCI (Newton's laws)	6.9	24.1	37.9	0.19
SRG (genetics)	27.3	54.5		0.38
CINS (natural selection)	75.0	85.0		0.40

The progression that Rachel made in writing explanations using the TFA over the two-year period is found in *Table 6.2*. At the beginning of Grade 9 she diligently completed pictures and wrote paragraphs that described what was happening, rather than giving an explanation of the underlying causes of these observations. For example, in the first TFA question Rachel reproduced some of the drawings that she had seen in videos and during class

discussions (see Figure 6.3).

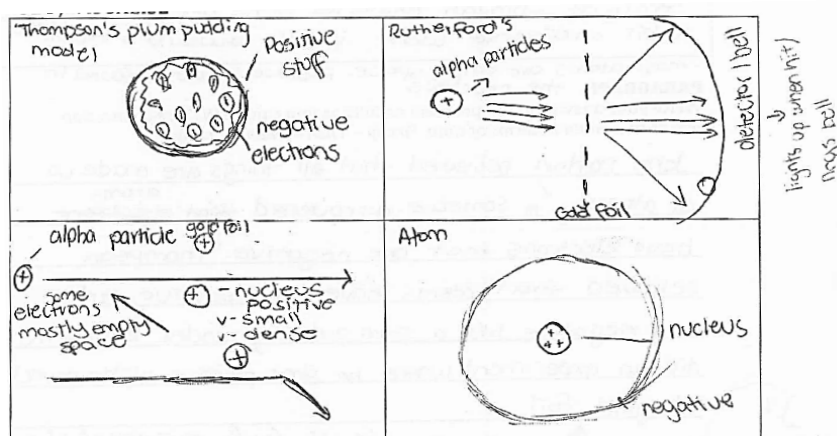


Figure 6.3. Rachel's visualisation explaining how we know about the structure of the atom.

Rachel wrote the following paragraph explaining how we know about the structure of the atom:

Rachel (TFA1): John Dalton believed that all things are made up of atoms, someone discovered that atoms have electrons that are negative. Thompson believed that atoms have some positive parts and negative like a plum pudding. Rutherford did an experiment where he shot positive alpha particles at gold foil. (LM 1; Claim 1, Evidence 0, Reasoning 0)

This explanation was a simple description of the Thomson model and did not describe the Rutherford model at all, even though she had drawn out an explanation of what the Rutherford experiment showed. She gave her own work a level 3 which suggests that she was unaware that she was not relating cause and effect in her explanation. This overestimation of their LM was common for all students in their first attempt at using the TFA

By the second semester of Grade 9, Rachel was growing in confidence in using the TFA and her LM scores regularly reflected that she paid careful attention to linking cause and effect and using scientific language (Table 6.2). Rachel began to participate in whole-class discussions, volunteering explanations. An example of the improvement in her written explanations by the end of Grade 9 can be seen in her paragraph explaining why a paper cup without water burns when placed over a Bunsen burner while one with water in it doesn't burn:

Rachel (TFA14): The paper cup with water doesn't burn because the thermal energy from the Bunsen burner went to the cup which the water absorbed, and because of thermal equilibrium (two objects have thermal energy balance,

therefore, the water will have the same temperature as the cup). The boiling point of water is 100°C therefore the cups ignition temperature will be higher and it will never reach it. The paper cup without water reaches its ignition temperature faster because it doesn't have the water to balance the thermal energy (thermal equilibrium). (LM 4; Claim 2, Evidence 2, Reasoning 1)

Rachel is using the terminology 'thermal equilibrium' incorrectly in her explanation. However, in previous lessons she learned that thermal equilibrium was reached when two objects are in contact and transfer of energy occurs through collisions of molecules. She is therefore using the term 'thermal equilibrium' here to indicate that energy is being transferred from the cup to the water because they are in contact with one another. Even though the term is not strictly correct her explanation implies an understanding that thermal energy is transferred through contact and that this fact led to the temperature of the cup remaining below the ignition temperature. She did not, however, explain why the temperature of the water never exceeds 100°C nor did she mention the high thermal heat capacity of water.

In the second year of learning using the TFA, Rachel continued to work diligently and enthusiastically participate in class discussions. Rachel engaged well with the topic of Newton's laws, working hard to understand concepts and write detailed explanations. She mostly attained LM scores of 4 or greater, although, like many other students, she initially found writing about Newton's third law more difficult (*Table 6.2*). By the end of the unit, however, she was able to write quite sophisticated elaborated causal explanations. In explanation of why two balls of 1kg and 2kg thrown at the same horizontal velocity from a cliff reach the ground at the same time and place she produced a detailed representation (*Figure 6.4 – Level 3.5*): This pictorial explanation utilises both annotated drawings and equations to explain what is observed. She has not fully understood the use of arrows to represent forces, however.

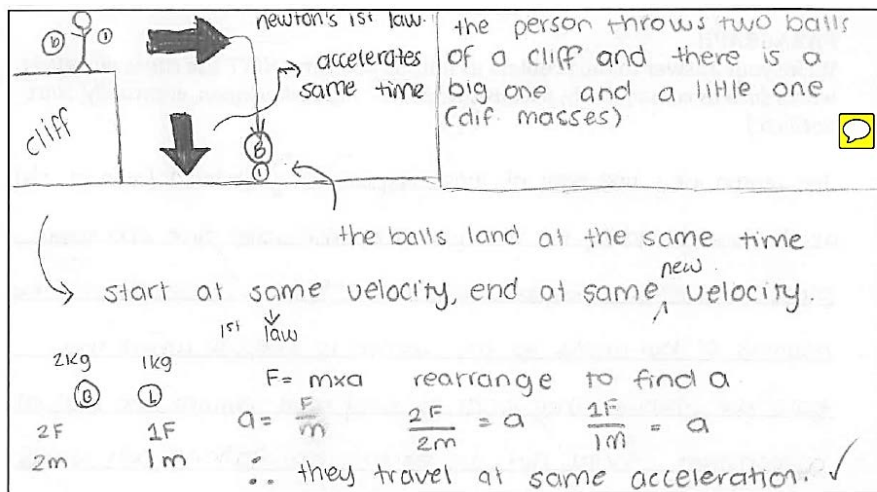


Figure 6.4 Rachel's representation of why two balls of different mass land at the same time and in the same place.

Rachel's written explanation synthesises her knowledge of Newton's first and second laws to explain the problem, linking these to the result that both objects accelerate at the same rate despite having different masses. She also recognises that they both travel at the same velocity in the horizontal direction, obeying Newton's 1st law and so landing at the same distance away from the cliff. She successfully uses scientific language and gave a detailed explanation using mathematical reasoning.

Rachel (TFA 6): The reason why two balls of mass 1kg and 2kg thrown from a cliff at the same velocity hit the ground at the same time and same place is due to Newton's first and second laws. The reason why Newton's first law applies to this scenario is because when the balls are thrown they want to stay in a straight line and at a constant velocity. But the earth's gravitational pull wants to pull the balls towards the earth (downwards) and the bigger ball has a greater mass meaning double the force [compared to] the mass of the small ball. So for the big ball $a = 2F/2m$ which equals to a and for the small ball $a = 1F/1m$ which equals to a. So therefore the acceleration must be the same. Thus meaning the balls fall at the same time and the same place. (LM 5; Claim 2, Evidence 2, Reasoning 2)

6.3.2 Rachel's small group interactions

Rachel benefited greatly from small group interactions with peers. The supportiveness of this interaction was evident from my observations as well as being a recurring theme in interviews with Rachel. She was placed in two different mixed-ability small groups for TFA lessons, one for the duration of Grade 9 and one for Grade 10. Her group was usually on

task, discussing the question in hand and co-constructing explanations through interthinking. In her interview at the end of Grade 9 she described her interactions in the TFA small group:

Rachel: I would say me and Melissa (Average $\langle g \rangle = -0.03$) are probably the ones who don't understand as much, but then Simon (Average $\langle g \rangle = 0.21$) and Mathilde (Average $\langle g \rangle = 0$), they're really good at picking out the ideas easily. And then without them giving you just the answer, we just talk about it, and then you get an idea. 'Oh, I actually understand now.' And so, then you can write your ideas down.

It is interesting to note that although Mathilde and Simon clearly provided a lot of support to Rachel in explaining concepts, Rachel was taking an active role in her learning. As she says, she was not just given the answers but was led towards deeper understanding of concepts so that she could form her own explanations.

Also, during the interviews at the end of Grade 9, Rachel, Mathilde and Patricia (Average $\langle g \rangle = 0.55$) explained that they often met outside of class to continue their TFA discussions.

Rachel: If we obviously can't catch up in person, we have a group message, us three on iMessage and we'll talk about our ideas about what we had for our thinking frames and stuff. It's like you're going to your teacher.

This proactive engagement with the small group highlights the benefits that Rachel clearly found in working together to construct understanding. Patricia was a high-achieving student who appears to have given Rachel further support in reaching a deeper understanding of concepts. Rachel seems to have developed mastery approach goals as a result of her small group experience. She is seeking out help which Hattie and Timperley (2007) notes is a very powerful feedback strategy to develop.

At the end of Grade 10 Rachel was interviewed again, and once again she expressed how helpful the small group discussions had been.

Rachel: I was lucky to have people who you could have a conversation with about different ideas, so that was helpful. And they were pretty on track most of the time. I had Bahardir (Average $\langle g \rangle = 0.57$), Kip (non-participant) and Eliza (Average $\langle g \rangle = 0.41$). We kind of all worked together. No-one really took charge. No-one said 'this is how you do it'. They would explain it rather than say, 'just write this down'. They explained how it works, which was good.

Bahardir was an enthusiastic student of moderate ability who willingly contributed his ideas and helped other students by explaining to them. It seems that the Grade 10 group Rachel was in was just as supportive as the Grade 9 group, the higher-achieving students willingly explaining to others but once again Rachel highlights that this didn't mean that others were doing the thinking for her. She was actively pursuing mastery goals as she built her own understanding throughout these discussions.

6.3.3 Rachel's use of multiple representations

Together with the support of the dialogic interactions in small group and whole class discussions, Rachel emphasised the importance of step-wise scaffolding during the TFA process as she constructed understanding of concepts. She developed a set of metacognitive strategies that worked together to support her in deeply processing understanding, particularly through drawing, which allowed her to form a mental representation of the concept that stayed with her for longer. By combining the ideas that she had developed while drawing and discussing these concepts, with the key scientific words that she had selected, she was able to more confidently write an explanatory paragraph. The steps of the TFA appear to have resulted in her developing greater intentionality and mastery goals. In interviews, Rachel highlighted the multiple representation aspect of TFA.

Rachel: I really like when we had the classroom discussions... you get everyone's idea of what they're thinking. And then we might go into our groups and then talk about it further. You separate the key words, and then you get to actually draw out what you think, even if it's really hard to draw, but you get to put it on paper what you think. You remember the picture that you drew instead of one you just looked at in the textbook. I find it helpful when you write the end statement thing - you look at your drawing and then you get an idea on what to put in your conclusion. You don't just forget it. It's not just note taking.

6.3.4 Rachel's improved confidence

Another important influence on Rachel's learning was her increased feelings of self-efficacy in both writing and understanding scientific concepts. In the interview at the end of Grade 10, Rachel confirmed that she felt a lot more confident in writing explanations and credited this change to the small group interactions and the way in which a series of TFA lessons built on the ontological model which supported her conceptual understanding.

Rachel: I feel like I have got a lot better at writing my explanations. I think it is due to understanding better and the group dynamic. When we were doing a thinking frame it would be like one little topic, but the next lesson it would

be something that linked on to that. So that if you could understand the topic from the lesson before, you would be able to understand the next day. It kind of all linked together.

Rachel also indicated that she felt more confident in understanding science in general, in understanding experiments and that the TFA had helped her remember concepts for tests. She still didn't have a very high self-concept in her ability in science but she believed that there had been a significant improvement. As mentioned above, prior to learning with the TFA, her negative activating emotion, worry, together with her performance goals, did not lead to deep cognitive engagement. However, the social commitment within the small group environment meant that she began to adopt mastery approach goals, which led to greater cognitive engagement and understanding which, in turn, led to increased self-efficacy, improved personal interest, and resulted in her experiencing a positive activating emotion – enjoyment. She was able to concentrate more fully in class because she felt involved in constructing explanations and she felt there was no other choice but to be intentional, especially compared to learning by reading from the textbook. She, once again, mentioned the class discussions as one of the causal factors for this change.

Rachel: Science, I used to, it's not that I didn't enjoy it, but I just, I didn't understand it a lot. I always worried about tests and exams. I find that the thinking frames are more helpful. I remember thinking back to the thinking frame and what we talked about in class, then I knew what to write about. I find that it's easier to remember than what you would've read off a textbook. Whereas if you have a classroom discussion, you're involved, you're forced to be involved in the conversation, so you're more likely to remember what you talked about than when you're drowsy reading and you're just not really focusing. I don't feel really good at science, but I feel I enjoy science more and I understand it more now than I did before.

When asked to think back and to rate her confidence in understanding science at the end of Grade 8, she gave a 3 or 4 out of 10 while she said that her present confidence level was 7 out of 10. When asked about her interest level, 2 years earlier she gave that a 3 or 4 out of 10 and a 7 out of 10 now – particularly for genetics and chemistry. When asked about whether her ability to understand concepts had changed, she believed that it had improved considerably, and that she had the capacity to understand. The mastery goals and deep processing strategies that she was now engaged in, together with her high level of self-efficacy and improved self-concept as a science student, led to her persisting for longer until she gained mastery of the topic.

Rachel: Yes, I think it's changed. I think that I understand a lot better, even though it might take me a while. In the end, I understand it.

In summary, it is evident that Rachel's significant improvement in conceptual understanding can largely be attributed to the supportive small group environment that she was placed in, combined with the process of building understanding through multiple representations using the TFA. The scaffolding in understanding provided by the TFA worksheets over a series of TFA lessons on a particular topic built understanding of the underlying ontological model and seem to have enabled her to produce detailed and convincing scientific explanations. The fact that she was able to visualise the scenarios successfully and produce detailed drawings of what she had visualised seems to have supported her recall and understanding in exams and conceptual tests.

Social support led to her actively using the metacognitive strategies available through production of multiple representations of her understanding, and to persisting even when concepts were difficult. She felt that she could ask questions and clarify her ideas freely within the small group, and her improved feelings of self-efficacy seemed to embolden her to ask and answer questions in the class. This was symptomatic of having developed mastery goals rather than just performance goals.

Overall Rachel's self-efficacy had increased considerably and she transitioned from being motivated by the negative activating emotion of worry to more positive activating emotions of enjoyment. This, in turn, led to greater intentionality in writing more detailed scientific explanations. With the improvements that she observed in her own understanding, her attitude towards science lessons and learning improved, which in turn, encouraged her to further engage with her small group even outside of class.

Before learning using the TFA Rachel said that she definitely didn't want to pursue any science in Years 11 and 12. After learning with the TFA, however, she chose to study General Science in another senior school. She returned to our school several times and asked to join my science classes for the day. She said that she missed the learning that she had experienced in the TFA classes.

6.4 Giselle and the TFA

Many of the students with higher than average NAPLAN numeracy scores, who were deemed to be high-achieving students, displayed higher than expected conceptual gains in the tests of conceptual understanding. Four high-achieving students, Will, Kyle, Margaret and Patricia all had moderately high average normalised gains of between 0.48-0.60. There were a number of higher-achieving students, however, who showed lower than expected

mean conceptual gains of between 0.14 and 0.28. Two of these students, Taylia and Barry, both had many absences from class and, additionally, Barry had mental health issues which resulted in him being withdrawn and not participating in many lessons. Giselle was chosen as an example of a student with a high NAPLAN numeracy score who showed a surprisingly low average normalised gain over the five conceptual tests (See Figure 6.1, blue cross).

Giselle was a diligent student who was recognised as a high-achieving student in many subjects. She was careful to thoroughly complete tasks, usually to a high standard, taking care to address all of the marking criteria. Her diligence led her to achieving A grades in all of her subjects. She usually worked hard to understand concepts and also achieved at a high level in tests. She expressed an interest in studying architecture or design at university.

6.4.1 Giselle's progression in conceptual understanding and written explanations

Giselle's conceptual test results and the corresponding normalised gains are shown in *Table 6.4*. She attained low normalised gains (Hake's) on the FCI (0.17) and CINS (0.14) tests, and actually showed much less conceptual understanding of concepts in the EPSE Set 2 post-test than the pre-test ($\langle g \rangle = -0.50$). The delayed post-test results for the FCI revealed that she had reverted to her previously held alternative conceptions after six months. The fact that she appeared to already possess many of the scientific concepts in the topic of natural selection as evidenced in the pre-test score (65%) may explain the small normalised gain in conceptual understanding in the post-test (70%). A moderate transfer from alternative to scientific conceptions in the TCE test was observed ($\langle g \rangle = 0.35$) and this persisted over a six-month period as shown in the delayed post-test results. The most outstanding gain was observed in the topic of genetics where Giselle began with no previous knowledge and possessed entirely alternative conceptions before learning while she transferred most of these alternative conceptions to scientific ones after the learning period ($\langle g \rangle = 0.82$). These mixed results were surprising. Even assuming that the EPSE Set2 results are an anomaly, she showed moderate gains but had a lower average standardised gain ($\langle g \rangle = 0.37$) than would be expected for her ability level compared to other higher ability students.

Table 6.4

Conceptual Test Results (pre-, post- and delayed post-tests) for Giselle.

Conceptual Test	Pre-test (%)	Post-test (%)	Delayed post-test (%)	Normalised Gain $\langle g \rangle$
TCE (thermal physics)	34.8	57.7	57.7	0.35
EPSE Set 2 (electricity)	40.0	10.0		-0.50
FCI (Newton's laws)	37.9	48.3	37.9	0.17
SRG (genetics)	0	81.8		0.82
CINS (natural selection)	65.0	70.0		0.14

The progression that Giselle showed over two years in writing scientific explanations can be seen in *Table 6.2*. Compared to the other two students, Giselle possessed greater proficiency in writing before joining the TFA class which was evident from her high NAPLAN scores in reading comprehension and writing (742 and 606) compared to Lawrence (635 and 558) and Rachel (583 and 595). She began the first year of TFA lessons with quite high LM scores. These scores remained quite similar throughout the two years of learning with the TFA. However, she generally achieved lower LM scores on physics topics than biology topics. This was consistent with her conceptual change results in *Table 6.4*.

From the beginning of Grade 9 when she started learning using the TFA, Giselle would draw detailed pictures that often explained her ideas stepwise in a cartoon-like format. For instance, the first TFA question on how we know about the structure of the atom clearly showed Thomson's model and Rutherford's experiment, followed by the conclusions that Rutherford drew (*Figure 6.5*).

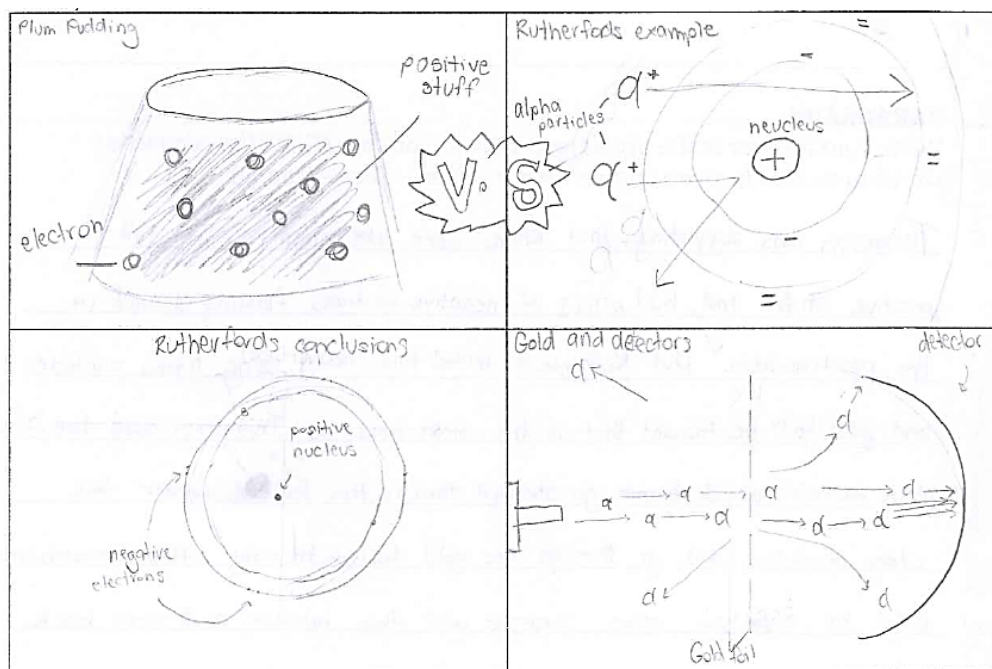


Figure 6.5 Giselle's visualisation of how our ideas about the atom changed.

Likewise, her paragraph explaining this question described the two models and linked the results of the experiment with the new model, using some scientific language, but did not successfully explain how the evidence justified her claims.

Giselle: Thomson was suggesting that atoms were like plum puddings – full of positive ‘stuff’ and had pieces of negative electrons floating around in the positiveness. But Rutherford tested this theory using alpha particles and gold foil. He thought that if the atom was as Thomson said the alpha particles

would go straight through the foil. However, the alpha particles did go through the foil with only little disturbance, until he saw one come straight off the nucleus and come back. Rutherford discovered that atoms were mainly ‘nothing’ with one positive nucleus because of his clever reasoning and careful experimentation. (LM 4; Claim 2, Evidence 2, Reasoning 0)
 Her level: Level: 2 It is not that detailed nor very clear of what actually happened. Sorry!

On the whole, Giselle’s visualisations were more explanatory than most students. For example, where most students just drew two cups describing what happened rather than why, her picture explaining why a paper cup with water in it doesn’t burn shows the particles in the water and she notes that the energy is being used to turn the water into a gas (Figure 6.6) While her written explanation mentions the high heat capacity of water and reasons that the thermal energy is being used to turn water into a gas, she does not explain thermal energy transfer or relate the concept of high thermal heat capacity to the slow rise in temperature.

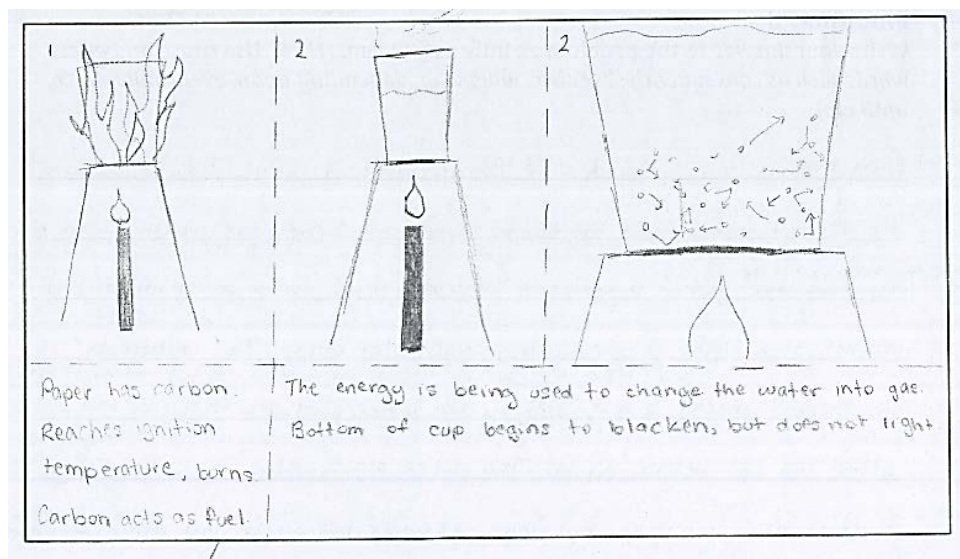


Figure 6.6 Giselle’s depiction of why a paper cup filled with water doesn’t burn

Giselle: When a paper cup is placed on a Bunsen flame it burns. This is because the thermal energy from the flame causes the carbon and oxygen to react and the temperature this occurs at is the ignition temperature. However, if you heat a cup full of water it will not catch alight, it only becomes singed on the bottom. This is because the thermal energy is being used by the water particles to break the attraction and become a gas. This is true since water has a very high thermal heat capacity. But when the water has all become steam/a gas the cup will burn as the energy is no longer being used. (LM

3.5; Claim 1, Evidence 1, Reasoning 1)

Her Level: 2 There may not be correct scientific language and it is not very complex/argumentative.

Notice that she once again had a very low view of the explanatory level of her own writing. This lack of confidence in her ability to understand new concepts fully and to express scientific arguments was a common theme in much of her work.

In the electricity topic, although she expressed that she found these lessons too rushed and that we did too many TFA questions, she produced some excellent explanatory diagrams to explain the challenge circuit that was given to them to solve. In both the drawings and her written paragraph, she appeared to have a good grasp of the concepts and very few alternative conceptions are visible. This makes the fact that she became even more committed to alternative conceptions in the EPSE post-test compared to the pre-tests more surprising. She apparently harboured some very persistent alternative conceptions about this topic that were resistant to change. She appeared to rely on Tom and me to explain and then wrote down what she had heard rather than truly constructing the argument for herself (see small group experience below).

Giselle showed an exceptionally high normalised gain in adopting scientific conceptualisations over her pre-existing alternative ones in the genetics topic. Throughout this topic her drawings and explanations were of a high calibre. Her final TFA 15 lesson analysing a pedigree gained a score of 5 on the Claim, Evidence and Reasoning rubric. She expressed to me several times during classes and in the final interview that she was very interested in the topic. This situational interest seems to have led to greater engagement with genetics concepts and may explain why she successfully transferred a significant number of her alternative conceptions to scientific ones during the learning period although she said in interviews that she needed the TFA less in this topic as she understood the concepts better than in other topics.

6.4.2 Giselle's small group interactions

Throughout the two-year period Giselle was in two different small groups and the group dynamic in each seem to have had a significant influence over her feelings about the TFA and her experience in learning science. Giselle was placed in a small group in Grade 9 where she was expected to be the ablest student, as she had always gained high grades in previous years and she had shown quite good understanding when answering questions in tests that required higher order thinking. Her small group experience in Grade 9 with Wendy, Ollie and Tom was overwhelmingly negative, from her perspective. She expressed some challenges that she found in interacting with this small group. Her interactions with Ollie

were frustrating as he was a particularly disengaged student who rarely completed a TFA task fully and was often off task. He had the lowest NAPLAN results in the class and achieved a very limited conceptual gain (Average $\langle g \rangle = 0.02$) across the five topics.

Giselle also mentioned that some students talked a lot in the small group which made it difficult for her to express her own ideas. Wendy, a student of average ability, was far more likely than Giselle to put forward her ideas in a small or large group discussion, as was Tom, also an average student in terms of NAPLAN numeracy scores. However, both of these students often became confused about what they were trying to explain, but nevertheless, were quite vocal in giving their explanations. Despite the level of talk from these students, it appears that there were times when they did look to Giselle for help in understanding, as she mentions that they 'copied' from her work, which she appeared to resent and this suggests a lack of willingness on Giselle's part to engage in interthinking. She also expressed discomfort when the other students looked to her to provide explanations as she felt unsupported in producing those explanations which is indicative of a low level of self-efficacy.

Giselle: [In the small groups] Sometimes you'll get a person who doesn't do anything, or maybe just like tries to copy off your work and you can't say no, but you want to help them, it's just a bit difficult. I don't really like talking in small groups, but also don't like how it's often one person just saying everything and it comes a bit difficult to have your thoughts heard or something like that, or if you have people who don't share at all, it's like, I'm kind of doing all the work, or I'm not doing anything. So, yeah, doesn't always work that way.

In comparison, interviews with Wendy showed that she appreciated the help that she did get from Giselle when she explained concepts to her. Wendy achieved an overall normalised conceptual gain of 0.25, while Tom achieved a gain of 0.21, both of which were consistent with their NAPLAN numeracy scores.

Giselle was generally passive in her learning in chemistry and physics, suggesting a low cognitive engagement, particularly in the topic of electricity where Tom seems to have taken over in setting up experiments and leading small group discussions. It is interesting that it was the EPSE Set 2 Test at the end of Grade 9 in which Giselle did so poorly ($\langle g \rangle = -0.50$) while Tom ($\langle g \rangle = 0.50$) and Wendy ($\langle g \rangle = 0.38$) showed significant improvement in conceptual understanding, which could be explained by the fact that Giselle felt she had lost control of her own learning and so was not really contributing to the group discussions and constructing her own explanations in the electricity topic.

Giselle: And for electricity Tom took charge. He set out the little experiment all the time and plugged in the bits and we watched.

In interviews, Giselle kept returning to the fact that she found the large class discussions more helpful than small group discussions. She consistently remarked on how much she relied on my explanations and drawings, as if she felt very uncomfortable in developing her own explanations for a topic. I noticed that Giselle hesitated to express ideas or make predictions in class discussions. She liked to work with other high-achieving students and tended to rely on them to answer more difficult questions. A frequent theme in her interview responses was that she preferred to be told the ‘correct’ answer by the teacher.

Giselle: Getting to hear everyone’s ideas [in big class discussions] and have each other thinking about the answers to the questions and then having you answer them for us is just very useful. Just listening to you helps me a lot because I listen and pick up things, just like that, but also the drawing, if you’re trying to explain something like the atoms, I think it’s like, I don’t understand anything, but then you like draw a diagram or like how they link or something like that, and I would just understand it.

The peer discussions that Giselle *did* find helpful in Grade 9 were with other students of similar ability:

Giselle: Talking with peers, I think, helps quite a lot, even if it’s not with a specific question or anything, just talking about it. I do it with Lawrence in class as, like, going through the stuff, but with Margaret, generally after class.

Neither Lawrence nor Margaret (Average $\langle g \rangle = 0.48$) were in her group but Giselle recognised them both as being of high ability and she sought help from them because they were willing to put forward their ideas and explanations in class.

Another limiting aspect in constructing understanding for Giselle was her high expectations of herself and her fear of failure in the eyes of the group or teacher. The high performance goals that she held led her to focusing on others’ perceptions of her as a learner, rather than being willing to engage in deep thinking and put forward her own ideas in class. When asked about her lack of participation in class discussions in an interview at the end of Grade 10, Giselle spoke about her fear of giving the ‘wrong’ answer in front of peers and the stress that she felt in speaking in front of the class. This stress was a negative deactivating emotion which also mitigated against deep engagement.

Interviewer: So, you didn’t say it aloud. Why?

Giselle: Well when I was a nervous bunny, it was probably a fear of being wrong and then everyone hearing that I was wrong but after that I just got used to that way of doing it, so I just kept it that way.

When asked about why it was difficult for her and others like her to take risks in giving answers, she suggested that being one of the students who has high status amongst peers, as someone who understands concepts better, can be a barrier for learning because there is a certain prestige to maintain. Even though she had high performance approach goals when completing individual work and when listening to me in class, when in small groups or when asked a question, performance avoidance goals were in evidence. She didn't want people to think she was stupid.

Giselle: They are so used to being right that they don't want to put themselves out there and be wrong and have everyone see that they were wrong. Especially when they are commonly thought of as being right.

Giselle also mentioned that she had always focused on getting A grades in all of her subjects and had found that this was becoming increasingly stressful by the end of Grade 9, once again highlighting the very high performance goals that she had set herself.

Giselle: Well, last year I was very much focussed on getting things right rather than understanding them fully. I was like, okay got to get all A's this year or something like that, but this year, I'm just like, okay, let's try to learn the concepts and understand them all.

Even though she recognised that understanding was more important than just focusing on getting A's in the class, her behaviour suggested that the external reward of A grades and being seen as a 'good student' were still strong motivating factors that influenced her classroom interactions. A fear of failure or of getting the wrong answer seemed to inhibit her ability to engage fully in classroom and group discussions that involved making predictions and seeing whether they were correct, or suggesting explanations based on her previous learning. As suggested by Clifford (1991), the reinforcement provided by the 'pseudo-symbols of academic success', such as receiving an A grade on relatively easy courses, mitigates against even moderate risk-taking in the classroom. This is consistent with Carlone's (2004) observations of high-achieving girls in a physics classroom who resisted engaging in an inquiry-based learning programme designed to promote deeper meanings of science because they felt that this may undermine their image as 'good students'.

In Grade 10 Giselle was placed in a different small group with Tom (Average $\langle g \rangle = 0.21$), Rebecca (Average $\langle g \rangle = 0.01$) and Bronwyn (Average $\langle g \rangle = 0.44$). Bronwyn was also a high-achieving student while Rebecca was a student with low self-esteem and

confidence. This combination seemed to suit Giselle and she felt more positive about participating more fully in small group discussions than she had in Grade 9, as they supported her more in expressing her ideas and she respected Bronwyn's explanations, which led to her activating some mastery goals with this group.

Giselle: It was good to talk with Bronwyn and Tom especially and then Rebecca had some good ideas too about genetics, about how the little parts worked. Well I was already pretty good friends with Tom and through that I became good friends with Bronwyn and Rebecca. We had a good group going by the end of the year. We are all pretty easy going. I feel like Bronwyn understood chemistry and physics better than I did so we would pair up and work it out and then explain it to the other two. But with natural selection Tom and I understood it a lot quicker than Bronwyn and Rebecca so we would help with them.

Giselle's greatest conceptual gains were in genetics, which was taught in the second semester of Grade 10. This may have been due to greater situational or topic interest and a more supportive social environment where she began to adopt some mastery goals which led to a move from negative deactivating emotion to a positive activating emotion and greater intentionality.

Giselle: Well, at the end of the first semester in Grade 10, I decided that this was the last chance to slack off before college so I decided that it was fine to get a B. And I think that was why I enjoyed it so much because I took the pressure off.

This willingness to see the big picture rather than stressing over the details, giving permission to herself to be less than 'perfect', appears to have benefited her participation and learning within the small group environment in semester two, Grade 10, especially in the genetics topic.

6.4.3 Giselle's use of multiple representations

The aspect of the TFA that Giselle found most helpful was representing the mental pictures that she held as drawings and this is consistent with the detailed explanatory drawings that she produced.

Giselle: [I like doing the] pictures. Because in a diagram you can still use words but I like to visualise things so that it is easier to show what is in your brain rather than changing it into words. The exercises we did helped me to write a more thorough answer.

6.4.4 Giselle's feelings of self-efficacy

As noted above, Giselle found evaluating her own work a challenge and was generally very critical of her written explanations, not believing that her own evaluations were valid. This was consistent with the levels at which she assessed much of her written work, usually LM 2, despite frequently being given feedback from the teacher that she was writing at level 4 or 5. One of the reasons for her undervaluing her own writing may be because she held high performance goals and saw herself as just copying what I was saying when writing her explanations, rather than really engaging intentionally in producing her own ideas.

Giselle: When hearing you explain it – I was often just copying exactly what you were saying in my writing so I felt that that didn't really count.

Overall, Giselle's response to the TFA seems to have been mixed. She claimed that she gained the most benefit from drawing her explanations. She still, however, seemed to prefer explicit teaching methods rather than being forced to construct her own understanding. Despite this, Giselle said that her confidence in understanding science at the beginning of Grade 9 was 4 out of 10 while it was 7 or 8 out of 10 at the end of Grade 10, possible due to improved outcomes in the topics of genetics and natural selection. Her confidence in writing scientific explanations, however, showed only a small improvement overall and is consistent with her critical attitude throughout of her own written explanations.

In summary, there appear to be several factors at play in Giselle's experience with the TFA which may have led her to have limited gains in adoption of scientific concepts. Firstly, her own high expectations of herself and her previous experiences of being a 'good student' led to her holding performance goals rather than mastery goals, which in turn led to her being unwilling to put forward solutions that she was not sure of for fear of being seen to be wrong. This, together with her negative deactivating emotions about the group she was placed in in Grade 9, inhibited her interactions in the class and in the small group.

Secondly, because of the mix of personalities in her small group in Grade 9 she felt unable to take a lead role in explaining to others. The other students held many alternative conceptions, which she was not comfortable to correct, and they were far more vocal than she in putting forward their ideas. When she was given the opportunity within the small group to explain her understanding she apparently felt unequal to the task and felt the lack of students whom she considered high achievers to support her in producing those explanations.

Giselle was not fully engaged in the social construction of her understanding and hence the benefits of some of the metacognitive strategies in the TFA, such as argumentation and production of verbal representations, were not available to her. This changed somewhat when she joined a new group in Grade 10 which appeared to give her more support. Once

again, she held back from truly expressing her ideas and relied on me or one of the other high-achieving group members to construct explanations. Since she was not actively involved in the construction, apart from in the genetics and natural selection topics, she did not benefit as much as other students from constructing her own explanations. Greater topic interest in genetics and natural selection appears to have led her to set aside some of her performance goals in favour of mastery goals. This, together with a more supportive social environment, led to her engaging in more interthinking with the group, further persistence and more productive use of metacognitive strategies.

Finally, she did participate in preparing detailed explanatory pictures throughout the two-year study and she did appear to gain some benefits from this and from preparing her written explanations. She continued to get quite high marks on tests which contained more 'knowledge' type questions rather than questions that challenged deeper conceptual understanding.

6.5 Cross Case Analysis

The in-depth analysis of these three students highlights the importance of the social construction of understanding. Rachel and Lawrence both benefited significantly from learning with the TFA while Giselle showed much lower conceptual gains in most topics than would have been expected for a student of her ability level. While Rachel and Lawrence both interacted enthusiastically and productively with other students in their small groups, Giselle was much more withdrawn and uncomfortable with those interactions.

Lawrence and Rachel were both in small groups where they were considered of average ability and where there was a student of higher ability who was willing and able to explain their understanding to them. They took advantage of this arrangement by seeking help from the higher ability students when necessary. Both students appear to have developed epistemic motivations that avoided closure, willingly seeking to re-structure their understanding (Kruglanski, 1989).

The small group arrangement gave Rachel confidence to ask more questions which she would not have done in the whole class. As she became more confident in her understanding, she began to put forward her own suggestions and explanations within both the small group and the larger class. She also extended the TFA small group situation by using social media to discuss and extend her understanding through interactions outside of class. As her small group supported her in constructing multiple representations of her understanding, the greater self-efficacy that she experienced due to improved writing and LM levels led to her adopting mastery goals and becoming more intentional in utilising the metacognitive strategies that the TFA provided.

In Lawrence's case, he began with greater confidence in his ability to understand concepts than Rachel did, and hence he participated more fully from the beginning in producing explanations within the small group. He particularly benefited from discussion with Kyle. The competition that he engaged in with Kyle was positive, in that both students worked together to improve their verbal explanations and then were motivated to achieve a higher score by carefully elaborating their written explanations. The peripheral persuasion that Lawrence experienced because of his admiration of Kyle's competence, led to his adopting strong mastery goals as well as performance goals. This led to an increased intentionality in using the cognitive strategies presented by the TFA process.

Giselle, on the other hand, displayed limited participation in group discussions. She struggled to construct understanding in certain topics, particularly in the electricity and Newton's laws topics. She was clearly searching for other students, who she felt had better understanding than herself, to explain to her and help her understand new concepts. Since she was placed in a group where she was the highest ability student, scientifically accurate explanations from others were not available to her. She was unwilling to put forward ideas that she thought might be 'wrong' because of high performance avoidance goals and hence she frequently left the construction of understanding to the other students in her group. This attitude changed when she was placed in a new group in the second year. She was clearly more comfortable learning when she perceived that there was a student, like Bronwyn, who was of greater ability than herself to help her. As she felt more support from her group, she also contributed more to developing explanations, particularly in the topics of genetics and natural selection.

Not feeling the freedom to make alternative conceptions visible to herself and others in the class by articulating them verbally seemed to be a stumbling block in Giselle's learning. In comparison, Lawrence, and Rachel enthusiastically embraced the practice of predicting what would happen in an experiment, demonstration or thought experiment and were very willing to share their ideas and explanations with others in their small groups and with the whole class. Rachel, in particular, grew in confidence in presenting her thinking to her peers over the two years of implementing the TFA.

Four other high-achieving students, Will, Kyle, Margaret and Patricia, were placed in four other small groups as the highest-achieving students in those groups. In comparison to Giselle, all were very willing to share their ideas and explain to others in their groups. They frequently contributed explanations that they had constructed to the whole class and to peers. Members of their groups frequently mentioned that these students helped them with their understanding. Patricia noted that, when she wasn't quite sure that her explanations were logical, she would turn to Margaret, who was in an adjacent group, and they would

quickly present their ideas to each other in order to clarify their understanding and then return to their groups to elaborate their explanations. As noted above, all four of these students showed moderately high average conceptual gains, much higher than those gained by Giselle.

These examples support the importance of the social constructivist aspect in implementing the TFA. One of the keys to success is the construction of the group environment. The teacher's input in creating appropriate groups is essential. Will, Kyle, Margaret and Patricia all embraced their role as explainers and encouragers within their small groups. However, while some groups like those that Lawrence and Rachel were part of, were successfully able to discuss, argue, defend and work together to construct scientific explanations, others groups were less supportive.

Giselle, as the student chosen to support academically weaker students' understanding in her group, was not confident in her own abilities and not willing to explain to other students, because she did not feel that she was capable of finding the 'right' answer alone. This left a void which was readily filled by more vocal students. It is interesting to note that the two students in Giselle's group who were willing to put forward their ideas, Wendy and Tom, both benefited from the opportunity to discuss their ideas, predict and explain their observations, showing greater average normalised gain in understanding than students of similar ability in the comparison class. Even though they did express many alternative conceptions in their small group discussions both Wendy and Tom replaced a significant number of these conceptions with scientific ones by the end of each topic, particularly electricity. Verbalising their ideas and discussing these with their peers and the teacher appear to have enabled them to undergo conceptual change.

Another notable difference in response to the TFA between Giselle, Rachel and Lawrence is in attitude towards constructing understanding. The epistemic motivation that Rachel and Lawrence developed was one of avoiding closure, which meant that they took advantage of the TFA process to enable them to restructure their own understanding. In comparison, Giselle continued to feel uncomfortable with this construction process, and her epistemic motivation appeared to be one of seeking closure as she consistently preferred the teacher to tell her the 'right' answer. When this was not available to her, she felt that she was not able to achieve a level of understanding that she was satisfied with and hence she continued to evaluate her own written explanations very critically. On the other hand, both Rachel and Lawrence expressed much greater feelings of self-efficacy in producing written explanations after learning using the TFA.

The resultant improvement in conceptual understanding that Rachel and Lawrence achieved improved affective aspects, such as mastery goals and intentionality, personal interest and positive activating emotions, particularly for Rachel. In turn, these positive student characteristics interacted with the epistemological, ontological and social aspects of the TFA process to further improve conceptual gain. Overall, students with supportive groups, who used the opportunity provided by the TFA to develop their own arguments, mental pictures and explanations through discussion, drawing and writing, were more likely to achieve greater conceptual change than expected when their ability level was taken into account.

Chapter 7. TFA Support to the Teacher

In order to understand how well the TFA acts as a systematic scaffold to the teacher in providing students with experiences that encourage multidimensional conceptual change this section reflects on my experience implementing the TFA in the classroom. My reflections are as a response to Research Question 4: *What were the affordances and limitations of the TFA in supporting me to implement a multidimensional approach to conceptual change?* My experience is critically examined in terms of the supportive and challenging aspects of using the TFA to address the epistemological, ontological and social/affective dimensions of conceptual change. Changes in my pedagogy and attitudes are noted. I also describe modifications that I made to the TFA process, suggestions for further improvements and ways forward in supporting teachers in its implementation.

Through the process of teaching with the TFA I have also undergone considerable conceptual change about my own pedagogy. Duit and Treagust (2012a) suggest that teachers need to undergo considerable restructuring of their conceptual understanding of effective teaching practice in order to successfully implement a social-constructivist approach that addresses multiple dimensions of conceptual change. A helpful way to view the mechanism by which I changed my pedagogical commitments is by use of the Cognitive Affective Model for Conceptual Change (CAMCC) (Gregoire, 2003), which describes important elements that are predictors of successful adoption of new pedagogies by teachers.

Initially, the TFA as a pedagogy challenged my identity as a teacher as it incorporated a number of methodologies such as small groups discussions, production of challenging demonstrations and drawing of conceptual understanding, with which I was unfamiliar or did not feel comfortable in implementing because of prior difficulties using such methodologies. For instance, I had never used drawing as a means of encouraging students' conceptual understanding and my previous experiences with small groups had been unproductive, as discussed below. Adoption of the TFA also created cognitive conflict between my belief that I was using student-centred, constructivist methodologies, prior to teaching with the TFA, and my recognition that I had been teaching from a teacher-centred, didactic ontological framework, frequently returning to teacher explanations rather than providing genuine opportunities for students to construct their own explanations.

In terms of the CAMCC (Gregoire, 2003) engagement with learning to use the TFA 'Implicated Self' as it posed a challenge to my previously held beliefs about teaching. At this point, recognition of the difference between my previously held pedagogy and beliefs with those presented was stressful, in that it meant that I was no longer comfortable with my

previous beliefs but felt challenged by having to adopt an unfamiliar practice. This is not necessarily a negative experience, especially if it leads to greater motivation to engage with the change process. My change to a student-centred multidimensional conceptual change pedagogy was mediated by my positive activating feelings of self-efficacy as it became evident that teaching using the methodologies of the TFA was resulting in significant improvement in conceptual understanding for my students. Positive experiences with small groups also overcame previously held negative emotions and beliefs surrounding their efficacy. Previous mastery experiences and the belief that I possessed sufficient content knowledge and resources available through the TFA's systematic framework to address this change also were motivating factors.

This led to what Gregoire (2003) calls a 'Challenge Appraisal' rather than a 'Threat Appraisal' and which resulted in my systematically and persistently engaging in the TFA process. Finally, the results from the study, my recognition of the efficacy of adopting the TFA together with an underlying change in my ontological commitments, led to long-lasting conceptual change about both the multidimensional components of the TFA and, more generally, about the benefits of social-constructivism. This conceptual change has resulted in my persisting in using this pedagogy, despite some initial resistance from students.

7.1 Developing Strategies to Address Epistemological Change

The structure of the TFA requires the teacher to firstly understand common alternative conceptions of students within a particular topic and to develop appropriate demonstrations and questions to challenge those conceptions. These aspects are consistent with the findings from conceptual change research that address epistemological understanding (Chi, 2013; Posner et al., 1982).

7.1.1 Investigation of students' conceptual understanding

The TFA lessons make alternative conceptions visible by challenging them through appropriate demonstrations or thought experiments and thus allowing students to discover how inadequate they were to explain observations. As an experienced science teacher, I was aware of some of the common alternative conceptions that students hold on a variety of topics; however, I had tended to directly teach students scientific models and concepts and had not considered the value of making alternative conceptions visible to students. I was more concerned with providing scientific explanations and avoiding alternative conceptions in whole class discussion.

As part of the TFA process I therefore began to seek out lists of common alternative conceptions on each topic. These are relatively easily found by a search on the internet,

although I suggest that greater access to lists of the most common alternative conceptions related to each topic taught in middle/high school science would make this aspect of the TFA process easier for classroom teachers who are time-poor and do not have access to education journals.

I also investigated various conceptual inventories and assessment instruments to determine whether students had undergone conceptual change through TFA lessons. The TFA does not require the use of conceptual inventories; however, I found that use of these extended my awareness of the alternative conceptions held by my students, and sometimes by myself! Students also began to enjoy testing their knowledge before starting a topic and after completion in order to understand how much their conceptual understanding had improved. One difficulty I encountered was in finding appropriate conceptual inventories. Many of the ones that are available were developed for older students and the language used and the level of concepts tested were not always accessible to younger students. I suggest that making age/grade appropriate conceptual inventories available to teachers would also be of benefit in further adoption of the TFA by classroom teachers.

7.1.2 Devising demonstrations to challenge alternative conceptions

On the basis of my understanding of these alternative conceptions I began to design my teaching of topics around the most prominent of these alternative ideas. The first step of the TFA makes students' alternative ideas visible to them by allowing them to predict what would happen in a demonstration designed to challenge those conceptions.

Production of appropriate demonstrations, thought experiments or scenarios and the corresponding guiding questions requires some careful thought (Gilbert & Reiner, 2000). I found that student engagement was the greatest when demonstrations used everyday items, as students tend to hold one explanation for "scientific" phenomena and another for everyday phenomena (Duit et al., 2008). The explanation with which students are encouraged to replace their previous conception must be clearly supported by the demonstration, without ambiguity. It is important to avoid inadvertently supporting other alternative conceptions through the demonstration. They must also take into account the developmental level of the student and not require conceptual understanding beyond the capacity of the students or the particular scientific model being presented.

Bearing these aspects in mind, a series of TFA lessons was relatively easy to design in the topics of thermal energy and the particle model of matter. Some topics, however, were more difficult to address with a demonstration. For instance, demonstration of Newton's first law requires an environment where no net forces are acting; however in the classroom, the existence of other forces, such as friction, can provide further support for some commonly

held alternative conceptions, such as that impetus wears out. I used a demonstration of removal of paper from underneath a beaker filled with water by pulling on it quickly to develop understanding of the concept of inertia. This was exciting and the results were counter-intuitive to many students; however, the explanations of the observation that the beaker remained in its place, were confused as they recognised that there was a force acting on the beaker - friction. Some students therefore thought that motion would occur when resistance was overcome.

I found that several demonstrations did result in observations, such as these, that appeared to confirm some students' alternative conceptions. It took me some time to trial demonstrations and find appropriate ones. With experience over the two years of using the TFA I was able to modify or replace these demonstrations with more productive ones. In topics such as genetics and natural selection it was not possible to carry out demonstrations and so I used thought experiments or scenarios instead. However, I suggest that sets of demonstrations and scenarios are developed to overcome such unintended results and that these are made available to teachers along with training in use of the TFA. On the whole, I was able to use demonstrations or scenarios, to successfully elicit and challenge alternative conceptions.

I observed that this was a much more powerful way of teaching these concepts than directly explaining them to the class. Students became more aware of their own alternative conceptions and the surprise that they felt in their predictions not being realised led them to ask deeper questions in the class discussions as they attempted to find a more satisfactory explanation which was consistent with their observations. Previously, as I explained common alternative conceptions, it was apparent from students' later explanations and questions that these alternative conceptions were still held by most students. These observations encouraged me to persist in understanding students' alternative conceptions and finding appropriate demonstrations to challenge them.

7.1.3 Developing interesting questions

Following on from the predictions and demonstrations, the TFA process requires the development of questions that encourage students to engage with their alternative conceptions and the scientific concepts to find causal explanations relating their observation with these scientific concepts. I found that it required considerable thought to develop TFA questions that were sufficiently challenging and required students to visualise and apply their understanding while not being so complex that students felt defeated before they began. Some of the questions that I asked students were too complex or had too many parts and in these cases the time constraints of the lesson meant that students did not complete the TFA

worksheet. With experience using the TFA I became more adept at asking questions of the appropriate level of complexity.

In some topics it was challenging to find questions which would encourage deeper thinking and explanation of causal relationships. In Grade 8, the topic of cells and body systems involved a lot of descriptive content so questions simply related to the structure of the cell or the organ systems would only result in students describing those systems – a level 2 on the Levels Mountain. The questions that I devised for the TFA needed to encourage students to develop deeper conceptual understanding relating the structure of different cell types and organ systems with their functions. For instance, in a TFA lesson about different cell types, I showed students pictures of several very different types of cells and asked them to think of reasons why these cells had such different structures, considering the jobs that they had to do. These kinds of questions allowed students to aim for higher levels of explanation.

In conclusion, the TFA process caused me to engage with identification of students' alternative conceptions and develop appropriate demonstrations that challenged those alternative conceptions. It also directed me in the production of appropriate questions which would allow students to produce causal scientific explanations of their conceptual understanding. Each of these aspects of the TFA allowed me to support students in replacing their epistemological beliefs with scientific understanding. A further consequence of these steps was that I was convinced of the power of addressing students' alternative conceptions through the use of discrepant events, discussion and construction of understanding rather than directly teaching scientific concepts.

7.2 Linking Student Thinking to the Ontological Model

As discussed in Chapter 2, change that occurs only on the epistemological level without addressing the underlying ontological commitments of the student has been found to be transitory or piecemeal (Chi, Slotta, et al., 1994; Duit & Treagust, 2003). The TFA was originally designed to encourage model-based thinking in students (Gilbert & Justi, 2016; Grevatt et al., 2007; Newberry et al., 2011; Newberry et al., 2005). To this end it used 'placemats' or one page pictorial summaries of the curriculum model for each topic. The curriculum model is one which provides an age-appropriate simplification of the scientific model as delineated by the curriculum (Grevatt et al., 2007). Therefore, at the heart of the TFA process is the goal of encouraging students to link their conceptual understanding with the scientific model. The Levels Mountain reinforces this goal by encouraging students to produce causal explanations using scientific language and arguing from the viewpoint of the scientific model in order to gain a Level 5 on this rubric (Newberry et al., 2005).

At the outset of my teaching experience with the TFA, I began by using the available ‘placemats’ with Grade 8. ‘Placemats’ for Grade 9 and 10 topics were not available, however. My observations of students’ use of the placemats was that they used them as prescriptive tools, which constrained the format of the drawings that they made, rather than encouraging development of their own representations, both internal and external. I wanted students to develop greater facility in imagining the model, for instance atoms moving and bouncing off each other, and to encourage creativity in representing these movements and interactions and hence I quickly abandoned use of the ‘placemats’. Some of the problems that I encountered with students producing pictorial representations will be discussed below.

7.2.1 Building understanding of the ontological model

Instead of the ‘placemats’ I chose to support students in developing a scientific ontological understanding through design of a series of TFA lessons based on different aspects of that model. I firstly researched characteristics of commonly held non-scientific ontological frameworks and ensured that I clearly understood the scientific ontology that I was wishing to present. As Chi (2013) suggests, it is difficult for students to make ontological category shifts without confronting the ontological categories that they presently hold and providing them with direct teaching about new ontological categories so that they can place their epistemological conceptual understanding within those scientific categories.

So as to provide students with an ontological schema which may be missing in their conceptual ecology (Chi, 2013), each unit included some explicit teaching of the scientific model, for example, the kinetic theory of matter (KTM). This might involve teacher explanations, analogies or visual simulations. For instance, to teach the kinetic theory of matter, a group of students was asked to model the behaviour of particles in a solid, liquid or gas. Peers were asked for comments and improvements and the teacher then showed students how their model differed from the scientific model. For example, most students held a flawed model where particles in a solid are stationary and this belief needed to be addressed before students began using the model to interpret and make predictions based on the TFA questions and demonstrations. An analogy, using the idea of dodgem cars, was used to explain transfer of energy between particles through collisions. These preparatory lessons were social constructivist in nature, in that they involved class discussions, students putting forward their conceptions and teacher questioning to lead students towards deeper understanding of the scientific model.

In order to focus students’ attention on building understanding and application of the scientific mental models, I linked multiple lessons together. By my doing so students had opportunities to apply their understanding of the model in different contexts and to

understand different aspects and consequences of the scientific model. For instance, in the topic of thermal physics, the KTM, which explains energy transfer through collisions, can be used to explain thermal equilibrium, latent heat of vaporisation, conduction, convection and thermal heat capacity. As students encountered each of these concepts, they gained practice in applying the KTM model in each context which resulted in their gaining greater understanding of the explanatory power of the scientific model. As it became clear to students that the KTM model was very useful in explaining a large variety of phenomena the status of this model was raised to supersede their previously held Caloric model.

A key aspect of the TFA in encouraging adoption of the scientific ontological model was teacher-student dialogic interaction, which will be discussed in 7.3.3

7.2.2 Use of multiple representations to develop deeper conceptual understanding

A central aspect of the TFA is the production of student-generated multiple representations to encourage students to construct their understanding of concepts and explanations of phenomena. In my previous teaching practice, I had used multiple representations to illustrate concepts but these were almost exclusively teacher-generated and not student-generated.

As my experience with the TFA progressed, it became clear to me that students' ontological understanding as well as their epistemological understanding was being supported through the 'productive constraints' (Tytler & Prain, 2013) of producing explanations in different modes. For instance, following on from producing a verbal explanation of their conceptual understanding, drawing their explanations in terms of the KTM model also supported their adoption of this ontological category, as they represented the particles moving colliding and transferring energy.

Production of multiple-representations of a students' understanding, verbal, pictorial and written, within each TFA worksheet, also enabled me to have a clearer view of each student's level of understanding, not only of the particular epistemological concept addressed, but also their ontological commitments. This also provided an opportunity to give individualised feedback to students about each of these aspects in a timely manner.

The brainstorming section of the TFA was designed to allow students to work together to think of words that could be used in their verbal and written explanations. It was suggested that all words are accepted and that students then cross off those words that they later decided were not useful when writing their final paragraph (Newberry et al., 2011). This process, together with the production of multiple representations, forms part of a process to support students in explaining the link between the ontological model and their newly acquired epistemological understanding using scientific vocabulary. I found this

section to be an important part of the process. Not all students valued this process. I did not insist on students crossing out those words that were not useful or based on alternative conceptions as they wrote their paragraph. I think that this may have been beneficial in supporting greater self-regulation for students. Later, in interviews it became apparent that several students used them productively as a check to determine whether they had addressed the topic thoroughly. In future I would put greater emphasis on the self-regulatory check that these keywords provide and remind students to add in any more useful words and cross off unhelpful ones as they plan their writing using the dot-points and to look back at these words when writing their paragraphs.

Initially, because of my own lack of ability in drawing, I tended to undervalue the drawing aspect of the TFA. Although I asked students to complete this section, I often did not ask them to evaluate this section from the Levels Mountain. This sent an unspoken message to students that this section was less valuable than the written explanations, which they and I did evaluate. As a consequence, many students would rush through this drawing or draw trivial pictures of the equipment rather than trying to draw explanatory diagrams. While some students would draw detailed, annotated pictures, several students expressed that they found this section the hardest as they didn't know what to draw for some questions. A small number of students avoided this section all together.

In hindsight I think that this section would have benefited from being regularly graded according to the Levels Mountain. This would have given greater weight to drawing explanatory pictures – an extrinsic motivation. More comprehensive comments and feedback about this section would also have increased its status and provided students with ideas of how to improve future representations. Also, more explicit guidance to students about conventions in scientific drawing, ideas about alternative ways to represent processes and examples of different kinds of causal drawings would give greater scaffolding to this section and increase its status as a useful component of the process.

Despite these limitations, when I interviewed students about their experiences in the middle of the first year of the study, I became aware that many students did in fact find the production of drawings extremely fruitful in supporting their understanding of the ontological model and their ability to visualise the processes that were occurring. As a result of my observations that students were more comprehensively adopting scientific ontological categories through use of the multiple representations, particularly drawings, I began to appreciate the value of this step in the TFA process and encourage students to make more elaborated explanatory drawings. By the second year of the study I began to develop questioning which encouraged self-regulation of students, such as asking them to look at their drawings from the eyes of another person to see whether they could understand their

explanation of the phenomena from the drawings alone. I also asked students to explain what different elements of the drawings meant and how they could improve their drawings to give them more explanatory power.

One of the greatest difficulties I found with the TFA was in pacing the lessons. Lessons were 50 minutes long. Students often spent a lot of time in discussion and working on the drawings which left insufficient time for some students to complete their written explanation thoroughly. I often had to hurry students along and tell them to stop drawing and start writing. I felt that it was important to complete the TFA questions in one lesson in order to ensure that they actively engaged in the process during class time rather than putting off the work to complete at home. Also, the probability of students losing their sheet or not completing them anyway if they took them home was fairly high.

Several students commented in interviews that the TFA lessons were sometimes rushed because it took time to understand the problem, discuss it with their group and decide on how they would draw their ideas as well as writing an answer. Some students stopped filling in the think/sequence (dot point) section as they said that after drawing the pictures they had a clear idea of what they wanted to say and in what order. In future I would suggest a period of 60-70 minutes to give time for students to complete each section of the TFA process.

In conclusion, the TFA showed moderate success in supporting conceptual change in the ontological dimension. The main supporting factors which helped me to encourage change on this level were the production of pictorial representations and the goal of writing a causal explanation based on the ontological model. Completion of a series of TFA lessons which addressed different aspects of the model and gave students opportunity to practise applying the model in different contexts also helped to support students in adopting a more scientific ontology. On further consideration, however, I think that the use of 'placemats' should be revisited and developed to provide further scaffolding to students in understanding and applying the scientific ontological model. However, the benefits of providing further scaffolding of understanding of the model must be weighed against the concern that students will take the representations provided on the 'placemat' as normative representations of reality, rather than models, and will simply copy those drawings, rather than constructing their own representations.

7.3 Addressing Social and Affective Aspects of Conceptual Change

Using the TFA brought about radical change in my pedagogy in four areas which supported students' social construction of understanding: productive use of small groups which encouraged student-student dialogic interactions; teacher-student dialogic interactions that

supported students in construction of scientific ontological models; greater engagement with and higher expectations of students with special needs and/or lower-achieving students; and more productive and timely feedback. Although these aspects are not explicitly stated in the description of implementing the TFA, I found that they were a natural consequence of the social arrangement of the TFA, PDEODE process and the use of the Levels Mountain.

7.3.1 The TFA and small heterogeneous groups

The results of student and teacher interviews presented in Chapters 5 and 6, highlight the centrality of the heterogeneous small group to the TFA process. This aspect presented, perhaps, the greatest challenge to my pedagogy.

Previous experience with small groups. Before I used the TFA, I was hesitant to assign any group work because I had previously found these unproductive. Generally, the small group activities I had used involved students choosing their own group. I found that students generally chose to work with friends and enjoyed conversations rather than engaging fruitfully in given tasks. When students chose their own groups, the tendency seemed to be for them to choose homogenous groups, for example students of higher ability would choose to work with others of similar ability. Even when students were placed in mixed ability groups, they often resisted engaging in deeper discussions with their peers and tended to work side-by-side but separately. Students often expressed how much they disliked doing group projects, as usually there would be some students who ended up doing most of the work and the less diligent ones would be disruptive, or their lack of effort would result in lower marks for the group as a whole. Very often the work given as group-work was of a trivial nature, involving knowledge acquisition rather than students constructing a deeper understanding by engaging with complex concepts or ‘ill-structured’ problems (E. G. Cohen, 1994; Schreiber & Valle, 2013).

Structuring small groups. As the TFA requires extensive small group work, this caused me to look into some guidelines for assigning groups. I carefully structured the small groups to include a mixture of high and low-achieving students (E. G. Cohen, 1994; Hooper & Hannafin, 1988; L. H. King, 1993; Swing & Peterson, 1982; Tudge, 1990). High-achieving students have been shown to benefit from the opportunity to explain to others (Swing & Peterson, 1982) while low-achieving students benefit from explanations given by the high-achievers and the opportunities to ask for clarification and express their ideas, much more so than if they were in homogeneous low-achieving groups (Hooper & Hannafin, 1988; Tudge, 1990). In order to address these findings, I placed one student in each group who had previously shown high levels of conceptual understanding. I then added a student into each

group who had found conceptual understanding challenging in the past. Two or three other students of varying ability were then added to make up the groups.

I also took into account the social skills of the participants in each group. This was important in order to maximise the interactions between group members (E. G. Cohen, 1994) as some combinations of students would not result in discussions and not all students who were able, would be willing to share their ideas with others. Some ‘trial and error’ was involved in finding the most fruitful combinations.

My experience of small groups when using the TFA. To my surprise, I found heterogeneous small groups worked exceptionally well with my students as noted in 5.1.3. I found that when students are consistently placed in small groups and have time, over weeks and months of using the TFA, to get to know the strengths and weaknesses of their group members, that they began to interact more deeply in discussions, helping each other understand and visualise the concepts, and then write explanations. The type of high order, ill-structured questions that were used in TFA lessons led students to develop greater reliance on peers and peer-tutoring and they made use of opportunities for genuinely constructing their own understanding (cf Gillies, 2004). Over the course of the year, as students became more comfortable with each other and the TFA process, the level of productive student talk within the small groups increased. Other benefits of the TFA small groups were discussed in Chapter 5. These observations increased my belief in the utility of these groups and my positive feelings about using them in my classroom. I would strongly suggest that these guidelines for choosing small groups be made an essential part of the TFA.

Challenges with small groups. Despite the successes experienced through students working cooperatively in small groups, there were some challenges I needed to attend to. Achieving successful groups took some time and modifications of those groupings were necessary in the first few months of implementation. For example, Giselle’s group (see Chapter 6) that had a good mix of high-ability and lower-ability students was not effective because Giselle was unwilling to contribute actively to discussions, while other, more vocal students, continued to put forward their alternative conceptions. The following year this group was re-organised to address this issue.

In a class of 30 students or less, I found that it was difficult to ensure that all small groups, consisting of 4 to 5 students, met all of the criteria for productive interactions. Not all of these challenges could be addressed as it was impossible to produce seven perfect groups within the classroom context. However, awareness of these challenges gave opportunities to reconsider each small group structure when designing small groups in other classes.

Consistent with Cohen's (1994) research some of the high-achieving students found having to explain constantly to the other members of the group frustrating as they expressed that they often did not have time to complete their own work and so had to take it home to finish off. In order to encourage these high achievers, I helped them to see some of the benefits of explaining to others and gave them the opportunity to consult with other high achievers in nearby groups when necessary. Some of the high-achieving students missed the security of having others of a similar ability level to corroborate their ideas.

As Cohen suggests, having 'positive goal interdependence' doesn't guarantee successful interactions. Some interesting effects in groups which generally resulted in girls being disadvantaged in terms of achievement in the group if there were boys present are noted in the literature (N. M. Webb, 1984). I observed one group where this was the case, in that, the two boys didn't want to interact with the two girls in the group and were irritated that their team members didn't understand and so tended to just work together, ignoring the female members. I tried to address this issue by encouraging the high-achieving boy in this group to be a facilitator of the discussions. In this case, the student was unwilling to perform the role and the girls were moved to another group where the group interactions would be more supportive.

7.3.2 The TFA supported social-constructivist dialogue

The fact that students work together in the TFA to produce predictions and explanations puts the teacher at arm's length during the discussion process and allows for more productive student-student dialogue than would normally occur in the classroom. This process increases the wait-time between the question being asked and the students giving their answers. However, because of time constraints, I felt that these small group discussions were sometimes rushed. A longer lesson period would allow these discussion times to be extended further. I usually gave approximately four to five minutes to each section of the PDEODE which meant that this process took up about half of the lesson. The benefits of the small group interactions through social construction have already been discussed in Chapters 5 and 6.

Teacher-student dialogue, particularly questioning, is an important feature of the TFA during the PDEODE process. The underlying assumption of the approach is that teachers are helping students to construct their understanding. Although not explicitly stated in the TFA, I found that this process made me think twice before giving my own explanations. As I began to gain a greater awareness of the benefits of students' construction of their understanding, I began to develop questioning strategies that supported students in becoming aware of their non-scientific conceptual frameworks and provided opportunities

for students to develop deeper understanding and engage with the scientific ontological model. From my experience, training to use the TFA should include teaching of questioning strategies to help teachers understand how to ask questions that draw students' attention to the scientific model, encourages elaboration and challenges alternative conceptions, without quickly giving students explanations.

Previous patterns of teacher-student dialogue. In my previous teaching experience, I had enjoyed having whole-class discussions where I sometimes used a Socratic-style questioning method to elicit student understanding of a topic and to challenge ideas. However, I noticed that I often quickly reverted to giving students explanations when they didn't seem to understand concepts and easily returned to direct teaching. This kind of lesson usually took place to introduce a topic, rather than as a regular element of every lesson. Although I encouraged dialogue in my classroom, the interaction did not encourage comparison of points of view and in this sense can be classified as authoritative-interactive rather than dialogic discourse (Mortimer & Scott, 2003). This type of whole-class discussion resulted in limited opportunities for students to participate. Even though I would nominate students to answer questions to ensure that all students had a chance to participate, many students were too shy or lacked confidence in their answers and so gave limited explanations. I often didn't wait long enough for students to form their explanations. Many students who had questions sat quietly and felt unable to ask these in front of the larger class. Although I thought that I was encouraging construction of student understanding with these discussions, when I look back now I realise that my pedagogy was more didactic than constructivist in nature.

Changes in questioning style. Initially, when using the TFA, I still tended to revert to giving scientific explanations after students had worked in their groups and come up with their explanations. This happened particularly when a lot of alternative conceptions were still evident. As I continued to use the TFA, however, I became aware of the way that I was providing explanations rather than encouraging students to develop their own understanding.

As a result, I began to develop questioning strategies which encouraged students to explore and compare their ideas, and to bring students' attention back to the ontological model, challenging their alternative conceptions. I used these questioning strategies after the PDEODE section and as I walked around the class, going from group to group, as they produced their drawings, dot-points and written explanations. I also noticed that I became more aware of giving students time to formulate their answers. Thus much of the classroom dialogue during the PDEODE section could now be classified as dialogic interactive, particularly as it encouraged students to negotiate in small groups and in class discussion to

construct their explanations (Mortimer & Scott, 2003). The PDEODE portion of the lesson was a major feature of the TFA, taking approximately 30-40% of the lesson time.

Examples of teacher-student dialogue during TFA lessons. In order to critically examine the teacher-student dialogue that had developed, transcripts of all TFA lessons in two topics, thermal physics and genetics, were analysed. These two topics were chosen as representatives of the physical and biological sciences. I critically analysed the types of teacher-student dialogue in TFA lessons during class discussions and as I moved from group to group.

Teacher-student dialogue was transcribed from video and audio recordings of all TFA lessons in the topics of thermal physics and genetics. Each teacher-student interaction was coded, as described in section 3.7.3, and the themes that arose were compared as a percentage of all teacher-student dialogic interactions within that topic. Results are found in *Table 7.1*. Thematic coding revealed that the majority of teacher-student dialogue drew students' attention to the underlying ontological model for each topic (85%). Types of dialogue ranged from explicit teaching of the ontological model and reiteration of student answers in terms of the model to use of questioning to encourage students to apply the model or to elaborate their answers.

Table 7.1

Frequency of types of student-teacher dialogue in thermal energy and genetics lessons

Teacher-student dialogue types	Frequency (%)	
	Thermal energy	Genetics
<i>Teacher-student dialogue that supported use of the ontological model</i>		
Explicit teaching of the ontological model/drawing students' attention to the model	17	39
Encouraging application of the model by questioning only	19	24
Questioning to encourage further elaboration using the model	22	18
Reinforcing correct student explanations as I reiterated their ideas in terms of the model	10	5
Encouraging students to imagine using the ontological model	4	0
I/students used another analogy to represent the ontological model	12	0
<i>Other teacher-student dialogue</i>		
Challenging the alternative conception through questioning	12	10
Encouraging students' correct use of scientific vocabulary	4	4

A considerable percentage of teacher-student interactions still involved authoritative-interactive dialogue as I gave *explicit explanations of the ontological model* and how their observations related to that model (*Table 7.1*: Thermal physics, 17%; Genetics, 39%). This did not occur during the PDEODE section of the lesson but was noticeable as students

worked in their groups producing the drawings, dot-point and written explanations. During the second half of the lesson I moved from group to group, giving them opportunities to ask questions and encouraging further elaboration. At times they would ask for clarification of points that hadn't occurred to them before. At this juncture, if the students were very confused and had not been able to apply the model to the situation, I gave further explanation in terms of the ontological model to clarify student thinking.

This was particularly noticeable in the genetics topic. This may have been as a result of the much larger volume of new vocabulary and the greater degree of unfamiliarity with the molecular/cellular basis for inheritance, which required extra support from the teacher through explicit explanations, since this was a "missing schema" (Chi, 2013) for many students. It is to be noted that the coding showed that, as the genetics topic progressed, students required less direct support as they became more familiar with the model. As a result of these observations I suggest that appropriate 'placements' of the models may have provided further scaffolding, particularly in unfamiliar topics, such as genetics and natural selection, to support students in adopting these missing schemata. I also recognised that I needed to continue to hone my questioning skills and be continually reminded to use those skills rather than returning to explicit instruction. However, I would also argue that there is still a place for further direct instruction about the ontological model by the teacher, particularly when students are becoming increasingly frustrated and confused. The teacher may then be able to bring greater clarity in order to sweep aside some of the confusion and the negative deactivating emotions attached to this confusion and re-set the process of construction of understanding for the student.

Despite the fact that varying degrees of direct teaching continued to occur in the TFA lessons, the majority of the teacher-student dialogic interactions involved questioning or encouraging students to self-regulate their work. During the PDEODE portion of the TFA lesson, many alternative conceptions became apparent as they presented their new explanations to the class. In order to encourage students to consider and apply the scientific ontological model to the phenomenon observed, a variety of strategies were observed. I frequently encouraged students to reconsider their explanations by *asking questions which redirected their thinking towards the ontological model* (Table 7.1: 19%, 24%). This questioning helped them think through some of the implications and consequences of their new theories and to discover whether their new explanations were compatible with the scientific model. It is important to note that this questioning did not directly state that the students' answers were wrong, but asked questions that would help them evaluate their explanations in terms of the ontological model. Thus, this dialogue can be classified as dialogic-interactive. For instance, when students were finding an explanation of how double

glazing helps a room retain heat, I used a series of questions to elicit from students that thermal energy is transferred by particle collisions (which they had already learned through the first TFA lesson in this topic). Questioning also produced discussions about how rapidly heat could transfer through conduction in air and finally to a discussion of what happens to the spacing between particles when there are higher energy collisions. This led students to proposing that the less dense air rose as the denser air replaced it. Similarly, in the genetics topic, when students were finding it challenging to understand how to predict the results of a monohybrid cross, I used questioning to remind students of the underlying microscopic/sub-microscopic model:

Teacher: Do you remember what gametes are? What is special about them, different about them from ordinary cells?

As the lessons progressed and students were writing their explanations in small groups, students often asked me for further input as I moved between groups to hear their explanations. Students were often eager to air their ideas with me as I moved around the classroom. Sometimes students wanted to check that they had understood correctly, and when students gave scientifically accurate explanations I *reiterated their answers, modelling a coherent scientific explanation* (Table 7.1: 10%, 5%) or encouraged *use of missing scientific terminology* (Table 7.1: 4%, 4%). Where alternative conceptions were evident that were contrary to their observations during the demonstration I would ask them to think back to what that demonstration had shown them, *challenging that conception* by reminding them of the cognitive conflict that they had experienced (Table 7.1: 12%, 10%). As students became more comfortable in applying the appropriate ontological model, I used questioning in order to *encourage further elaboration* of student explanations in terms of the model (Table 7.1: 22%, 18%).

Another strategy that was evident in the thermal physics lessons was the *use of alternative analogies* (Table 7.1: 12%) and asking students to close their eyes and *imagine what was happening on the sub-microscopic level* (Table 7.1: 4%). Students generated some of these analogies. For instance, the analogy of the ‘hot potato’ game was suggested by a student to explain the movement of outer-shell electrons in a metal that is conducting heat. As the potatoes heat up, the people will pass them on faster and faster along the row. This analogy reveals a deep engagement with the ontological model relating thermal energy to particle movement. Students did not use other analogies when explaining elements of the genetics topic, possibly because of its greater level of complexity.

In conclusion, development of questioning strategies by the teacher is an important aspect of the TFA, particularly in supporting students to undergo ontological conceptual

change; however, I found this one of the most challenging elements of the process. Although I became more adept at using questioning strategies over the two-year period, as can be seen in the analysis of genetics lessons, I still felt constrained to explain concepts to students, particularly if they were very confused or many alternative conceptions were evident. Further refinement of questioning skills is required and I suggest that training in the use of TFA should include support for the teacher in developing the kinds of questions that scaffold student construction of their own explanations.

7.3.3 More fruitful engagement with lower-achieving students

Although the TFA was used in regular classrooms (Newberry et al., 2011), it appears that the TFA was thought to be particularly beneficial for gifted and talented students (Grevatt et al., 2007). My experience teaching with the TFA, however, has led me to recognise the benefits to lower-achieving students. This can be seen in the case studies of Rachel and Lawrence in Chapter 6. While using the TFA, I have noticed my engagement with and attitude to the learning of lower-achieving students has changed significantly.

As a teacher I have related particularly well to the higher-achieving students, who seemed to appreciate the high expectations that I had for their learning. However, I sometimes clashed with some of the lower-achieving students who were disruptive in class and would be frustrated with their lack of application. Although I encouraged them to learn and gave them extra help if necessary, I wonder if I really had low expectations of the deep conceptual learning that they could achieve. Similarly, as a teacher of many students with additional needs, I sometimes found it difficult to provide them with genuine learning experiences with appropriate modifications to address their needs.

Seeing these students begin to improve in their writing ability and conceptual understanding has given me much greater insight into how to help these students achieve. The careful formation of the heterogeneous small groups and the interactions within these groups have contributed greatly towards building the confidence of these students. The scaffolding that the TFA provides for students in producing quality explanatory paragraphs as a result of the process of writing keywords, visualising and drawing, dot points and finally writing a comprehensive explanation has benefited these students and given them opportunities to succeed where they often 'failed' before, in their own estimation (see Chapters 5 and 6).

As a consequence of this improvement in the lower-ability students and students with additional needs, my relationship with those students improved immensely. I observed that they felt more comfortable in asking me questions and for other help and they realised

that I am willing to listen to them. I think that they see that my goal is to help and encourage them, not to make them feel inadequate.

One of the outstanding consequences of all students' ideas being taken into account was that previously lower-achieving students began to gain in intentionality and mastery goals, displaying greater personal interest in science and more positive activating emotions. Results from conceptual test data also showed that students with all levels of ability underwent significant conceptual change (Figure 6.1). This evidence has changed my attitude to these students and their learning as I recognised that each of these students had valuable ideas to contribute within the class and had much more capacity to undergo conceptual change than I had previously acknowledged. When encouraging teachers to use the TFA it should be stressed that this strategy is beneficial for students of all abilities. Further development of 'placemats' also may further benefit lower-achieving students.

7.3.4 Changes in the provision of feedback

The TFA process includes a self-evaluation rubric for students and teachers to use to help them to visualise the progress that they have made in producing causal answers and relating their observations to the scientific model (Newberry et al., 2005). I aimed to address both students' conceptual understanding and communication of that understanding through written explanations and hence I combined aspects of the Levels Mountain and the Literacy Ladder (Newberry & Gilbert, 2007) in order to provide students with a way of understanding how their explanations should progress – the modified Levels Mountain (LM) (Appendix B).

Even though the TFA encourages students to self-assess their work and give a reason for that assessment, followed by teacher assessment, I found that use of the TFA resulted in a change in my provision of feedback. I became more likely to give a combination of feedback about the process (FP), prompts to self-regulation (FR) and/or feedback which gave specific information about how to improve their written explanations (FT), rather than the less productive feedback about the student (FS) (Hattie & Timperley, 2007).

Teacher feedback to students. While I had previously been convinced of the importance of prompt feedback to students, in practice collecting and marking students' written work took a lot of time and as a consequence, only a limited number of summative assessment tasks were marked each semester and given brief comments as to how the students could improve. I usually collected some end of chapter question sets for formative assessment, which would take hours to correct. Consequently, students would have moved on to other topics before receiving adequate feedback and often seemed uninterested in the comments, focusing on the mark and superficially engaging with the written comments, then

putting their work aside. The time that lapsed between the students' completing the work and receiving feedback was often in the order of weeks and consequently students had mostly forgotten their thought processes in the intervening time.

While using the TFA, students completed one A4 sheet addressing one question only. This could be collected at the end of the lesson, graded with comments correcting students' alternative conceptions or adding in extra explanations that showed students how they could improve their explanations, and returned to the students the following day. This process generally took less than an hour to complete for one class of thirty students, ensuring that the task was not too onerous since it only required me to think about the best way to express the answer to one question. Hence, I was more motivated to give regular feedback.

Students' TFA worksheets also provided much clearer feedback to me about the degree of conceptual change that was taking place and areas which needed further teaching or discussion. For instance, use of certain alternative conceptions or misuse of scientific terminology was highlighted to me and these issues could be rapidly addressed in the following lesson. Previously, I had often been unaware of these persistent alternative conceptions amongst students until a considerable time after the teaching period, for instance, when correcting test papers. I observed that students were more able to absorb the feedback because each TFA question is based on one question only, compared to when feedback is given on a larger number of disparate questions (Hattie & Timperley, 2007).

As noted in Chapter 5, most students commented during interviews on how useful the prompt feedback was to them, enabling them to understand the mistakes that they had made, recognise the correct use of the scientific vocabulary and to clearly comprehend how to achieve a higher level on such a question in the future. The students and I recognised that the goal was to move up the ladder on the LM and hence this prompted me to give more meaningful feedback with specific ways to improve explanations, use scientific language and relate their observations to the scientific model in order to move up the ladder (FT).

In order to illustrate the types of feedback given on student worksheets, examples of common levels of feedback are found in Appendices G and H. Bronwyn was quite confused about how to answer a question about how one car towing another can move forward if the force on car 1 from car 2 is equal and opposite to the force of car 1 on car 2. As she hadn't really addressed parts of the question, I reminded her to look back and check that she was actually answering the question posed (FR). I corrected some scientific terminology but because she had not been able to address the question in hand, I gave a sample answer to help her understand what she could have written (FT).

In the second example, Ven showed a much better understanding of the question and addressed many of the issues, addressing cause and effect and using scientific language correctly. I added in two sentences that further linked his explanation to the scientific model (FT). I also added some words to his sentences to make the meaning clearer (FT). I asked him to consider why the temperature of the cup and water do not go over 100°C, which is an essential factor in explaining why the cup doesn't burst into flames (FR). Finally, I gave each student an indication of which level I believe their explanation is at in terms of the LM framework (FP).

Introduction and emphasis on student self-assessment. Use of the TFA requires students to evaluate their written work against the LM framework. I found that this process reminded me to encourage students to be more self-regulatory as they prepared different representations of their understanding. I frequently asked students to think about their work in terms of the LM and to find ways that would transform their explanations from descriptions to causal explanations using scientific language. In hindsight, inclusion of the importance of use of scientific model to the levels of the LM rubric may have helped students to recognise that their written explanations would benefit from explicitly applying those models.

Determining the level of students' written work was not always straightforward because their explanations often contained elements of scientific understanding and alternative conceptions. Sometimes the temptation was to give students a higher level than their work warranted if they were displaying improved level of effort; however, generally this process was also quite quickly completed. When TFA sheets were handed back to students they immediately looked to see what level they had achieved and I often noted that they carefully read my corrections and questions to see how they could improve on their answers for next time (see Chapter 5). As discussed in 7.2.2, ensuring students evaluate their drawings and give a reason for that evaluation may increase students' attention to this part of the process. Also I regret that I did not put more effort into evaluating students' drawing in terms of the LM and give them more feedback on how to make those drawings more explanatory.

Changes in affective aspects of the classroom due to the TFA. There has been a lot of laughter and positive interactions within the classroom. This was noted by the teachers, particularly Mr Malcolm who said that there was a "bright bubbly level of noise and activity and discussion present during TFA lessons" (see 5.2.4). Student anxiety in sharing their ideas has been reduced. I still expect students to take turns in speaking and give me their attention when I have something to share, and I still have very high expectations of what they can achieve. However, I feel that there is much more of a reciprocal relationship

between me and my students – we are learning together. Students are learning to think deeply, question their assumptions and explanations and to write causal scientific explanations, while I am learning more about their alternative ideas, and to trust all students can indeed construct their understanding with motivation and support from me as a teacher.

Chapter 8. Discussion

This chapter is divided into five sections. The first four sections will discuss the TFA and how successfully it can be used as a multidimensional conceptual change strategy. The fifth section addresses how the TFA functions as an intervention that addresses multiple areas of science education, including topics within physics, chemistry and biology.

8.1 Introduction

As many studies have shown, conceptual change is a complex phenomenon which involves convincing students that their non-scientific conceptual beliefs and the ontological frameworks underpinning those beliefs are less plausible, intelligible and fruitful in terms of explaining their experiences, than the scientific conceptual understanding presented by their teachers (Posner et al., 1982). As discussed in Chapter 2, a multidimensional approach to conceptual change has been proposed as being the most effective way in which to support and encourage students to transfer their allegiance to the scientific models of nature (Treagust & Duit, 2008b). However, as Duit and Treagust (2012a) note, supporting student learning by addressing the three aspects of conceptual change, epistemological, ontological and affective, can be a daunting task. In the light of Sinatra and Mason's (2013) list of cognitive, social and affective aspects that must be addressed (presented in Section 2.1.9) it is not surprising that few multidimensional conceptual change interventions have been studied in the normal classroom (Duit & Treagust, 2012b). A discussion of the support that teaching with the TFA gave me in addressing the multiple dimensions of conceptual change in the classroom was presented in Chapter 7.

This chapter will discuss the evidence presented in Chapters 4-6 to show that teaching using the TFA did address all three dimensions of conceptual change and the mechanisms by which change in the epistemological and ontological dimensions appears to occur. Equal weight is given to both cognitive and social/affective aspects of learning, based on the conceptual change literature from science education, cognitive and social psychology. Changes in learner characteristics in the affective dimension as a result of learning using the TFA, that were observed and reported in Chapters 5 and 6, will also be discussed in the light of the social-cultural literature on conceptual change, presented in Chapter 2. As noted in Chapter 2, while there are many studies on the ways in which social factors and characteristics of the learner influence the degree to which students are motivated to engage with conceptual change strategies, there are few studies investigating the effects that a

conceptual change strategy has on characteristics of the learner. This study hopes to go some way to redressing this imbalance.

In this chapter I will be adopting Chi's (2013) theory of ontological category shift and four sub-types of misunderstanding to understand and probe epistemological and ontological change using TFA. As discussed in Section 2.1.6, there is some overlap when addressing the epistemological and ontological dimensions of understanding. For this reason, some of the factors that supported change in both dimensions will be discussed at the end of Section 8.3.

Similarly, there are many social and affective aspects of learning with the TFA which supported epistemological and ontological change and these will be addressed in Section 8.4.

8.2 The TFA Addresses Epistemological Conceptual Change

8.2.1 Evidence from conceptual tests

From the evidence presented in Chapter 4, the TFA supports change on the epistemological level. Table 4.2 showed a statistically significant and sustained transfer of understanding from alternative to scientific conceptions by the experimental groups compared to those of the comparison groups. A statistically significant increase in choice of the scientifically acceptable interpretations for phenomena over common alternative conceptions was observed across three grade levels, Grades 8-10, after learning with the TFA, and was evident in topics spanning physics, chemistry and biology.

8.2.2 Mechanism of action

Understanding students' alternative conceptions and challenging those conceptions with discrepant events to create cognitive conflict. Consistent with the 'classical' CCM (Posner et al., 1982) and the results from the meta-analysis of Guzzetti et al. (1993) which showed that the use of cognitive conflict is an effective method for bringing about conceptual change in the epistemological dimension, the TFA successfully used discrepant events to challenge students' alternative conceptions and bring about restructuring of epistemological commitments. Posner et al. (1982) suggest that genuine restructuring of understanding would not occur unless the scientific understanding was shown to be more plausible and fruitful than the students' previously held conceptual framework. The epistemological aspect of conceptual change is addressed by the TFA as the teacher discovers the students' alternative conceptions and challenges those conceptions, by providing experiences which create cognitive conflict in the minds of students. These experiences are contradictory to the predicted outcomes based on their current

epistemological beliefs. The scientific model, however, effectively explains their observations and hence the scientific belief gains in status as plausible and fruitful in the minds of students.

Making students' alternative conceptions visible to them through teacher-student, student-student dialogue. Students mentioned in interviews that the PDEODE (Coştu et al., 2012; Savander-Ranne & Kolari, 2003) portion of the TFA lesson helped them to build their scientific understanding. This part of the lesson involved teacher-student, whole-class dialogic interactions where the teacher used questioning to give opportunities for students to present their ideas and to encourage students to elaborate those ideas. Students also engaged in student-student dialogue in their heterogeneous small groups, firstly to determine their predictions of what would happen, and then to produce revised explanations after observing the demonstrations. (These dialogic interactions will be further discussed in 8.3 and 8.4) This process makes the students' alternative beliefs both visible to them themselves and the teacher, and supports them in recognising that their previously held explanations are no longer plausible in light of their observations (Clement, 2013). This experience causes them to consider the scientific explanation presented to them as a more plausible possibility. The status of the scientific explanations was also raised during this process, both through central and peripheral routes to persuasion (Dole & Sinatra, 1998). This will be discussed further in 8.4. Extensive and long-term transfer, however, depends on how intelligible the scientific alternative is to the students.

Production of student-generated multiple representations, including drawings, brainstorming of keywords and production of dot-points, to scaffold construction of verbal/written representations of concepts, worked together to increase the intelligibility of the scientific explanations. These aspects will be discussed further in 8.3.

Social and affective aspects of the TFA proved to be particularly effective in bringing about conceptual change in the epistemological dimension, as noted in Chapters 5 and 6. These include: small group dynamic which encourages co-construction of understanding and 'interthinking', as all students participate and contribute ideas; self-evaluation of written answers which encouraged self-regulation; and teacher feedback, which was important for clarifying false beliefs or flawed mental models. Changes in student characteristics also supported greater intentionality in engaging with these processes. These will be discussed further in 8.4.

These activities address 'inaccurate' categories of student understanding – false beliefs and flawed mental models. Whether students' conceptual ecologies were held as 'knowledge as pieces' or 'knowledge as theory' (Özdemir & Clark, 2007), from their

predictions at the beginning of each TFA lesson it was evident that students held both ‘false beliefs’ and ‘flawed mental models’ and change was needed in, at least, the epistemological dimension. Chi’s theory of Ontological Categories (Chi, 2013) suggests that these ‘inaccurate categories’ should be relatively easily replaced or revised as it becomes evident that these categories are, in fact, inaccurate. This awareness occurred as the students experienced cognitive dissonance and recognised that their presently held beliefs were insufficient or erroneous, as they did not allow them to predict outcomes accurately. Each of the aspects of the TFA discussed above led to assimilation or accommodation of scientific concepts. Thus, certain epistemological beliefs, previously held, became much less prevalent within the cohort. For instance, most students underwent revolutionary conceptual change from a belief that heavier objects accelerate faster towards the earth, to the scientific understanding that the acceleration due to gravity is independent of mass (see *Table 4.8*), after they completed a TFA lesson on this topic. This, however, did not mean that most students underwent a similar revolutionary conceptual change in terms of their understanding of Newton’s 2nd law, as many students simply assimilated this new belief into their impetus ontological model of motion (Hestenes et al., 1992).

8.3 The TFA Addresses Ontological Conceptual Change

8.3.1 Evidence for ontological change

In some conceptual inventories, it was possible to combine students’ answers to a set of questions, or to analyse the alternatives that they chose within each question, to determine students’ underlying ontological beliefs. In Chapter 4, ontological categories and the changes that students underwent in terms of these categories are presented in the topics of Newton’s laws, energy, electricity and the particle model of matter.

There was statistically significant transfer from non-scientific to scientific ontological models observed in certain conceptual categories based on the EPSE-Set 2, EPSE Set 8, ECA and FCI tests. As noted in Chapter 4 (*Table 4.8*), a significant number of students in the experimental group successfully adopted Newton’s 1st and 3rd laws and used these laws to choose the correct explanation for a number of questions based on those laws. As noted above, however, there was no significant adoption of Newton’s 2nd law, and students appear to have remained committed to their impetus model of motion.

In the topic of electrical currents several non-scientific ontological frameworks have been identified (Métoui et al., 2007; Millar, 2006; Millar & Hames, 2002). Prior to teaching, approximately half the students held an attenuation model and a quarter of students held an inconsistent model (*Table 4.7*). This suggests that most students do in fact hold a relatively coherent conceptual ecology in this topic, consistent with the ‘knowledge as theory’

understanding, whereas a much smaller percentage of students gave answers which showed no coherent model – suggesting a ‘knowledge in pieces’ framework (Özdemir & Clark, 2007).

After teaching with the TFA, 59% of students had transferred their allegiance to the scientific, conservation of charge model. There was still a significant proportion (20%) of students who maintained the attenuation model and a small number (10%) who still had no consistent model. In terms of Chi’s Ontological Categories, many students appeared to have held a ‘flawed mental model’ – that the flow of electrons slowed down as it went through a light bulb. Having experienced cognitive dissonance when they observed that the current was the same on either side of the bulb, verifying Kirchhoff’s 1st law, which they then addressed in the TFA exercise to explain their observations, many students relatively easily adopted the conservation model.

As Chi notes (2013), achieving conceptual change of flawed mental models is relatively easy if the flawed assumptions underpinning the flawed model are addressed and shown to be inaccurate. This may explain why both the experimental and the comparison group underwent statistically significant ontological conceptual change, although 59% of the TFA group held the conservation model after teaching compared to 47% of the comparison group (*Table 4.1*).

The TFA also addressed ‘incommensurate’ knowledge that students held which may be as a result of ontological category mistakes and missing schemata (Chi, 2013). As suggested by Chi and colleagues (Chi, 1992, 2013; Chi & Roscoe, 2002; Chi, Slotta, et al., 1994), category mistakes are generally made as a result of students holding matter-based ontologies rather than process-based ones. Students must swap ontological branches (Thagard, 1992) in order to adopt the scientific model effectively to use its predictive and explanatory power. This process is much more difficult than dealing with false beliefs or flawed mental models because it is a revolutionary rather than an evolutionary change, which requires a change in the dimensions of the category (Chi, 2013).

In the topic of genetics, students must come to terms with the process-based model of inheritance as they recognise the molecular basis of genetic traits, the transfer of these traits through meiosis and hence the complex relationship between genotype and phenotype. This change can be classified as overcoming category mistakes as many students believe that characteristics are matter-based rather than as a result of this process. Students who learned using the TFA displayed statistically significant conceptual change in the genetics topic (*Table 4.1*). They also displayed statistically significant improvement in all reasoning types as identified by Tsui and Treagust (2010). Particularly notable is the conceptual change in

reasoning types V and VI that indicate that a process-based understanding had been adopted over a matter-based understanding in the SRG test, and indicating that considerable ‘tree-swapping’ had occurred (Thagard, 1992).

The most difficult form of incommensurate knowledge to address in a conceptual change strategy, identified by Chi (2013), is that of missing schemata. Ontological conceptual change in topics such as natural selection require not only a transfer from a matter-based understanding of genetic inheritance to a process-based ontology, but also an understanding of a new and unfamiliar category, the emergent process rather than a sequential process (Chi et al., 2012).

The experimental group, that learned using the TFA, displayed statistically significant conceptual gains in the topic of natural selection as measured by the CINS (*Table 4.1*) compared to no gains within the comparison group. Analysis of the CINS results by category (*Table 4.10*) showed that many of the component concepts that make up an understanding of the mechanisms of natural selection had gained in status amongst students. Considering Nehm and Schonfield’s (2008) criticism of the CINS in accurately identifying conceptual change in the ontological dimension, experimental group students’ remarkably high results in the ORI-cheetahs pen and paper test (Nehm & Reilly, 2007) suggest a significant adoption of the natural selection ontological model and a considerable ontological change away from a Lamarckian ontology. However, lower scores on the more advanced concepts that indicated an adoption of an ontological understanding of natural selection as an emergent process, showed that many students had not fully adopted this schema and it was still a missing schema for many. Even so, a number of students did appear to have adopted the emergent model and used elements of this model in their written explanations. These results from the pen and paper test were consistent with one quarter of the class having achieved a score of greater than 80% on the CINS test, which Anderson, Fischer and Smith (2009) suggested indicated a good understanding of natural selection.

Evidence for conceptual change in the ontological dimension may also be found in students’ written explanations and drawings found in Section 4.10 and the case studies in Chapter 6. Claim, Evidence and Reasoning matrices measured at the beginning and end of the teaching period suggest statistically significant improvement in forming claims, providing evidence and using reasoning based on the scientific model, which gives further evidence that ontological change had taken place. Similarly, students’ use of drawings, particularly in the topics of thermal energy and the particle/kinetic model of matter, which indicated process-based explanations, suggest that some students were developing scientifically consistent internal models which they were using to interpret, predict and

explain phenomena. Space limitations in this thesis did not allow for further investigation of this aspect of the TFA.

Finally, students themselves believed that they had engaged more deeply with the underlying models of science and had gained a deeper understanding of the ontological categories (*Table 5.1*). They also corroborated that a series of TFA lessons based on the ontological model caused them to understand that model more fully and to be able to make connections between observations and the model (*Table 5.1*)

8.3.2 Mechanism of action

Using a series of lessons based on the scientific ontological model. In the planning of TFA lessons, a series of lessons were designed which required students to apply the scientific ontological model to explain different phenomena. In order to fully understand the scientifically acceptable concept, students learn to visualise the ontological basis for the conceptual model that they are applying as they answer each TFA question. As Gilbert (2005) suggests, as students practise using the model, their ability to visualise the model is strengthened, they become more adept at retrieving and amending the model from memory and gain greater fluency in applying the model. Students also gain fluency in imagining the underlying ontological model, which is the basis for the scientific concepts presented, by completing a series of TFA lessons which develop their understanding as they apply that model to different aspects of the topic (for example application of the kinetic/particle model of matter to thermal equilibrium, conduction, convection). Thus, they gain confidence and facility in representing the ontological model in multiple formats: pictorial, verbal and written.

As students constructed a more consistent understanding of the underlying ontological model and practised applying that model in a variety of situations, the fruitfulness of the scientific model became apparent. The persistence of the conceptual change achieved, as evidenced by the delayed post-test results found in *Table 4.1*, suggest that many students had indeed undergone a tree-change and acquired the appropriate ontological scientific model as a basis for understanding and applying their observations. This is corroborated by the comments of students that the TFA process had enabled them to more deeply understand and visualise the model, which in turn helped them to retain understanding as it was gained at a deeper (ontological) level (*Table 5.1*).

Explicit teaching of the missing schema followed by TFA lessons to reinforce understanding. In cases where students had missing schemata, for instance, in the topics of genetics and natural selection, as Chi (1992) suggests, explicit teaching of the model was

essential prior to engaging with experiences that would challenge their non-scientific ontological frameworks.

The analysis of teacher-student dialogue in the thermal physics and genetics units, found in *Table 7.1*, reveals that the majority of the dialogue in both contexts involved the teacher using questioning to draw student attention back to the scientific ontological model, to encourage further elaboration of the model or to challenge students' alternative conceptions by asking how their ideas were consistent with the scientific model. The scientific model was quite familiar to students in the topic of thermal physics as they had encountered the kinetic/particle model of matter in grade 8. Therefore, less explicit teaching of the model was required compared to the genetics topic, where the model was unfamiliar to students and took the form of a missing schema for many.

PDEODE and teacher-student dialogue. Teacher-student dialogue using Socratic questioning during the PDEODE portion of the TFA lesson was used to encourage application of the newly acquired scientific model or to reinforce its use. The PDEODE process, together with teacher-questioning strategies, made students aware of their presently held ontological categories, and enabled them to see that these categories are insufficient to explain the phenomena being observed or that they result in incorrect predictions of those phenomena. Students were then more willing to revise their ontological categories and to reassign their understanding across lateral categories to a new ontological 'branch' (Chi, 2013).

The power of social-construction. These new schemata are difficult for students to articulate and apply. Social construction of understanding through heterogeneous small group discussion, combined with teacher questioning, was powerful in supporting students in coming to group consensus and individual understanding. Group 'interthink' to solve these ill-structured questions strengthens all students' understanding of the underlying ontological framework. These aspects will be discussed further in 8.4.

Supporting representational change. Vosniadou (2013) discusses the importance of students undergoing representational change to complement epistemological and ontological change. The TFA increases the intelligibility of both epistemological and ontological scientific concepts as it supports student understanding, by having them represent their newly acquired conceptual understanding in a variety of formats - pictorial, verbal and written - and thus enhancing their familiarity with and comprehension of the scientific concepts. As students practise producing pictorial representations of phenomena during the TFA process, based on the ontological model, they gain fluency in the use of the model, they refine their internal representations – resulting in more coherent ontological categories.

These ontological categories are retained for longer because they have gained considerable status in the students' conceptual ecology (Hewson & Thorley, 1989). This fluency is further enhanced as students produce other external representations of the scientific model, through developing verbal defences of their understanding of the phenomena in terms of the model and writing scientific explanations. Thus the underlying ontological model gains in status as being intelligible, plausible and fruitful (Posner et al., 1982).

Harnessing the productive constraints of each type of representation. The TFA encourages students to use multiple representational forms as they construct and develop their understanding, both in the epistemological and ontological dimensions. The constraints imposed by the use of each of these formats encourages a broadening of understanding (Tytler & Prain, 2013). Students must think how to represent their understanding pictorially, for example, by showing molecules moving and interacting, verbally, by linking the newly acquired understanding to their observations in a way that will be persuasive to others (Berland & Reiser, 2009), and in a written format, by ordering their ideas to present a reasoned argument explaining observations and choosing vocabulary which will accurately represent their understanding (Berland & Reiser, 2009; Yore et al., 2003). As many students acknowledged, this iterative process, through production of multiple representations of their understanding, allowed students to gain deeper and more long-lasting conceptual change as they adopted the scientific concepts (*Table 5.1*).

Following is a list of the different representational challenges presented by the TFA and their particular constraints:

Keywords – students identify the most useful words, including the appropriate scientific terminology. As students brainstorm useful words to use when producing both verbal and written explanations during the TFA lesson, they provide meta-cognitive prompts, both for production of an explanation and for using the scientific vocabulary.

The set of words is constructed socially as students suggest which words might be useful. If all words are accepted students must critically evaluate which of those words are going to be useful. The presence of scientific terminology in this list serves as a reminder to use those words in the written explanation. Students noted in interviews that working together to produce these keywords gave them greater confidence in writing and using scientific vocabulary (see *Table 5.1*).

Drawing – students visualise their internal representation of what is happening on a molecular level or on a conceptual level. As noted by Gilbert (2013), students require support in development of different forms of visual representations, in particular in understanding how to transfer between representations on the macro, microscopic and sub-

microscopic levels. Many of the students using the TFA didn't know what to draw at first. They complained that they didn't know how to draw or weren't good at drawing; however, as they persisted they began to understand that what was required was an explanatory drawing. At the beginning of the year they began by just drawing pictures on the macro level - the equipment used in the demonstration. Later, for instance in the thermal energy unit, students began to draw diagrams showing sub-microscopic particles, movement of particles and collisions. They began to represent energy through the movement of the particles using a variety of symbols, indicating a deeper understanding of the process-based ontological model of thermal energy and its transfer.

Having to draw their understanding constrained students to imagine on the sub-microscopic level. As this became more familiar to them, through repeated TFA lessons, they became more adept at retrieving this ontological category and applying it to different phenomena (c.f. Gilbert, 2005). Even when students did not draw very elaborated pictures during the TFA lessons, some like Lawrence (see Chapter 6), mentioned that the very process of thinking about how to draw an explanatory picture led to their having a much more elaborated internal representation of the particles and their movement. Further development of methodologies to support and encourage greater elaboration of explanatory diagrams could be a powerful method of improving student conceptual understanding.

Dot points – The dot points constrained students to produce a list of statements describing the logical steps in the process they had observed. Many of these were causal statements that needed to be linked with evidence or reasoning to justify these statements. After producing these dot-points they could then transfer these ideas into a written paragraph. As Patterson (2001) suggests, the pre-writing tasks of determining keywords and organising ideas into dot-points benefited students by enabling them to plan their explanations. This planning enabled them to write more persuasive causal explanations to higher-order questions (c.f. Hand et al., 2000). This can be seen in the improvement in written explanations as measured by the 'Levels Mountain' rubric and CER rubrics over the period of the intervention (see Chapter 4.10). Some students used the dot-points as fading scaffolds (c.f. McNeill et al., 2006), in that, as the year progressed, they wrote fewer or no dot-points as they felt more confident to complete elaborated, logically sequenced explanations without this scaffold.

Written paragraph – many students saw this as the culmination of the whole TFA process, believing that the verbal discussions, both within their group and with the class together with the drawings and the dot points, led to production of an elaborated written explanation (see Chapter 5). The status of written scientific text was therefore raised. All of the other TFA tasks acted as a scaffold for production of a more highly elaborated, causal

written argument, the evidence for which can be seen in the improvement in results from written work over the one-year period (see Chapter 4).

In interviews, students recognised that there were different constraints in producing a written explanation compared to a verbal one. Several students mentioned that in a verbal explanation you could be more relaxed about the form of the explanation as you could go back and explain what you meant further; however, in a written explanation they needed to find the correct vocabulary and organise their explanations into a logical and persuasive sequence. Many students found this challenging but fruitful.

Conceptual gains through the combination of multiple representations. In Chapter 5, a frequently mentioned aspect of the TFA which supported students in constructing conceptual understanding was the combination of multiple representation required within a TFA lesson. Students felt that this enabled them to construct deeper understanding and write more elaborated scientific explanations. Several students mentioned that their capacity to visualise the concepts in terms of a mental model was developed through construction of a series of external representations. These observations were consistent with other research of the benefits of production of multiple representations (Boulter et al., 2000; Rivard & Straw, 2000; Tytler, Prain, Hubber, & Waldrip, 2013).

As mentioned in 8.2, social aspects of construction of understanding as a result of working together in small groups and teacher-student dialogue and feedback worked together with cognitive aspects to increase the status of the scientific ontological framework. These aspects will be further discussed in 8.4.

8.4 The TFA Addresses the Social and Affective Dimensions

The powerful interaction between social/affective aspects of learning and the cognitive gains in conceptual change through the structured TFA process can be seen in the student and teacher interview results found in Chapter 5 and the three case studies in Chapter 6.

8.4.1 Social aspects of learning in the TFA and how they supported cognitive gains

Underpinning this whole TFA process were the opportunities that students had to construct their understanding in a social context as they argued with peers in small group discussions and whole class discussions. These interactions, together with the feedback that they received during and after the TFA lessons, resulted in persuasion via both central and peripheral routes to adopt and apply the scientific model and this supported the level of conceptual change in both cognitive dimensions.

Dialogic interactions. According to Vosniadou (2013) and other researchers (Duit & Treagust, 2012b; Mercer, 2008), whole-class discussions between teacher and students, can lead to greater engagement and conscious reviewing of beliefs. As discussed in 8.2 and 8.3, during the PDEODE portion of the TFA lesson students' beliefs became visible to the teacher and themselves. It became evident that many of these beliefs were not consistent with their observations and questioning from the teacher encouraged students to apply the ontological model to the observed phenomena.

Teacher-student dialogue within the TFA provides an important platform for addressing category mistakes and missing schemata on the ontological level and false beliefs and flawed mental models in the epistemological dimension (Chi, 2013). The categories of teacher-student dialogue found during a TFA lesson, based on the categories of Mortimer and Scott (2003), are mainly of the Interactive/Dialogic type during the PDEODE period. Less frequently Interactive/Authoritative dialogue was used (see *Table 7.1*), particularly when missing schemata (Chi, 2013) were evident in students' conceptual ecologies.

The teacher plays an important role in guiding discourse within the classroom in terms of introducing scientific knowledge and encouraging all students to participate in the whole-class discussion through use of a variety of questioning strategies (Mortimer & Scott, 2003; Scott, Asoko, & Leach, 2007; Scott et al., 2006). During the teacher-student dialogue in TFA lessons, questioning led to students' evaluating, defending and /or revising their explanations (Ford & Forman, 2006; P. Webb & Treagust, 2006). This period of whole-class discussion provides an opportunity for students to think more deeply about their conceptual framework and, as Chinn and Brewer (1993) suggest, undergo more radical ontological shifts rather than just make small adjustments to their understanding.

Student-student dialogue was also an important factor in students' constructing scientific understanding. Various studies have shown that presentation of a variety of explanations within a small group dialogue results in greater conceptual gains (Ames & Murray, 1982; Howe et al., 1995; Mercer, 2008). During interviews, many students also said that hearing multiple views from peers during small-group discussions was valuable in building their understanding (*Table 5.1*). Petrus, for instance, said that hearing multiple explanations was helpful as he then evaluated each one to determine which explanation was the most profitable in explaining their observations.

The PDEODE portion of the lesson also provided opportunity for students to use argumentation skills as they proposed predictions and explanations within their small groups. This gave students more time to produce scientific arguments than would otherwise occur in purely whole-class discussions and more students could be involved in presenting their

arguments. As Berland and Reiser (2009) suggest, having the opportunity to persuade peers during small group discourse, encourages the presentation of supporting evidence for the arguments and raises the possibility of schemata being modified.

Heterogeneous small group interaction. Apart from the benefits of increased student-student dialogue, interaction within heterogeneous small groups had other advantages. Elements of Mercer's (2000, 2013) 'interthinking' were evident from student interview responses and the case studies of Rachel and Lawrence. Within the TFA small groups, students had the shared goal of producing a persuasive explanation based on the evidence presented for the observed phenomenon. As they worked together towards this goal, students collaborated by sharing their knowledge, as noted by students, who said that they benefited from having peers explain their understanding to them (*Table 5.1*). The second aspect of 'interthinking', co-constructing understanding, was also frequently mentioned in interviews (*Table 5.1*) and was particularly evident in the case of Rachel and her small group (Chapter 6) where they worked both inside and outside class to produce and refine their explanations. Finally, the third aspect of 'interthinking', argumentation to justify claims to transform reasoning, was discussed above.

Many students were involved in explaining their ideas to others within their small group and hence they also benefited by acting as a teacher which gave them opportunity to express and refine their understanding as they provided persuasive explanations to peers (Hausmann et al., 2004). This was once again evident from student interviews and in the cases of Rachel and Lawrence. Giselle's other group members also seemed to benefit via this mechanism because they were also actively involved in producing and presenting their own explanations, both to the small group and to the whole class.

A prominent benefit of the small-group discussions and 'interthinking' was the increase in student confidence in expressing their ideas (see *Table 5.1* and Chapter 6). They expressed that they had greater opportunity to take part in the discussion within the small group than they would have in whole-class discussions and that they were less intimidated by putting forward arguments in front of a small group of peers rather than the whole class and the teacher. As noted in Chapters 5 and 6, several students who previously had rarely, if ever, been willing to express their ideas within class discussions, began to gain confidence and began to advance their opinions within the whole-class discussions as well (see Rachel's case study).

Feedback. Another important aspect of the TFA lessons, which students recognised as being an important factor in the level of conceptual understanding that they gained, was the role of feedback (see Chapter 5, *Table 5.1*). The TFA lessons encouraged provision of

the three most effective types of feedback according to Hattie and Timperley's (2007) study. At the end of every TFA lesson students' worksheets were collected and the teacher provided extensive feedback about the task (FT) to each student, as well as determining the level of their written explanation. This feedback took the form of correction of faulty reasoning, writing questions for further consideration, as well as sometimes providing exemplar sentences to model how to use the scientific vocabulary. This type of corrective feedback has been shown to be more effective than simply correcting incorrect information (Hattie & Timperley, 2007). Many students, such as Bahardir, noted that this feedback helped him to clarify his thinking and improve his written explanations in further TFA lessons and tests. The rapid turn-around of this feedback is also one of the benefits of the TFA, as students can engage with the comments before they have forgotten their thought processes. This rapid feedback on task has been shown to be particularly beneficial to student learning (Clariana et al., 2000).

The second type of feedback was provided during the TFA lessons as students were preparing their multiple representations. This feedback was on the process (FP), and included questions about how they would represent certain aspects of their explanations, drawing their attention to the need to produce explanatory drawings, rather than descriptive ones, asking students to explain their drawings to the teacher as she moved through the classroom. The combination of provision of both FP and FT has been shown to increase student confidence, self-efficacy and deep learning (Earley et al., 1990) and this was also observed in this study. The influence of this aspect of the TFA on affective factors will be discussed further below.

Finally, the brainstorming section, dot-points and the Level's Mountain act as tools for self-assessment (FR). The teacher encourages the students to look back to the words that they thought would be helpful and check whether they have used these, including the scientific vocabulary. Likewise, students can check their written paragraphs against the dot-points that they produced. The teacher asks the students to evaluate their work according to the Level's Mountain, so this acts as a reference rubric to remind students to write elaborated causal answers rather than descriptions.

It was also noted that students much more frequently asked for clarification and checked understanding with the teacher as she moved around the classroom during a TFA lesson compared to other types of lessons. As Karabenick and Knapp (1991) note, willingness to seek help is a valuable skill but one which is frequently avoided in the normal classroom for fear of looking foolish. The TFA process appears to reduce the cost and raise the benefits of expressing doubts or confusion and seeking help, both from peers and from the teacher (*Table 5.1*).

Central versus peripheral routes of persuasion. Although all students had the same opportunity to engage with the cognitive aspects examined in 8.2 and 8.3, as well as the social aspects of learning using the TFA, motivation can depend on other factors. The CRKM model of conceptual change of Dole and Sinatra (1998) incorporates the role of persuasion in determining just how much a student will engage in the learning experiences offered. Both central and peripheral routes of persuasion were evident in TFA lessons. The central route of persuasion is displayed in the PDEODE part of the TFA lesson, where students' alternative conceptions are revealed as being insufficient to explain their observations. The greater the level of engagement with the central route to persuasion due to interest, relevance and characteristics of the learner, the more persistent its effects in terms of conceptual change (Petty & Cacioppo, 1986). These aspects will be discussed below. However, there are other peripheral routes of persuasion in the social context which can influence students to choose to consider scientific concepts and adopt them (Petty & Cacioppo, 1986).

During interviews with students it was evident that both routes of persuasion were active in TFA lessons. Several examples of peripheral routes to persuasion being activated due to relationships with peers within the small group setting are described in Chapters 5 and 6. For instance, Lawrence (Chapter 6) became more engaged in discussions within his small group because his friend, Kyle, was in the group and he clearly looked up to Kyle and wanted to compete with him to attain higher levels on the Levels Mountain. This led to greater motivation and intentionality to engage with the central route to persuasion and led to greater conceptual change.

Similarly, Josh, (Chapter 5) was removed from his unengaged and distracted friends and intentionally placed in a small group of girls whom he admired as learners, who had a greater level of engagement and motivation to learn and who were willing to explain their ideas. As a result, he displayed a consistent improvement in both engagement and motivation to learn. He attributed the change in his attitude to learning and his greater conceptual understanding to the small group in which he had been placed. Rather than being persuaded by the cognitive conflict or class discussions, his admiration for the other members of his small group motivated him to pay attention to their explanations and these social aspects of his small group appear to be the main motivating factor for the conceptual change that he underwent.

Another peripheral route to persuasion was also evident from interviews with students: the competition that arose between students to attain the higher levels on the Levels Mountain (see Chapter 5). This extrinsic factor appeared to be a motivator for some students and led to greater levels of engagement in other aspects of the TFA lessons.

8.4.2 The TFA influences characteristics of the learner to overcome motivational-affective barriers to change

As noted in Chapter 2, although students may hold similar conceptual ecologies and experience the same cognitive processes in the classroom, whether conceptual change occurs has much to do with the student's motivation to learn (Pintrich et al., 1993). According to Heywood and Parker (2009), student motivation is "influenced by students' self-efficacy, goals, intentions, beliefs, expectations and needs (p24)". These characteristics of the learner have been extensively studied to determine the effect that they have on students' motivation to engage with conceptual change strategies; however, as has been discussed in Chapter 2, very little research has been carried out to determine the effect of using a conceptual change intervention on these student characteristics of learning. By positively influencing these characteristics students can become more motivated to participate in constructing conceptual understanding through deep and 'elaborated' engagement (Petty & Cacioppo, 1986).

All but four of the 43 students of the experimental group who were interviewed expressed that they felt more motivated and intentionally engaged in science lessons due to learning with the TFA (*Table 5.1*). Such greater motivation and engagement of students were corroborated by learning support aides who were also present in the classroom. It has already been noted that students were more engaged in discussions of the ontological model on a deeper level in small groups and more frequently put forward their own predictions and arguments than they had previously. Students were also more motivated to ask for clarification from peers and from me as I moved from group to group. As student and teacher/parent interviews were analysed it became apparent that students had also been motivated to participate more fully due to a number of other affective factors which are described below.

Intentional Conceptual Change and the TFA. Sinatra and Pintrich's (2003a) definition of intentional conceptual change involves students paying *conscious* attention to cognitive and meta-cognitive strategies. During interviews, 25 students from Grades 8 and 9 explained that the TFA lessons required a deeper level of attention and understanding than they usually gave to other types of lessons where they would simply copy material (*Table 5.1*). For example, Patricia (Chapter 5) explained that she had been able to get away with superficial thinking in other lessons but that the TFA lessons did not allow her to do that and she felt constrained to engage on a much deeper level with TFA lessons in order to complete them to her satisfaction. Some students expressed some resistance at the beginning of TFA lessons. When asked about this Warren said that it was because they knew that they would have to think deeply and be engaged fully for the whole lesson. This agrees with Hatano and Inagaki's (2003) observation that truly intentional conceptual change may only occur when

there is no other choice, as a lot of effort is required. The TFA appears to put students into a position where they must choose to be intentional about their learning through actively engaging in discourse, thinking deeply to produce multiple representations and acquiring deeper understanding of the ontological model.

All but five students interviewed displayed evidence of greater intentionality in their learning (*Table 5.1*). The case studies of Lawrence's and Rachel's experiences (Chapter 6) also display increased intentionality in both students' behaviours. Lawrence was motivated initially by peripheral routes to persuasion through working with and competing against Kyle. This competition led to his developing high performance goals together with mastery goals, which, in turn, led to his intentionally engaging more fully in the meta-cognitive and cognitive strategies presented in the TFA, such as self-regulation using the keywords and Levels Mountain, actively processing the feedback that he was given and developing greater awareness of the steps required to improve his written explanations.

Likewise, Rachel showed evidence of increased intentionality in her approach to TFA lessons as she actively participated in presenting ideas and using meta-cognitive strategies. This increased intentionality seems to be as a direct result of the peer support that she received during and after TFA lessons which is consistent with Hatano and Inagaki's observations (2003). Her social commitment to her small group meant that she felt there was no other choice than to be intentional about her learning. Giselle, on the other hand, appeared to possess less intentionality than these other two students, possibly because of possessing high performance goals and some negative deactivating emotions which resulted in more superficial engagement (see below).

Changes in achievement goals as a result of learning with the TFA. Another important student characteristic, which appears to provide the basis for student engagement with conceptual change and how intentionally they do so, is the type of achievement goals that they possess (Linnenbrink & Pintrich, 2003). Mastery goals appear to lead to deeper processing strategies (Ranellucci et al., 2013) and more self-regulation (Pintrich, 2000) while performance goals, particularly performance avoidance goals, generally lead to more shallow processing (Ranellucci et al., 2013). Evidence from student interviews showed that 72% of the students interviewed showed aspects of adoption of mastery goals (*Table 5.1*)

The evidence from the literature relating goals and engagement were confirmed in this study. In particular, the case studies of Lawrence, Giselle and Rachel show the benefits of developing mastery approach goals to learning. From her interview responses, it became clear that Giselle held performance avoidance goals, which were particularly evident when she was faced with topics which she believed were difficult, such as electricity. Her desire to

be viewed by others as a 'good student' caused her to adopt performance avoidance strategies: not participating willingly in class and small group discussions, preferring to copy what the teacher or others said, rather than engaging more deeply in predicting and constructing her own understanding. The lower than expected conceptual gains that she obtained, particularly on topics such as electricity, are consistent with Ranellucci et al.'s (2013) observations.

On the other hand, Lawrence displayed both high performance and high mastery goals. The performance goals that he held were approach rather than avoidance goals. This was evident by the engagement with strategies and intentionality that were discussed above. The very high levels of conceptual gains that he obtained are consistent with Elliot's (2005) study which showed that the highest conceptual gains were obtained when there was a combination of high performance and mastery approach goals. It appears from Lawrence's interview responses that a change from performance goals to the combination of performance and mastery goals occurred during the learning period with the TFA.

In the case of Rachel, it is very clear that a change in achievement goals occurred over the period of learning with TFA. Prior to learning with the TFA, Rachel had possessed performance avoidance goals as evidenced by her unwillingness to give any responses to questions in class. She did work hard, but this was based on her desire to please her parents who had expectations that she did her best in class. These performance goals led to her engaging in shallow rather than deep processing (Ranellucci et al., 2013). However, as noted in Chapter 6, the process of learning with the TFA, particularly the supportive social aspects, led to a radical restructuring of her achievement goals to those of a mastery approach. She actively engaged in small group and whole-class discourse, she became very intentional in developing deep processing skills through production of multiple representations and she engaged in self-regulation to improve those representations, particularly her written explanations. Consequently, her level of conceptual understanding increased significantly and she displayed unexpectedly high overall conceptual gains. This had the effect of improving her feelings of self-efficacy and confidence to persevere in understanding difficult concepts.

Changes in epistemic motivation and self-concept. During interviews, 25 students displayed evidence of having adopted epistemic motivation avoiding closure and 13 students had improved self-concept, seeing themselves as capable learners of science. For example, Patricia expressed the belief that she was able to understand new concepts and a desire to continue searching for deeper understanding of those concepts, for instance, when she watched science programs on TV. This is consistent with an epistemic motivation avoiding closure (Kruglanski, 1989). It is interesting to note that Patricia showed very little epistemic

motivation and belief before learning with the TFA. It appears that the self-efficacy that she developed during this period led to a change in Patricia's characteristics as a learner and her perception of herself as a competent learner of science. It is noteworthy that, although up until Grade 9, when she began learning with the TFA, Patricia had no interest in studying science as a subject, after learning with the TFA, she chose to study Physics in Grades 11 and 12 and is now studying Mathematical Sciences at university.

Changes in interest. A total of 63% of students in Grades 8 and 9 interviewed expressed that they found science lessons more interesting and enjoyable when learning using the TFA. This was despite the fact that some students also complained that these lessons required considerably more work and deeper thinking than other types of lessons. The learning support aides, present in the classroom, corroborated this increased level of interest in science. For instance, Jane and Eliza both said that they found science lessons interesting. Eliza's comment, in particular, indicates that after studying with the TFA she now had greater confidence in understanding which resulted in her seeing the value of what she knows and even thinking that she might be able to explain these concepts to others in the future.

It seems that Jane, Eliza and Patricia developed personal interest in science, not just situational interest. Murphy and Alexander (2008) suggest that individual interest is usually a stable quality, developed over a long period of time. Yet in the cases of these three girls, despite previously not being interested in science, they developed personal interest in science, even considering studying a science subject in senior school. This is noteworthy when we consider the trend observed in studies of attitudes and interest in science, which show that interest in science declines considerably from ages 10-14 and even more rapidly after 14, particularly for girls (Osborne & Dillon, 2008; Osborne et al., 2003).

Observations in this study are compatible with Franke and Bogner's study (2013) which showed that students who learned with a conceptual change approach that challenged alternative conceptions developed greater interest as a result, which then led to greater conceptual change. On the basis of students' comments in this study, however, increased personal interest in science also seems to have developed in response to greater understanding of science concepts through the TFA, combined with a change in self-concept—evolving from students who saw themselves as not good at science to those who could understand and explain scientific concepts. This increase in interest, self-concept and self-efficacy, combined with cognitive processes within the TFA lesson, seem to have motivated students to become more intentional in their learning and thus to bring about significant conceptual change for each of these students.

Increased self-efficacy. One of the most general and powerful influences learning with the TFA had on student characteristics appears to be in increasing students' feelings of self-efficacy. As a result of learning using the TFA students reported improved feelings of self-efficacy in both their ability to understand new scientific concepts (67%) and to write elaborated scientific explanations (77%), and this contributed towards student motivation to engage further with the scientific model, to persist when they encountered challenging concepts and when writing the explanations of the phenomena observed. This increase in confidence was frequently noted by the learning support aides present in the classroom. Students also felt more confident in using scientific vocabulary and felt that that they could form explanations with greater fluency as they retrieved and applied the ontological model. There are many examples described in Chapters 5 and 6 of students who began the year with low self-efficacy, yet felt quite a high level of confidence in understanding and writing about scientific concepts after the year learning with the TFA. As noted in the literature (Bandura et al., 1996; Bouffard-Bouchard et al., 1991; Pajares, 2002; Schraw et al., 2006; Sinatra & Mason, 2008), these higher levels of self-efficacy have the effect of acting as a motivating factor for increasing intentionality to engage with meta-cognitive strategies and persist when students encounter difficult tasks. This was the case for Rachel, who said, "*I think that I understand a lot better, even though it might take me a while. In the end, I understand it.*"

TFA lessons provide short-term goals with immediate and frequent feedback which Bandura and Schunk (Bandura & Schunk, 1981; Schunk, 1983, 1987) claim improve self-efficacy by showing students whether they have gained mastery of these tasks. The students attributed their improvement to their own efforts as they worked to gain mastery of the concepts through producing multiple representations of their understanding, and this further improved their feelings of self-efficacy (Schunk, 1987). As Bahardir said: "*So you basically just helped us to get to the next step but we were actually the ones who did most of the thinking.*"

Increase in positive, activating emotions. Finally, changes from deactivating to activating emotions were observed by teacher support aides and reported by students in 74% of interview responses (Chapter 5). Prior to this study, negative, deactivating emotions regarding learning science were frequently encountered. These included boredom, hopelessness (a feeling that they would never be able to understand science), seeing science as 'scary', anxiety and feeling threatened (for example Fred, Carl, Patricia, Rachel, Eliza and Jane). These deactivating emotions undermine conceptual change by reducing motivation and distracting students from engaging in tasks (C.-J. Liu et al., 2014; Sinatra & Mason, 2013). Reduction in deactivating emotions, such as anxiety or 'scariness', and increased positive, activating emotions were seen in all of the above cases. Students reported finding

science enjoyable, having pride in their understanding and looking forward to science lessons which had the effect of increasing motivation to intentionally use meta-cognitive strategies, develop their critical thinking and elaboration of explanations (c.f. Broughton et al., 2013; C.-J. Liu et al., 2014; Taasoobshirazi et al., 2016).

In conclusion, the interaction between cognitive aspects of the TFA lessons - the PDEODE and cognitive conflict strategies - together with production of student-generated multiple representations and the social aspects of dialogue, that is, small group interactions and feedback - resulted in both central and peripheral routes to persuasion being activated and supported conceptual change in both the epistemological and ontological dimensions. Various aspects of the TFA process positively influenced a number of student motivational characteristics such as intentionality, transfer from performance to mastery goals, epistemic motivation and belief, interest, self-efficacy and emotions. The change in these student characteristics, in turn, led to greater cognitive engagement with the TFA process, creating a positive feedback loop which resulted in the significant and persistent conceptual change that was observed. Rachel's case study illustrates the power of using the TFA as a strategy to bring about multidimensional conceptual change in the regular classroom.

8.5 The TFA Across Multiple Dimensions of Science Education

In comparison to previous studies, this research investigates the TFA as a strategy to improve conceptual change across a wide variety of areas of science. The evidence presented in Chapter 4 indicates that it is a highly effective approach in addressing students' alternative conceptions in physics, chemistry and biology. An important aspect of the TFA is the way in which it addresses the epistemological aspect of conceptual change through creating cognitive dissonance with students' presently held alternative beliefs (Treagust, Won, & McLure, 2018) and by using PDEODE to make those alternative beliefs visible to the student and raising the status of the scientific concepts to encourage re-structuring of students' conceptual understanding.

In Guzzetti, Snyder, Glass and Gamas' (1993) meta-analysis of text-based and non-text-based interventions to elicit conceptual change carried out in the classroom using quantitative or semi-quantitative data, they found that the majority of studies focused on the physical sciences (particularly laws of motion), with biological science, earth science and combined sciences receiving more limited treatment. In comparison to this thesis, there was only one non-text based study which investigated conceptual change in more than one branch of science (Griffiths, Thomey, & Cooke, 1988). This indicates the need for strategies such as the TFA which can be generalised across many conceptual domains in the general science classroom.

Each area of science addressed holds its own set of common alternative conceptions; therefore, determining appropriate means of eliciting a sufficient level of cognitive conflict which will lead students to replace their alternative conceptions with scientific ones can be challenging for the teacher/researcher. It is worthwhile looking at the different types of activities used to elicit conceptual change in each field of science and determining whether the strategies vary between each field.

8.5.1 Differences in strategies for physics, chemistry and biology

Within the topics addressed in this thesis in the areas of Physics and Chemistry, the literature investigating interventions to support conceptual change reveals a variety of different strategies. In the areas of particle models of matter (including states of matter, phase changes and evaporation), thermal physics, Newton's laws of force and motion and energy, many of the recent studies address students' alternative conceptions. Many studies directly challenged those conceptions through demonstrations, experiments or computer simulations, creating cognitive conflict (Baser, 2006; Coştu, Ayas, & Niaz, 2010; Coştu, Ayas, Niaz, Ünal, & Calik, 2007; Özmen, 2011; Tao & Gunstone, 1999; Thomaz et al., 1995; Thornton & Sokoloff, 1998), while others addressed students' underlying alternative conceptions through direct teaching, small group dialogues, Socratic questioning, comparative scenarios, inquiry-based learning and discussions, role play analogies or use of conceptual change texts (Beerenwinkel, Parchmann, & Gräsel, 2011; Harrison, Grayson, & Treagust, 1999; Pinarbaşı, Canpolat, Bayrakçeken, & Geban, 2006; Trumper, 1993; Tsai, 1999; Viiri, 1996).

By comparison, in the two biology topics of genetics and natural selection, interventions to bring about conceptual change which directly addressed students' alternative conceptions were rare. For instance, one study measuring conceptual change set out to create cognitive dissonance with students' alternative conceptions by providing discrepant data and asking students to solve problems on the basis of Lamarckian and Darwinian theory (Jensen & Finley, 1995) while another directly addressed students' alternative conceptions about genetics through an online interactive module (Heitz, Cheetham, Capes, & Jeanne, 2010).

Cognitive conflict strategies require the researcher to identify students' presently held conceptions, followed by presentation of events or data which are inconsistent with the students' conceptions and predictions and which then lead, through discussion, to adoption of a more scientific explanation of the observations (Limón, 2001). In the areas of genetics and natural selection, production of demonstrations or experiments which would create cognitive dissonance in students' minds is difficult, and the complexity of these topics may have led many researchers to use other strategies such as computer simulations, direct teaching methods, computer games and discussions and problem-solving (Andrews et al.,

2011; Annetta et al., 2009; Okebukola, 1990; Reinagel & Speth, 2016; Tsui & Treagust, 2010). These strategies require an understanding of students' alternative conceptions but do not necessarily address them directly or make them visible to the student.

8.5.2 Addressing physics, chemistry and biology topics with the TFA

This study set out to examine the level of conceptual change achieved by implementation of the TFA across Grades 8-10 and in a variety of topics addressed in the Australian National Curriculum (ACARA, 2013). Each TFA lesson was designed to address one or more prominent alternative conceptions held by the students. In order to do so, a demonstration challenging that conception, a thought experiment or a scenario was devised. As students predict what will happen and explain why they believe it will happen their alternative conceptions become evident, both to themselves as they discuss in their small groups and to the class as a whole as each group presents their ideas. As they observe the demonstration, or are given more data/information about the results of the thought experiment and participate in Socratic dialogue led by the teacher, students experience cognitive dissonance and begin to question their previously held conceptions. The students are presented with a guiding question (see Tables 3.6 -3.12) which causes them to engage with the scientific model and produce explanations based on scientific concepts. Difficulties in developing appropriate demonstrations, thought experiments or scenarios were discussed in section 7.1.2.

The types of activities employed during the PDEODE phase can be classified into two groups: demonstrations or experiments that directly challenged the students' alternative conception; and thought experiments or scenarios, where directed Socratic questioning was necessary to lead students to express their alternative beliefs and then led them to re-interpret the results in terms of the scientific explanation. These thought experiments were mainly of the 'teaching thought experiment' (Gilbert & Reiner, 2000) type which used scenarios familiar to students and allowed them to predict the outcome of these experiments.

Several examples of the first type of activity were developed in the thermal physics and particle model of matter units. These units in particular lent themselves to the development of practical demonstrations. For instance, because many students hold that metals are intrinsically cold and that 'cold energy' flows, the demonstration of ice blocks on a metal plate compared to a ceramic plate resulted in immediate cognitive dissonance as most students predicted that the ice on the metal plate would melt more slowly, as they believed that the metal is colder and the cold from the ice would flow to the metal, making it even colder. Similarly, the collapsing can experiment surprised students who had seen the can with air in it remain intact when cooled and expected a similar situation when the can with a small amount of water in it was heated and cooled. This challenged their concept that

gases take up a slightly larger space than liquids and their alternative conceptions about air pressure. Another alternative conception that was easily challenged through demonstration was that temperature and heat are the same and that providing the same amount of thermal energy to objects will increase their temperature equally. Predictions and comparison of water and lead being heated at the same rate and watching the temperature of both clearly demonstrated that this assumption was incorrect and demonstrated the principle of thermal heat capacity. Many of the topics related to thermal energy, Newton's laws and the particle nature of matter could be addressed in this way.

The second category of thought experiments or scenarios required more discussion before students' alternative conceptions were made visible. For example, in order to challenge the conception that action-reaction forces cancel each other out, the famous example of a car towing another car was given and students were asked to explain how they could be moving if the force each car exerts on the other is equal and opposite. This is an example of a destructive thought experiment (Gilbert & Reiner, 2000). Students recognise that the car moves but they are at first perplexed because they know that Newton's third law says that the action force of one car on the other is equal and opposite to the reaction force from the other. This example did not immediately elicit the alternative conception that action/reaction forces act on one body, but by phrasing the problem in this manner students became aware of this commonly held alternative conception and had to determine what the source of the net force was that enabled the car to accelerate. Some of the scenarios used to investigate the energy topic were also of this type. The interactions in this topic are complex and require understanding of several concepts in order to explain observations. For instance, it is difficult to directly measure energy in its different forms to show conservation of energy. The scenarios provided gave opportunities for discussion of the different forms of energy involved. For instance, in the scenario about a car crash it is not obvious to students that the kinetic energy of the car has been transformed and that energy has been conserved. Careful questioning surrounding this scenario to remind them of previous experiences with transfer of energy is required for students to recognise that their initial assumption that the energy has 'disappeared' may not be correct.

Similarly, the idea that heat intrinsically rises is very pervasive; however, finding a demonstration that would challenge this idea was difficult. The scenario of a heater in the lower corner of the room and someone sitting on the other side gradually getting warmer led to a discussion of how this could happen. This is an example of a constructive thought experiment (Gilbert & Reiner, 2000) as students use their imaginations to explain a phenomenon which gives evidence for the KTM. The role of the teacher in using questioning

to draw attention to the underlying ontological model and encourage further elaboration was discussed in section 7.3.2.

In the biology topics of genetics and natural selection, the thought experiments were exclusively used. In this case scenarios were developed which required students to grapple with their presently held understandings and apply their understandings of the molecular basis of inheritance in order to address the problem which the scenario provided. These thought experiments were mainly of the constructive type. Scenarios were presented and students asked to work in groups to determine their explanations. After presenting those explanations, once again I used questioning to elicit students' underlying assumptions. Once these were brought to light students were asked to re-think their explanations. This often required questioning which asked students to think about what the consequences of their reasoning would be, using questions in the form of: If that were the case, what would happen if.....? It is not possible to actually carry out most of these experiments in the laboratory and hence these kinds of thought experiments and scenarios are the most appropriate way to challenge students' conceptions.

As suggested in the literature, conceptual change without addressing students' alternative conceptions, and challenging the status of those conceptions (Hewson & Thorley, 1989) by enabling students to investigate the greater plausibility, intelligibility and fruitfulness (Posner et al., 1982) in explaining their observations may be limited. As can be seen, with careful development of a series of questions or scenarios and teacher-guided dialogue it is possible to use the TFA strategy to make students' alternative conceptions visible and to challenge those conceptions across multiple fields in science.

Chapter 9. Conclusion

The research in this thesis investigated the efficacy of the TFA as a multidimensional strategy to bring about conceptual change in the regular classroom. This chapter will summarise the data and analysis of results presented in Chapters 4-7, in response to the research questions. A summary of the overall conclusions based on this evidence will then be presented. Following this I will discuss how the findings from this work can contribute to the practice of science education and implications for further research will be presented. Finally, limitations of this study will be discussed.

9.1 The Effectiveness of the TFA

Chapter 4 presented the analysis of pre- and post-test data from a number of conceptual inventories administered to both the experimental and comparison groups as well as an analysis of experimental group students' written explanations throughout the two years of the study in order to answer Research Questions 1a : *To what extent does the Thinking Frames Approach build scientific understanding of concepts and lead to epistemological and ontological conceptual change?* and 1b: *To what extent does teaching using the Thinking Frames Approach enable Grade 8-10 students to give coherent scientific explanations using written text?* This data probed the effectiveness of the TFA in the epistemological and ontological dimensions of conceptual change.

9.1.1 The TFA led to statistically significant epistemological and ontological conceptual change

In response to Research Question 1a, comparison of pre- and post-test data for experimental groups in Grades 8 and 9 in 2014 and for Grades 8, 9 and 10 in 2015 (*Tables 4.1 & 4.2*) revealed that students had replaced a statistically significant number of their alternative conceptions with scientific ones in all topics after learning with the TFA. Cohen effect sizes were exceptionally high for all topics, ranging from 0.88 to 2.04 ($M=1.34$, $SD=0.41$), when comparing understanding before and after tests. An effect size of greater than 0.80 is considered large, greater than 1.2 is very large and greater than 2.0 is huge (J. Cohen, 1988; Sawilowsky, 2009). Delayed post-tests administered six months after completion of the energy, thermal energy and Newton's laws topics all showed that improved conceptual understanding in the epistemological dimension had persisted since the post-tests were administered.

In the same topics, students in the comparison groups who were taught the same concepts using many of the same demonstrations as the experimental group, only achieved

statistically significant conceptual gains in the topics of electricity and genetics when comparing pre- and post-test results. In all concept tests except for the electrical current test, students of the experimental groups achieved significantly higher post-test scores than those of the comparison groups.

Further analysis of results from experimental and comparison groups was carried out using multiple regression analyses to compare the influence of factors such as NAPLAN numeracy and reading scores, pre-test results, gender and being in the treatment group, on post-test scores. In all tests, being in the treatment group (i.e. learning using the TFA) had a statistically significant positive influence on a students' learning and, in most cases, this was the most significant influence on how well a student would perform in the post-test.

These results strongly support the conclusion that learning with the TFA leads to statistically significant and sustained change of a students' epistemological conceptual ecology in a broad range of physics, chemistry and biology topics. The change that is observed is significantly greater than the change observed when using more traditional forms of instruction.

Analysis of conceptual inventories in terms of ontological categories revealed that statistically significant transfers from non-scientific ontological frameworks to scientific models were observed, particularly in the adoption of scientific ontological categories of energy forms and transfer (*Table 4.3*), the kinetic theory and particle theory of matter (*Table 4.4*), a KTM understanding of heat transfer, conductivity and equilibrium (*Table 4.5 & 4.6*), conservation model of charge in currents (*Table 4.7*), Newton's 1st and 3rd laws (*Table 4.8*), the process model of genetics based on molecular understanding of meiosis (*Table 4.9*), and natural selection as an emergent process (*Table 4.10* and ORI results).

9.1.2 The TFA enabled Grade 8-10 students to give coherent scientific explanations using written text

In response to Research Question 1b, analysis of students' written explanations over the year/s of teaching using the TFA in Grades 8-9 using the LM and CER frameworks revealed that there had been a statistically significant progression from writing simple explanations and presenting unsupported claims to production of elaborated causal arguments using scientific vocabulary, which provided evidence and reasoning based on scientific models ($d > 0.90$). Grade 10 students, who were learning using the TFA for the second year, continued to write elaborated causal arguments. The increased conceptual difficulty of topics covered in this year was evident in the progression in LM and CER scores within each topic as students became more familiar with how to use the appropriate scientific vocabulary and in expressing conceptual understanding within these fields. This evidence suggests that,

while the TFA has the primary aim of supporting multidimensional conceptual change in student understanding, it has the added benefit of supporting students' skills in communicating their understanding in a written format.

9.2 Mechanisms of Action of the TFA: Students' and Teachers' Perspectives

In response to Research Questions 2a and b: *What do students perceive as the supporting aspects of TFA for learning science in terms of the epistemological, ontological and social/affective dimensions?* and *What main features and benefits do other teachers observe during implementation of the TFA in terms of how it supports multidimensional conceptual change?* chapter 5 presented an analysis of interviews with students of the experimental group, teachers and learning support aides, who were present in lessons, to determine their perceptions of the TFA process and how it supported them in undergoing conceptual change in each dimensions. The evidence presented indicates that the TFA effectively acts in all of the dimensions, and that elements of each dimension support change in other dimensions, including positive change in student characteristics.

9.2.1 Students' perceptions of the mechanism of action of the TFA

Coding of students' interview responses in terms of the influence of the TFA identified a number of aspects of the TFA which contributed to students' conceptual change. These were organised in terms of those which addressed epistemological, ontological, social and affective dimensions to answer Research Question 2a. Aspects of the TFA which specifically addressed one dimension had effects in other dimensions.

Supportive aspects of the TFA that brought about conceptual change in the epistemological dimension. Students particularly appreciated the use of multiple representations and the step-by step progression inherent in the TFA process in supporting them in building conceptual understanding in the epistemological dimension. These steps included aspects of the social dimension, such as teacher-student and student-student dialogic interactions and feedback. Students found the PDEODE section of the TFA made them more aware of their alternative conceptions and the fruitfulness of the scientific conception, based on the scientific model. An increase in situational interest due to the use of challenging questions, demonstrations and dialogic interactions was observed, which led to deeper engagement in argumentation and intentionality in using the TFA steps.

Supportive aspects of the TFA that brought about conceptual change in the ontological dimension. Students noted that they were thinking much more deeply about the underlying ontological model due to the TFA. They appreciated that a series of TFA lessons allowed them to use the scientific model in different contexts, which allowed them to

construct deeper understanding of the model and recognise its utility in providing explanations of phenomena.

The benefits of social construction in the TFA process. Students overwhelmingly recognised the benefits of social construction of understanding in supporting their ability to construct understanding, particularly the benefits of working in small heterogeneous groups. In particular, they noted that the small group discussions resulted in interthinking, co-construction of understanding, peer tutoring and opportunities for all students to participate in putting forward their arguments to persuade others. Teacher-student dialogue supported construction and application of the ontological model and encouraged elaboration. The support that students received from both teacher and peers resulted in greater feelings of self-efficacy and consequent adoption of mastery goals in understanding and in writing explanations. Other social aspects that students identified as benefiting their conceptual understanding in the cognitive dimension were the feedback provided, and the use of the LM to self-regulate their written explanations. Examples were given of students who developed greater mastery goals and intentionality in using the metacognitive strategies of the TFA to build understanding and improve written explanations as a result of support from their small groups.

The effect of the TFA on students' affective characteristics. Based on student interview responses, one of the most profound effects of learning using the TFA was the increase in student's intentional use of metacognitive strategies during the TFA lesson. Students believed that the TFA gave them no other choice but to intentionally engage with the TFA processes and think more deeply (cf Hatano & Inagaki, 1996). Many students also showed evidence of having adopted mastery goals, particularly in their productive use of feedback and self-regulation of their written explanations. A number of students had also replaced the negative deactivating emotions that they felt prior to learning with the TFA, with positive activating emotions, such as enjoyment and excitement. Some students had also developed epistemic motivation avoiding closure as they expressed a desire to discover more.

Students overwhelmingly felt greater self-efficacy in understanding new scientific concepts, writing scientific explanations and correctly using scientific vocabulary as a result of learning with the TFA. Increased situational interest due to the interesting questions, demonstrations and social support, led to greater intentionality, which, in turn, led to improved outcomes and self-efficacy. This resulted in positive activating emotions which further encouraged students to intentionally engage with the metacognitive strategies provided by the TFA. Development of greater personal interest in science was also evident and many students expressed an interest in pursuing science subjects in Grades 11 and 12.

9.2.2 Teachers' perceptions of the mechanism of action of the TFA

In response to Research Question 2b, in addition to corroborating the students' observations of each of the actions of the TFA within each of the dimensions of conceptual change, teachers noted that the TFA was particularly effective in supporting the conceptual change and participation of lower achieving students and those with additional learning needs. They identified the reduction of negative deactivating emotions, such as anxiety in giving explanations and participating in small groups, as well as the step-wise scaffolding of understanding as some of the main supporting factors for these students. They also noted the development of other positive activating emotions such as enjoyment which led to greater engagement within the classroom. The acting principal noted that there had been a significant increase in interest in science in the senior years, particularly amongst girls, and the possible cross-curricular benefits of using the TFA.

9.3 Case Studies of the TFA Process

In response to Research Question 3: *What can be learned about a multidimensional conceptual change approach from analysis of individual students' progress in learning with the TFA throughout the two years of the study?* Chapter 6 presented and compared longitudinal case studies of three students in order to provide insight into possible mechanisms of action of the TFA in bringing about multidimensional conceptual change. Lawrence, an average ability student who achieved outstanding levels of conceptual change, and Rachel, a lower-achieving student who also achieved unexpectedly high levels of conceptual change, were compared with Giselle, a high-achieving student who achieved lower than expected levels of conceptual change. For both Lawrence and Rachel, the social support within the TFA small groups seemed to be the initiating factor for deeper engagement with the metacognitive processes of the TFA framework.

Factors of peripheral persuasion, due to admiration and competition with Kyle, led to Lawrence's adopting mastery goals along with high performance goals. This led to greater intentionality in engaging with the PDEODE aspect of the TFA as he developed arguments. It also resulted in greater self-regulation in production of multiple representations, productive use of feedback to improve his written explanations and to construct deeper understanding of concepts. Likewise, Rachel replaced her performance avoidance goals with mastery goals as she developed greater self-efficacy in completing each of the metacognitive steps to produce representations, through the social support of the small group. As she developed greater understanding of scientific concepts, her negative deactivating feelings about school and science were replaced with positive activating emotions which further influenced her to intentionally engage in conceptual change.

In comparison, Giselle continued to hold high performance goals, which were often performance avoidance goals, due to negative experiences within her small group and her desire to retain her 'good student' status, and this prevented her from taking risks in construction of her own understanding. This resulted in low or superficial levels of conceptual change. An improvement was seen in the second year of the study where she was placed in a more supportive group.

These case studies suggest the importance of carefully choosing small group members, but also, once again, highlight the integrated multidimensional nature of the TFA and its effectiveness in bringing about, not only conceptual change in the cognitive dimension, but also change in students' characteristics that positively influence learning.

9.4 The Teacher's Experiences

In response to the concerns expressed in the literature (Duit & Treagust, 2012a, 2012b) that strategies that address multidimensional conceptual change are, by their very nature, complex and therefore put considerable stress on the resources of the teacher in the regular classroom, my experiences using the TFA were critically examined. The affordances and limitations of the TFA as a strategy to bring about multidimensional conceptual change were analysed in Chapter 7 (Research Question 4: *What were the affordances and limitations of the TFA in supporting me to implement a multidimensional approach to conceptual change?*). Modifications were suggested which may further support the teacher in implementing multidimensional conceptual change theory in the regular classroom.

The TFA as a structured approach that addresses all dimensions of conceptual change supported implementation of a multidimensional approach in a number of ways. Firstly, it constrained me to determine students' alternative conceptions, through further reading and use of appropriate conceptual inventories. Secondly, the approach required me to design demonstrations and thought experiments and scenarios which would make students' alternative conceptions visible and which would challenge those conceptions, making the scientific concepts more plausible. It also required the development of interesting questions which resulted in students' engaging in higher order thinking about experiences in their daily lives. Each of these elements supported me in addressing the epistemological dimension. There were some difficulties finding appropriate demonstrations, thought experiments or scenarios that were age and developmental stage appropriate and would not cause confusion by introducing ambiguities.

In order to address students' non-scientific ontological dimensions using the TFA, I chose to replace the 'placemats' which had been used to remind students of the curriculum model, with a series of lessons based on the scientific ontological model and began each

topic with direct teaching of that model. This gave students opportunities to use this framework in different contexts. Use of multiple representations within each TFA lesson gave opportunity to deepen students' understanding of the ontological model. This was combined with the development of teacher-student dialogue, particularly questioning, which supported students in constructing their understanding of the model and its application through dialogic-interactive discourse. There was some resistance to drawing amongst students and this section was somewhat undervalued. Further support is needed in developing this aspect of the TFA. Greater attention to using the LM rubric to assess drawings and provide productive feedback on these was suggested. Also, the value of including specific reference to using the scientific model in writing explanations in the LM would highlight the importance of adoption of the model and explanation of observations in terms of the model. I suggest the possible benefits of adopting appropriate 'placemats' to provide prompts to students as they produce explanations in different formats but also warn of some limitations of this method.

Adoption of the TFA as a conceptual change strategy brought about radical changes in my use of and attitudes towards social construction, particularly use of small groups, questioning strategies, wait times and provision of feedback. The PDEODE section of the TFA reduced the level of didactic teaching that I engaged in with the students and allowed me to step back and let them work together to socially construct their understanding. There were some difficulties ensuring that all small groups were equally supportive.

As I continued to use the TFA, I recognised the importance of developing questioning skills consistent with a constructivist approach. However, particularly in topics less familiar to the students such as genetics, where students had missing schemata, my tendency to explain concepts directly to students when they became confused, through authoritative-interactive discourse, was evident and my questioning skills require further development.

Use of the LM gave opportunity to provide fruitful feedback in terms of the task, process and self-regulation. This skill developed over time and I suggest that training of teachers to use the TFA as a multidimensional conceptual change approach includes training in questioning skills and provision of productive feedback. The obvious benefits of social construction to the students in terms of the improved conceptual understanding resulted in a change in my affective stance towards each of these strategies.

In terms of the CAMCC (Gregoire, 2003), which describes the ways in which a teacher undergoes conceptual change to adopt an unfamiliar pedagogy, using the TFA 'Implicated Self', I became aware of the conflict between my perception of myself as a

constructivist teacher and the reality that I had actually been using a teacher-centred didactic approach. This led to a 'Challenge Appraisal' as the structured nature of the TFA supported me in working towards adoption of a genuinely social-constructivist conceptual change pedagogy. My experience suggests that, with some modifications and opportunities for training, the TFA could be successfully used to support teachers in implementing multidimensional conceptual change in the normal classroom.

9.5 Analysis of the TFA as a Multidimensional Approach to Conceptual Change

In summary, the evidence supports the efficacy of the TFA in supporting significant, long-term conceptual growth. The mechanism of action of the TFA is clearly multidimensional in nature. Conceptual change in the epistemological dimension occurs through presentation of discrepant events that challenge students' alternative conceptions, then teacher-student and student-student dialogue makes students' alternative conceptions visible to them and raises the status of scientific concepts. Production of multiple representations of their understanding results in the scientific concept becoming more intelligible and plausible. The small group environment provides support to students in constructing understanding and producing these representations. Feedback that is provided creates further awareness of alternative conceptions and provides corrections of these flawed models or beliefs.

Conceptual growth in the ontological dimension is supported through teaching of a series of TFA lessons which are based on the underlying scientific ontological category and which allow students to practise applying that category in a number of contexts. This develops fluency in storing, retrieving and modifying students' internal representation of that model. Explicit teaching of missing schemata and teacher-student questioning brings students' attention back to the scientific ontological category. Students undergo representational change towards a more fruitful understanding of the scientific model as they interact with the productive constraints of producing multiple representations of the phenomena in terms of the model. This is supported by interthinking, peer tutoring and argumentation within the small group and feedback provided.

The social aspects of the TFA are essential in supporting conceptual change in the cognitive dimension through teacher-student and student-student dialogue, small group interactions and feedback. The structured approach of the TFA results in increased positive student characteristics being developed which allow students to overcome motivational and affective barriers to conceptual change. These include increased feelings of self-efficacy in understanding scientific concepts, adoption of motivation approach goals influenced by active social construction and peripheral persuasion, epistemic motivation that avoids closure which results in greater engagement, higher levels of personal interest in science and

changes from negative deactivating to positive activating emotions, all of which lead to greater intentionality in engaging with the TFA process and willingness to undergo conceptual change.

The TFA as a generalisable pedagogical approach to address multiple topics across the domains of chemistry, physics and biology was discussed and different types of questions and experiences that can be presented to students in order to challenge their alternative conceptions were presented. Two types of activities for use during the PDEODE phase were identified: experiments that directly challenged the students' alternative conception and thought experiments or scenarios where directed Socratic questioning was necessary to lead students to express their alternative beliefs and then led them to re-interpret the results in terms of the scientific explanation.

9.6 Contributions to Understanding and Practice in Science Education

At the beginning of this thesis the need for systematic teaching models which supported multidimensional conceptual change was discussed. The evidence presented in this thesis strongly suggests that the TFA can be effectively used to address many of the conclusions that arise from the conceptual change literature about factors that need to be addressed in the epistemological, ontological, social and affective dimensions in order for multidimensional conceptual change to occur.

This study suggests some mechanisms of action for this multidimensional conceptual change approach as a result of fine-grained analysis of student and teacher experiences, including detailed case studies. The powerful combination of PDEODE together with social construction of multiple representations in small groups in the TFA appears to constrain students to intentionally engage with conceptual change and to support the incremental construction of their understanding. This intentionality and step-wise support in a social context result in significant conceptual change in the cognitive dimensions.

Missing from the literature are studies which investigate the ways in which implementing a multidimensional conceptual change approach may overcome some of the barriers to that change presented by student characteristics in the affective dimension. This study suggests that the TFA may be successfully used to address many of these barriers and provide a more positive learning environment for students, which results in greater engagement with the conceptual change process.

As a result of my experience using the TFA, improvements to the original TFA were described, including the production of a series of TFA lessons linked to the underlying ontological model to support conceptual change in the ontological domain and the provision

of greater support to students, through questioning, in producing explanatory diagrams and making full use of the affordances available in this modality of representation.

My experience implementing the TFA in my regular classrooms suggests that this systematic approach could be valuable to other teachers as they struggle to come to grips with the complexity of addressing the conceptual change literature in the classroom. Using the TFA may also be a supporting factor in teachers' undergoing their own conceptual change about the pedagogies that they use and developing a more consistent social-constructivist approach to their teaching.

Finally, an added benefit to using the TFA within the classroom may be the support to students in developing skills to produce elaborated causal explanations of phenomena using scientific language. The support that use of the TFA gives towards improving students' literacy skills is of national interest and an essential aspect of the general capabilities that should be addressed as described in the Australian Curriculum (ACARA, 2013).

9.7 Implications for Further Research

This study has been limited to my experiences in teaching a variety of science topics to Grade 8-10 students. Further research into the generalisability of the TFA in other topics in science and with younger and older students and by other teachers would strengthen understanding of the effectiveness of such a multidimensional approach. As discussed in sections 7.1.2 and 8.5.2, further development of demonstrations in a variety of domains, which challenge students' alternative conceptions, is needed. Also production of more thought experiments, which either provide cognitive conflict with students' alternative conceptions or build upon their presently held conceptions to develop a deeper understanding of the scientific consensus model, would be beneficial in extending the range of topics which can be addressed using the TFA.

As this study progressed, the need for the development of more conceptual tests that allow for determination of students' ontological models as well as epistemological commitments became evident. These tests need to be age appropriate in terms students' literacy and developmental levels.

Results from this study indicate the value to students of producing drawings as explanations of their conceptual understanding. However, analysis of the types of drawings that students produce was beyond the scope of this study. Future research questions may be as follows: Are there ways to support this drawing process and provide meta-cognitive steps as students' access their internal representations and make them explicit? What would be the effect of giving guidance to students about conventions in scientific drawing or ideas about

alternative ways to represent processes using examples of different types of causal drawings? Is it more powerful to encourage other creative ways of representing conceptual understanding, for example, through the use of cartoons or analogical drawings, than providing scaffolding to produce scientifically orthodox representations? Furthermore, the use of 'placemats', as summaries of ontological models, should be revisited and the effects of using these on students' creativity in drawing and forming mental models would benefit from investigation.

This study has shone some light into the interaction between cognitive and social/affective aspects of learning using the TFA approach. Evidence of adoption of mastery goals, intentionality and personal interest was presented and suggest that various aspects of the TFA supported change in students' characteristics which had previously acted as barriers to conceptual change. Further investigation and elaboration of the mechanisms for these changes in student characteristics would be valuable to educational research.

9.8 Limitations of the Study

Practical considerations within the school environment meant that I, as teacher-researcher, was unable to teach both the experimental and comparison classes. Thus, this study can only be classified as quasi-experimental. Although there was frequent consultation between me and the teachers of the other classes and the same topics were taught using many of the same demonstrations, the effect of the teacher on class performance cannot be underestimated. In order to obtain better understanding of the degree of conceptual change in the comparison class, 9C in 2014, comparison of post-test results with those of a pre-test would have been ideal; however, these results were not available.

Also, as a teacher/researcher there were limitations on the number of video cameras that were available and could be controlled by a single researcher. Further study of group interactions by videoing and analysing student talk would have increased the fine-grained analysis of the social and affective aspects of using the TFA, as well as the process of conceptual change in terms of the changes in flawed beliefs and mental models, category mistakes and schemata through student discussions, and could have been used for greater triangulation with students' experiences as expressed in their interviews and with teachers' observations. In further studies, use of cameras and sound equipment capable of capturing each small group's discussions would be of benefit. Another issue surrounding the limitations of the available technology was the sound quality of the video/audio that was captured. Because of the large number of students interacting at one time it was often difficult to hear clearly all of the discussions that were captured.

One source of difficulty in measuring conceptual change was in finding tests which

were appropriate for the age of the student and which specifically addressed the topics studied. After an extensive search of the literature, I found very few age-appropriate, validated conceptual inventories. Many of the concepts tested were beyond the scope of a Grade 8/9/10 student and included complex language structures and vocabulary. Some of the tests that I did use were designed for senior high school or university level students (TCE, FCI and CINS). Availability of more age- or grade-appropriate conceptual inventories for topics covered in Grades 8-10 would be very useful to monitor students' alternative conceptions and their transfer to scientific understandings.

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Appendix A: Conceptual Change Intervention Studies (2007-17): Epistemological, Ontological and Affective Dimensions Addressed.

Topic	Reference	Methodology/Results
Epistemological conceptual change only addressed		
Buoyancy, projectile motion, internal forces	(Klein, Piacente-Cimini, & Williams, 2007)	Pre/post-tests, two demonstrations, students produced analogies in one of three formats: speaking only, writing only, think-aloud-writing. The greatest CC with writing only.
Refraction of light	(Treagust, Harrison, & Venville, 2007)	A study investigating the influence of learning with analogies on conceptual status and hence CC.
Cellular respiration	(Luz, Oliveira, & Poian, 2013)	A dialogic teaching intervention in which students formulated hypotheses and designed experiments and discussed outcomes.
Forces and motion	(Caballero et al., 2012a)	Matter and Interactions curriculum (microscopic models) vs traditional curriculum. CC measured using FCI. Traditional curriculum significantly better.
Simple current circuits	(Osman, 2017)	A quasi-experimental study of CC through implementation of a learning cycle approach.
Excretion	(Ebenezer, Chacko, Kaya, Koya, & Ebenezer, 2010)	Utilised the Common Knowledge Construction model based on Phenomenography (concepts are related to contexts) to address excretion.
Human heart and circulatory system	(Gadgil et al., 2012)	Experimental model. Comparison of students' CC when they compare a diagram based on a flawed student mental model with an expert model (holistic confrontation) to those who just described the expert model. Significantly greater acquisition of the scientific model.
Electricity concepts	(Potvin et al., 2012)	An experimental study comparing learning with and without classroom explication of initial conceptions. All students were taught using a video lesson and a hands-on problem solving activity. Students whose initial conceptions were made visible showed a significant benefit in CC.
Particle model of matter	(Pimthong et al., 2012)	A conceptual change approach with pre-post-test evaluation including role play, experiments and discussions and problem solving.
Genetics	(Al khawaldeh, 2013)	Quasi-experimental comparison of a prediction/discussion learning cycle and conceptual change text on CC.

Genetics	(Poehnl & Bogner, 2013)	Compared text-book/computer instruction with the addition of alternative conceptions. Assessed cognitive load and CC. No significant difference in CC but an increased cognitive load.
Electrical potential and energy and electromagnetic induction	(Dega, Kriek, & Mogese, 2013)	Comparison of CC due to cognitive perturbation vs cognitive conflict strategies using computer simulations. Cognitive perturbation was more effective.
Electric circuits	(Korganci, Miron, Dafinei, & Antohe, 2015)	Effects of teaching electric circuits using a water circuit analogy. Use of the water analogy brought about more CC than traditional teaching.
Chemical bonding	(Ganasen & Karpudewan, 2017)	Comparison of effects of computer assisted instruction vs traditional teaching on CC
Core disciplinary understanding	(Schuster, Cobern, Adams, Undreiu, & Pleasants, 2017)	Comparison of learning by active-direct vs guided-inquiry methods. A longitudinal study – found no significant difference – the teacher made the greatest difference.
Natural selection	(Heitz et al., 2010)	Interactive online module based on common alternative conceptions compared to learning using non-interactive format. Significant conceptual gain for students who got <80% on initial test.
Evaporation	(Coştu et al., 2010)	PDEODE based on alternative conceptions – cognitive conflict with experiments, discussions. Significant sustained improvement on conceptual test.
Boiling	(Coştu et al., 2007)	Predictions, experiments to challenge alternative concepts. Significant sustained improvement on conceptual test.
Condensation	(Coştu et al., 2012)	Use of a POEODE strategy led to sustained conceptual change.
Particulate nature of matter	(Özmen, 2011)	Animation enhanced conceptual change texts challenging alternative conceptions. Greater CC than control group.
Particulate nature of matter	(Beerenwinkel et al., 2011)	Conceptual change texts addressing common alternative conceptions. Significant CC compared to control as measured by pre/post-test.
Newton's 1 st and 2 nd laws	(D. A. Muller, Bewes, Sharma, & Reimann, 2008)	Pre/post-test with conceptual inventory, compared four different online multi-media interventions: lecture presentation, lecture with additional interesting information, common alternative conceptions presented and refuted, student-tutor discussion of these conceptions. The most effective was the fourth treatment.

Ontological dimension addressed

Sound	(West & Wallin, 2013)	Measurement of ontological change from matter to process-based understanding of sound transmission after use of a teaching-learning sequence. Analysis of written answers.
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Epistemological and ontological dimensions explicitly addressed

Particulate nature of matter	(Adadan, 2013)	Comparison of an intervention including multiple representations vs verbal representations. Multiple representations showed greater CC.
Phases and the KTM	(Stern, Barnea, & Shauli, 2008)	Use of a computer simulation – changes measured using written explanations and questionnaire. Small change but little understanding of KTM.
Natural selection	(Andrews et al., 2011)	Active learning vs traditional learning – discussions, problems solving, clickers. CC measured using CINS conceptual test and a written explanation. Analysis of written explanations for ontological framework. No significant difference.
Genetics	(Reinagel & Speth, 2016)	Production of conceptual models, group discussion, feedback produced significant improvement in understanding of model.
Energy	(Nordine, Krajcik, & Fortus, 2010)	Integrated approach driven by a project-based learning question. Demonstrations and discussions. Students showed significant conceptual improvement measured using concept inventory, interviews about instances and analysis of frameworks.
DC circuits	(Taşlıdere, 2013)	Quasi-experimental study using a concept-change-oriented cartoon worksheet and simulation with scenarios. CC measured using three tiered pre/post-tests. Conceptual models were determined. Treatment group showed significant CC.
Atoms	(She & Liao, 2010)	Scientific Concept Construction and Reconstruction adaptive online learning project based on the dual situated learning model (DSLML) which addresses epistemological, ontological and motivational aspects (although these were not addressed in the paper). Scientific reasoning was supported.
Evolution	(Frasier & Roderick, 2011)	Active learning by problem solving and applying evolutionary thinking to everyday topics, popular books based on evolutionary thinking. CINS test, questionnaires- intervention more effective in ontological and epistemological change.

Learning from a socio-cultural perspective

Genetics	(Furberg & Arnseth, 2009)	Analysis of students' learning using problem solving in a group setting – focusing on discursive and interactional aspect of meaning making. How they grappled with using the language of genetics as they solved problems.
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Influence of social aspects on cognitive aspects of conceptual change

Forces and motion	(Suppapittayaporn et al., 2010)	Peer tutoring and structured inquiry, including discrepant events, compared to traditional teaching. Measured using the FMCE conceptual test. Experimental group had moderate gains.
Floating and sinking	(Decristan et al., 2015)	A quasi-experimental study of the effects of additional guidance on CC in inquiry-based learning. Students were given formative assessment, peer assisted learning or scaffolding through instructional discourse.
Chemical bonding	(Eymur & Geban, 2016)	The effect of a cooperative learning conceptual change approach vs traditional teaching on CC. Greater effect on experimental group. In interviews student expressed greater motivation.
Particulate nature of matter	(Adadan et al., 2009)	Discussions in small groups and class, with or without presentation of multiple representations including animations, student-generated drawings and verbal/written explanations. Alternative conceptions identified but not specifically challenged. Experimental group showed significant gains.
Floating and sinking	(Yin et al., 2013)	A quasi-experimental study comparing a learning progression sequence with/without several formative assessments and feedback. The treatment group showed significantly greater CC.

Influence of cognitive aspects on affective aspects

Newtonian mechanics	(Lee & Byun, 2012)	Analysis of types of student affective responses to a cognitive conflict demonstration.
Climate change, energy, sustainability	(Chen, 2017)	The effect of making 'promisingness' judgements on understanding and epistemic beliefs.
Gene technology	(Franke & Bogner, 2013)	Students were given alternative conceptions of peers as well as scientific conceptions and the effect on students' feelings of interest and well-being examined. These feelings were then compared with cognitive achievement tests.
Acids and bases	(Cetin-Dindar & Geban, 2016)	Comparison of the effect of the 5E learning cycle with traditional teaching methods on CC and motivation. Higher CC and motivation in the experimental group.
Planets	(Broughton et al., 2013)	Investigated the effect of emotions on attitudes and conceptual change. Emotions influenced attitudes and CC. Use of CC strategy positively influenced emotions.
Genetics	(Annetta et al., 2009)	Effect on CC and engagement measured between a group who used a video game and a control group after learning genetics. No difference in CC but greater engagement of experimental group.

Influence of affective aspects on cognitive aspects of conceptual change

Newtonian mechanics	(Ranellucci et al., 2013)	A think-aloud intervention to determine the relationship between students' achievement goals, deep and shallow processing and CC measured using FCI pre/post-tests.
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Heavy/fast conception	(Allen, 2010)	An experimental study looking at CC in students who learned about dropping heavy/light objects by making predictions, carrying out experiments in order to induce strong emotional responses and engagement. The stronger the emotional response the greater the gain.
The common cold	(Jones et al., 2015)	Application of the CRKM model to determine the relationship between task value, attention allocation and conceptual change using refutational texts. Task value had a positive relationship with attention allocation and CC.
Newtonian mechanics	(Taasobshirazi & Sinatra, 2011)	The CRKM model of CC was tested to find relationships between goal orientation, cognition, motivation and course grade.
Newtonian mechanics	(Taasobshirazi et al., 2016)	The CRKM model of CC was tested to find the relationship between emotions, goal orientation, need for cognition, deep cognitive engagement, motivation and CC. Enjoyment was linked to deep cognitive engagement, motivation and CC.
Scientific Inquiry Skills	(Ting et al., 2014)	A computer-simulation model designed to model CC with and without components of affect. The model which addressed aspects of self-regulation and of other aspects of affect was the most effective in bringing about CC.
Natural Selection	(Petersen, 2016)	The effect of a hands-on simulation modelling natural selection on CC and transformative experiences.
Natural Selection	(Linnenbrink-Garcia, Pugh, Koskey, & Stewart, 2012)	Use of profiles of motivational beliefs and prior knowledge to determine effects on conceptual change. The most effective cluster for girls was high interest/efficacy with moderate prior knowledge. For boys – high interest/efficacy with moderate knowledge or moderate interest/efficacy with high knowledge.
Planets	(Broughton et al., 2013)	Investigated the effect of emotions on attitudes and conceptual change. Emotions influenced attitudes and CC. Use of CC strategy positively influenced emotions.

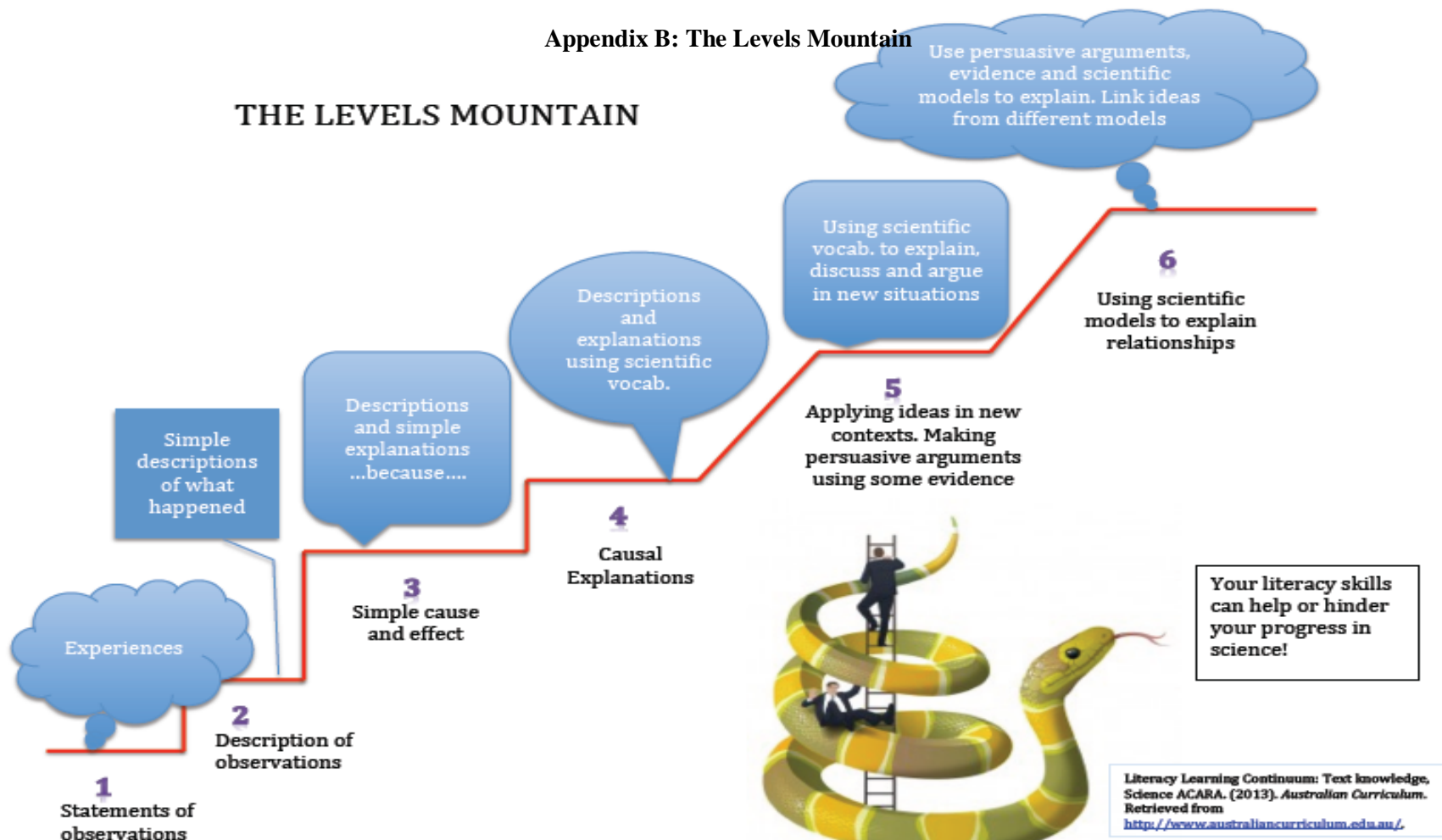
Addressing and/or measuring ontological, epistemological and social/affective aspects of conceptual change

Simple electric circuits	(Kock et al., 2013)	An investigation of open inquiry based learning together with classroom practices, such as collaborative learning, teacher-led whole class discussion in order to support socio-cultural aspects. CC did not take place. Affective aspects not measured.
Climate change	(Lombardi et al., 2013)	A quasi-experimental intervention promoting critical evaluation (based on epistemic practices of scientists) to determine the effect on plausibility judgements and hence sustained conceptual change (based on CRKM model). Significant and sustained improvement in understanding and plausibility judgements of scientific model. Students seemed to have deeper engagement. Not clear how committed students were to the new ontological model.

Genetics (Mbajorgu et al., 2007) Pre/post-tests, comparison group. Used scenarios to make students' strongly held ontological beliefs about the cause of disease such as sickle cell anaemia visible. Intervention based on conceptual change theory and used cognitive conflict. Addressed motivational issues by use of relevant scenarios and culturally appropriate vocab. Experimental group underwent significant conceptual change as measured by biology concept test and worldview test.

Appendix B: The Levels Mountain

THE LEVELS MOUNTAIN



Adapted Levels Mountain Rubric. From “Visualising progression through the science curriculum in order to raise standards”, by M. Newberry, J. K. Gilbert & D. Hardcastle, 2005, *School Science Review*, 86(316), p. 90. Copyright 2018 by the Association for Science Education. Permission to use granted by Professor John Gilbert (5.06.18), the Primary Science Teaching Trust (15.06.18) and the Association for Science Education (8.06.18)

Appendix C: TFA Worksheets

Thinking Frame

Thinking Skills

Name(s) _____ Date _____

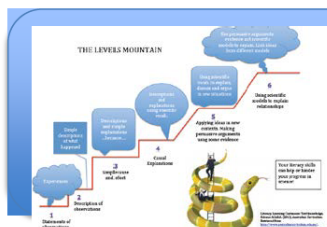
Explain WHY _____

BRAINSTORM

Key ideas(s) to use in the explanation: ENERGY/FORCES/PARTICLES/CELLS

KEY WORDS

SEE / VISUALISE



I/We think that these ideas are at level _____
Because.....

adapted from www.thinkingframe.com

Thinking Frame

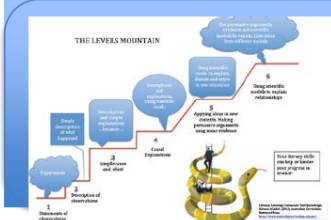
Thinking Skills

THINK / SEQUENCE

What happens	→	Why
<ul style="list-style-type: none"> • • • • • 		

PARAGRAPH

Write your answer to the problem as fully as you can. *(HINT Use cause and effect words such as consequently, because, whenever, depending upon, eventually, since, until etc)*



I/We think that these ideas are at level _____
Because.....

adapted from www.thinkingframe.com

Thinking Frame

Thinking Skills

Name(s) _____ Date _____

Explain HOW _____

BRAINSTORM

Key ideas(s) to use in the explanation: ENERGY/FORCES/PARTICLES/CELLS

KEY WORDS

SEE / VISUALISE



I/We think that these ideas are at level _____
Because.....

adapted from www.thinkingframe.com

THINK / SEQUENCE

-
-
-
-
-

PARAGRAPH

Write your answer to the problem as fully as you can. *(HINT Use connection words to explain in terms of time. Firstly - Then - Then - Finally)*



I/We think that these ideas are at level _____
Because.....

adapted from www.thinkingframe.com

TFA worksheets. Adapted from “Using the 'Thinking Frames' approach to improve pupil engagement and attainment in science,” by M. Newberry, 2006. Paper presented at the teacher research conference, London, UK. Found in *Modelling-based teaching in science education* p211 by J. K. Gilbert & R. Justi, 2016, Switzerland, Springer. Copyright 2016 by Springer International Publishing. Permission to use granted by Professor John Gilbert (5.06.18) the Primary Science Teaching Trust (15.06.18) and the Association for Science Education (8.06.18)

Appendix D: Energy Concept Assessment

Energy Concept Assessment (*English corrected*)

- 1) Two identical cars are being driven with same speed but on two different roads. One road is located in a valley, the other on a hillside. Item AT1[1-4]



Both cars possess energy.	A
Since the speed of both cars is the same, each car has the same amount of kinetic energy.	B
	C

What can you tell about the energy of these cars?

- The car on the hillside road possesses more energy because in addition to its kinetic energy the car possesses more gravitational energy.
- The car being driven on the valley road only possesses kinetic energy. The car on the hillside road only possesses gravitational energy.
- Both cars possess the same amount of energy because both cars have the same amount of kinetic energy.
- The car being driven on the hillside road possesses less energy because it has less gravitational energy than the car in the valley road.

2) A car runs out of petrol while being driven on a flat road. Item AT3[1-4]

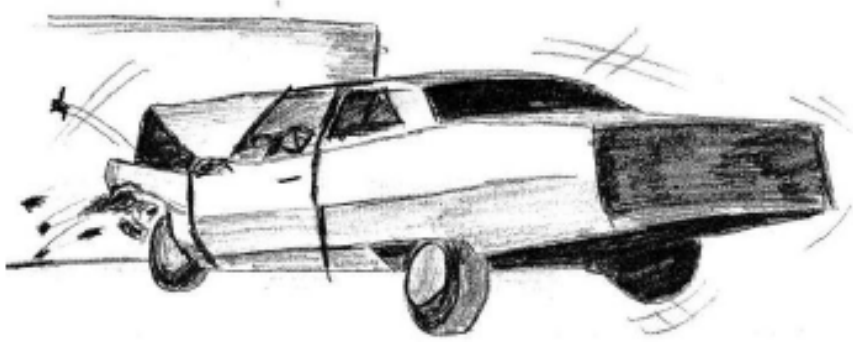


There is friction.	A
	B
	C

Why does the car slow down and then stop after it runs out of petrol?

- As long as the car is powered by petrol, there is no friction. Friction only occurs when there is no petrol left, then kinetic energy of the car is transformed into thermal energy until the car stops.
- Kinetic energy is transformed into thermal energy due to friction. Since the car is no longer powered by petrol, the car's kinetic energy decreases until the car stops.
- When the car is not powered by petrol there is no kinetic energy. Without kinetic energy the car cannot overcome friction and stops.
- When the car is no longer powered by petrol, the car's tires turn more slowly. When the tires no longer turn, friction occurs and kinetic energy is transformed into thermal energy.

3) During a crash test, a car is crashed into a wall and comes to rest. Item AT4[3,4]

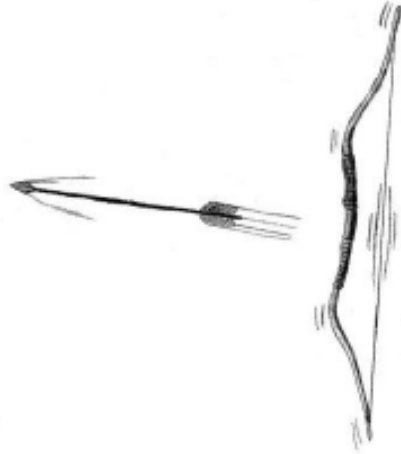


	A
	B
	C

What happens in the crash?

- The total energy remains the same. The car's kinetic energy is transformed completely into kinetic energy of the wall. However, since the wall is much more massive than the car, the wall does not move.
- The total increases. This must be the case because the car is dented during the crash, which requires internal energy. This energy is provided by the wall.
- The total energy decreases. This is because the kinetic energy of the car is lost after the car is stopped by the wall.
- The total energy remains the same. The car's kinetic energy before the crash is as large as the increase of internal energy of the car and wall after the crash.

4) An arrow is shot into the air using a bow. Item BO1[1-4]



	A
	B
	C

What could be stated about the arrow from a physics point of view?

- In physics one would say the arrow has no energy because the arrow has no drive system.
- In physics one would say the arrow has gravitational energy because of the arrow is flying quickly.
- In physics one can say the arrow has kinetic energy because the arrow is moving.
- In physics one says the arrow has no energy because the arrow is not a living thing.

5) Imagine you are riding a bike. Item FR2[1-2,4]



In doing so energy is transformed.	A
	B
	C

What happens when you are cycling?

- Your muscles transform chemical energy from food into kinetic energy of your legs. Afterwards, the pedals and the chain transfer kinetic energy from you to your bike.
- Chemical energy from food is transformed into kinetic energy of your muscles. Afterwards, the pedals and chain transform kinetic energy into speed.
- Kinetic energy from food is burned up in your muscles. Afterwards, the pedals and chain transfer kinetic energy from you to your bike.
- Chemical energy is produced by combustion of food in your muscles. Afterwards, the pedals and chain transform chemical energy into kinetic energy.

6) An airplane is landing on an airstrip and brakes. Item FZ4[3-4]

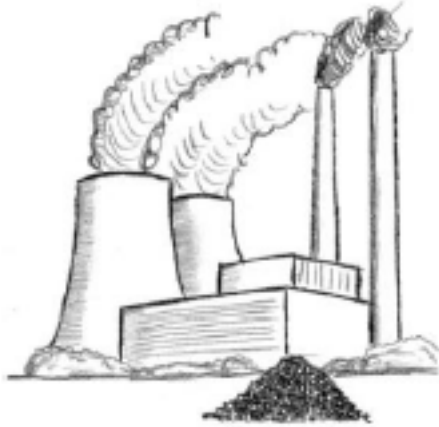


There is energy conservation	A
	B
	C

Which statement is correct?

- The increase of internal energy equals the gravitational potential energy of the airplane as it hits the ground. Since gravitational potential energy is not transformed into thermal energy due to friction the temperature of the brakes does not change
- The increase of internal energy when the airplane slows down is equal to the energy of the airplane as it took off. Since temperature is independent of internal energy, the temperature of the brakes does not change
- The increase of internal energy is smaller than the kinetic energy of the airplane as it hits the ground. The remaining kinetic energy leads to wearing of the brakes
- The increase of internal energy is equal to the loss of kinetic energy of the airplane as it hits the ground. The airplane's brakes grow warm since kinetic energy is transformed into thermal energy due to friction

7) A coal-burning power plant generates electricity. Item KW2[1-4]

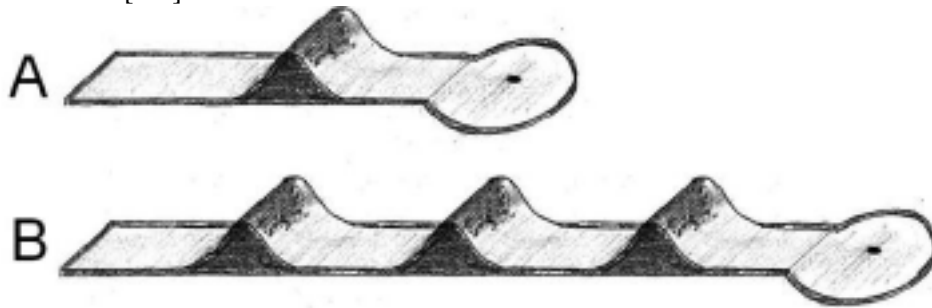


There is energy transformation.	A
The energy that is stored in coal is used to produce steam, which moves at a high speed.	B
	C

How could you describe electricity generation in a coal-burning power plant?

- Chemical energy of the coal is used to produce steam. Afterwards, the chemical energy of the hot steam is transformed into electric energy.
- Through burning the coal chemical energy is produced, which is then transformed into kinetic energy of the steam. Afterwards, this kinetic energy is transformed into electric energy.
- Chemical energy of the coal is transformed into kinetic energy of steam. Afterwards, the kinetic energy of the steam is transformed into electric energy.
- Through burning the coal chemical energy of coal is transformed into kinetic energy of steam. This kinetic energy is transferred to the electrons which are used to generate electricity.

- 8) On a miniature golf course there are two miniature golf lanes, A and B: Item MG3[1-4]

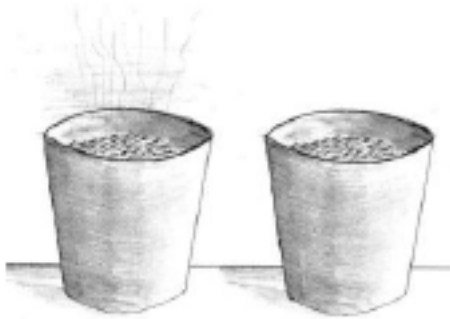


On each of the lanes friction forces act on the golf ball.	A
Therefore, the kinetic energy of the ball is biggest right after it is hit.	B
	C

On which course do you have to hit the ball harder to get the ball to reach the hole?

- You would have to hit the ball harder on course B than on course A. The ball loses more kinetic energy on the long course because the ball has to get over more humps than on the short course.
- You would have to hit the ball harder on course B than on course A. Due to friction, the ball loses more kinetic energy on the long course than on the short one.
- It does not matter how hard the ball is hit. As the kinetic energy of the hit is stored in the ball, it is sufficient just to take aim carefully.
- You would have to hit the ball harder on course B than on course A. Because there are more bumps on the long course, the ball gets additional kinetic energy and can move further.

- 9) On a table one glass is filled with cold milk and one glass is filled with hot milk. There is the same amount of milk in each glass. Item MI1[1-4]

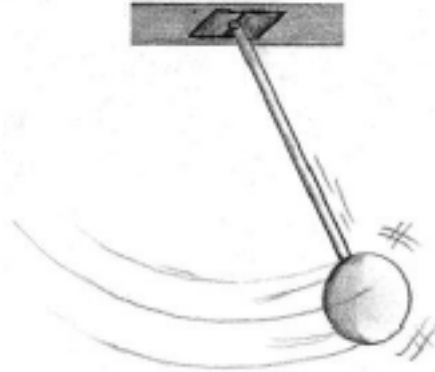


The milk in each glass possesses energy.	A
The cold and the warm milk differ with respect to their amount of thermal energy each has.	B
The larger the amount of thermal energy in the milk the higher the milk's temperature.	C

Which statement about the energy of the cold and hot milk is correct?

- Only the hot milk possesses thermal energy. The cold milk does not possess any thermal energy at all.
- The cold and the hot milk possess the same amount of thermal energy. However, the hot milk has a higher temperature than the cold milk
- The cold and the hot milk possess thermal energy. However, the cold milk possesses less thermal energy than the hot milk.
- Neither the hot nor the cold milk possess thermal energy. Only moving things possess energy.

10) A pendulum is swinging back and forth. Item PD2[1-4]



	A
	B
	C

How can a swinging pendulum be described using the term 'energy'?

- When moving upward, the kinetic energy of the pendulum is transformed into gravitational potential energy. When moving downward, the pendulum's gravitational potential energy is transformed back into kinetic energy.
- The kinetic energy of the pendulum decreases when moving upward. When the pendulum is moving downward, the kinetic energy of the pendulum is increasing. The gravitational potential energy of the pendulum never changes because the pendulum is fixed at the pivot point.
- While moving upward, the gravitational potential energy of the pendulum is transformed into kinetic energy. Afterwards, while moving down, kinetic energy is transformed back into gravitational potential energy
- Kinetic energy of the pendulum is transformed into gravitational potential energy at a constant rate. As a result, the amount of kinetic energy is decreasing and the pendulum eventually stops swinging.

11) A skater goes back and forth in a half-pipe without pushing. Item SK3[3-4]



	A
	B
	C

Which statement is correct from the physics point of view?

- The Kinetic energy of the skater is transformed into thermal energy due to friction. Because energy cannot be destroyed, the skater continues to move until he brakes.
- The skater needs to push at least once to overcome friction. But since he is not pushing, his kinetic energy is transformed into thermal energy until the skater stops.
- While moving down the walls of the half-pipe, the gravitational energy of the skater is transformed into thermal energy due to friction. This is because he is not pushing until he finally stops.
- Due to friction, the kinetic energy of the skater is transformed into thermal energy. Thus, the kinetic energy of the skater decreases until he stops.

12) You pick up a stone and let it fall. Item ST4[3-4]

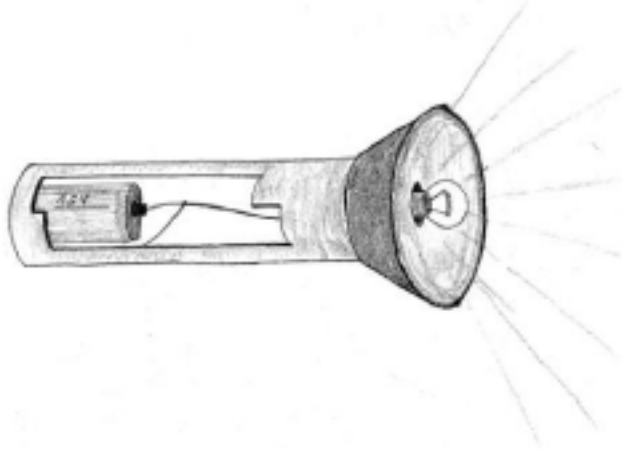


There is energy conservation	A
	B
	C

What can you tell about the energy forms involved and the total energy?

- The gravitational potential energy is zero before lifting the stone and after the stone hits the ground but additional internal energy is created after the stone has hit the ground. Thus, the total energy increases.
- Because the gravitational potential energy is zero before lifting the stone and after the stone is let go, there is no transformation of energy. The total energy remains constant.
- The chemical energy that is used to lift the stone is completely transformed into internal energy as the stone hits the ground. The total energy remains constant.
- The chemical energy that is used to lift the stone is lost when the stone hits the ground. Thus, the total energy decreases.

13) A flashlight is switched on and left on until the battery is used up. Item TL4[1-2,4]



The sum of all energy forms remains constant.	A
As long as the flashlight is lit, the amount of the different kinds of energies changes.	B
In the flashlight electrical energy is transformed into thermal energy.	C

Which statement is correct after the battery is used up?

- The energy of all the emitted light and the increase of thermal energy are as large as the energy that was provided by the battery.
- The energy of all the emitted light is as large as the energy that was provided by the battery.
- The energy of all the emitted light, all the electric energy and all the increase of thermal energy are as large as the energy that was provided by the battery.
- The energy of all the emitted light and all the increase of thermal energy are as large as all the electric energy and all the energy that was provided by the battery.

- 14) A gymnast can use a trampoline to jump higher than she could jump without one.
Item TR1[1,3-4]

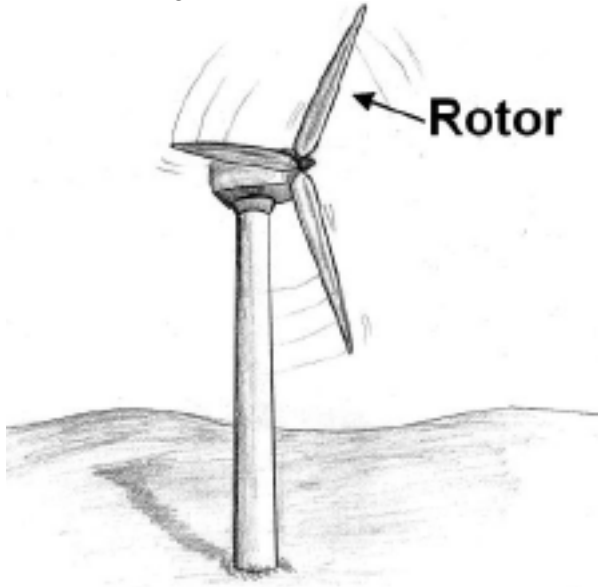


The trampoline can store energy.	A
	B
	C

Which statement is correct?

- The stretched trampoline has no energy. The trampoline only provides tension.
- The stretched trampoline has no energy. Only living things can possess energy.
- The stretched trampoline has elastic energy. The amount of elastic energy is independent on how much the trampoline is stretched.
- The stretched trampoline has elastic energy. The elastic energy depends on how much the trampoline is stretched.

15) The figure below shows a wind turbine for generating electricity. Item WK2[1-4]

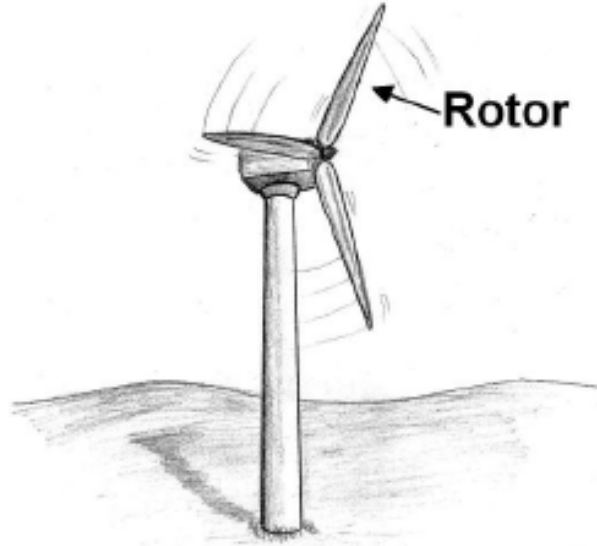


The wind turbine transforms energy.	A
The wind transfers energy to the rotor which starts to rotate.	B
The faster the rotor moves the more electricity is generated.	C

How can you describe the generation of electricity with a wind turbine?

- The wind transfers kinetic energy to the rotor. Afterwards, kinetic energy of the rotor is transformed into electric energy.
- Kinetic energy of the wind is transformed into electric energy of the rotor. Afterwards, this electric energy is transformed into electricity.
- Kinetic energy of the wind is transformed into kinetic energy of the rotor. The kinetic energy of the rotor is then transferred to the electrons to produce electricity.
- The force of the wind is transferred to the rotor. The spinning rotor transforms this force into electric energy.

16) A wind turbine is used for generating electricity. Item WK3[1-4]

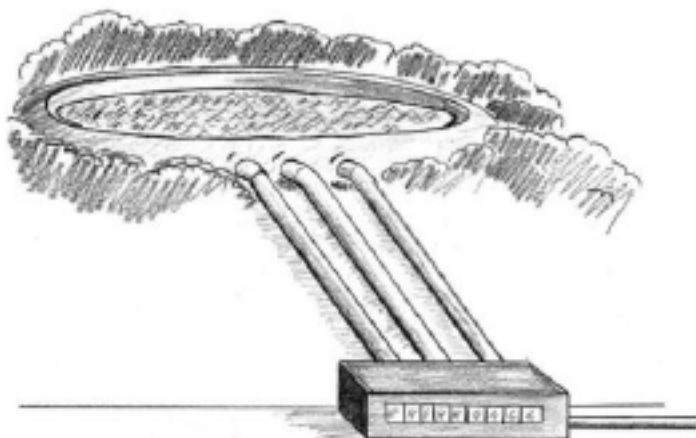


When the rotor is spinning, there is friction at the axis of rotation.	A
Friction results in a transformation of kinetic energy into thermal energy.	B
Thus only part of the energy of the wind can be transformed into electric energy.	C

How could the transformation of wind energy into electric energy be best described?

- Due to friction at the axis of rotation, it is hard to spin the rotor. Only strong winds can overcome friction. Then without any loss of energy electricity can be created.
- When the rotor is spinning, kinetic energy is transformed into thermal energy due to friction at the axis of rotation. Thus, only a part of the energy of the wind can be transformed into electric energy.
- Due to friction at the axis of rotation, the rotor can only spin with one speed. This is independent of the wind speed. This means the wind turbine can provide a constant amount of electrical energy.
- The wind causes the rotor to spin. Due to friction, the kinetic energy of the wind is transformed completely into electric energy.

17) A hydroelectricity power plant generates electricity. Item KW1[1-4]



The water in the lake is an energy carrier.	A
The energy that is stored in the water can be used because the water of the lake is located at a higher altitude than the power station.	B
	C

What can you tell about the water in the lake?

- The water in the lake only has thermal energy, since the water has a certain temperature.
- The water in the lake has no energy, because the water is not flowing in a specific direction.
- The water in the lake has gravitational potential energy, since the water is located at a higher level than the power station.
- The water in the lake has electrical energy, since the water is used in the power station to produce electrical current.

The Energy Concept Assessment. Adapted from “Towards a learning progression of energy,” by K. Neumann, T. Viering, W. J. Boone & H. E. Fischer, 2013, *Journal of Research in Science Teaching*, 50(2), Supplement. Copyright 1999-2018 by John Wiley & Sons, Inc. Permission to use granted by Professor Knut Neumann (31.05.18)

Appendix E: Claim, Evidence, Reasoning Marking Rubrics

Year 8 TFA1 “*Explain why cells need to be so small*” - Explanation Rubric

Component	Level		
	0	1	2
Claim	Doesn't make a claim or makes an inaccurate claim.	Makes an accurate but incomplete claim. <i>Nutrients need to get into the cell.</i>	Makes an accurate and complete claim. <i>Nutrients need to get to the centre of the cell quickly for the cell to survive.</i>
Evidence	Does not provide evidence or inappropriate evidence.	Provides appropriate but insufficient evidence. <i>The iodine didn't get as close to the centre of the potato when the cube was bigger.</i>	Provides appropriate and sufficient evidence. <i>The surface area to volume ratio gets bigger, the smaller the cell. The iodine got closer to the centre of the potato cube more quickly the smaller it was.</i>
Reasoning	Does not provide reasoning or only provides reasoning that doesn't link evidence to claim.	Provides reasoning that links the claim and the evidence; repeats the evidence and/or includes some scientific principles but not sufficient. <i>Links need for quick absorption of nutrients with size but doesn't relate this to SA/V ratio.</i>	Provides reasoning that links evidence to claim and includes appropriate and sufficient scientific evidence. <i>Explains how SA/V ratio increases the rate of absorption and relates experimental results with the need of cells to absorb nutrients quickly.</i>

Year 8 TF11 “*Explain what happens (and why) when a bike rider at the top of a hill takes his feet off the pedals and releases the brake*” - Explanation Rubric

Component	Level		
	0	1	2
Claim	Doesn't make a claim or makes an inaccurate claim.	Makes an accurate but incomplete claim. <i>One form of energy is transferred to another.</i>	Makes an accurate and complete claim. <i>Energy is conserved. The GPE at the top of the hill is converted to other forms.</i>
Evidence	Does not provide evidence or inappropriate evidence.	Provides appropriate but insufficient evidence. <i>The bike accelerates down the hill and then slows down when he gets to the flat.</i>	Provides appropriate and sufficient evidence. <i>The bike is up high and as it gets lower it accelerates until it is going fastest at the bottom of the hill and then slows down when he gets to the flat. The parts/tires get hotter.</i>
Reasoning	Does not provide reasoning or only provides reasoning that doesn't link evidence to claim.	Provides reasoning that links the claim and the evidence; repeats the evidence and/or includes some scientific principles but not sufficient. <i>A partial explanation of how energy is being conserved. Explains transfer of one type of energy to another.</i>	Provides reasoning that links evidence to claim and includes appropriate and sufficient scientific evidence. <i>At the top of the hill – high GPE. At the bottom of the hill – no GPE and high KE. Friction of tires with road. A complete explanation of how energy is conserved linking types of energy with the idea of conservation of energy through transfer from one type to another.</i>

Year 9 TF1 “Explain how we know about the structure of the atom” - Explanation Rubric

Component	Level		
	0	1	2
Claim	Doesn't make a claim or makes an inaccurate claim.	Makes an accurate but incomplete claim. <i>“There are different models for the atom” “atoms have electrons and are mostly empty space”.</i>	Makes an accurate and complete claim. <i>“Our model for the atom has changed over time because of experiments” Correct model/s.</i>
Evidence	Does not provide evidence or inappropriate evidence.	Provides appropriate but insufficient evidence. Provides one piece of evidence <i>eg Rutherford's experiment but doesn't expand on it.</i>	Provides appropriate and sufficient evidence. <i>Describes an experiment such as Rutherford's experiment in detail.</i>
Reasoning	Does not provide reasoning or only provides reasoning that doesn't link evidence to claim.	Provides reasoning that links the claim and the evidence; repeats the evidence and/or includes some scientific principles but not sufficient. <i>Eg Describes what change in ideas of the atom Rutherford's experiment led to but doesn't justify those ideas sufficiently.</i>	Provides reasoning that links evidence to claim and includes appropriate and sufficient scientific evidence. <i>Eg Justifies the changes in idea about the atom on the basis of each of the results of Rutherford's experiment.</i>

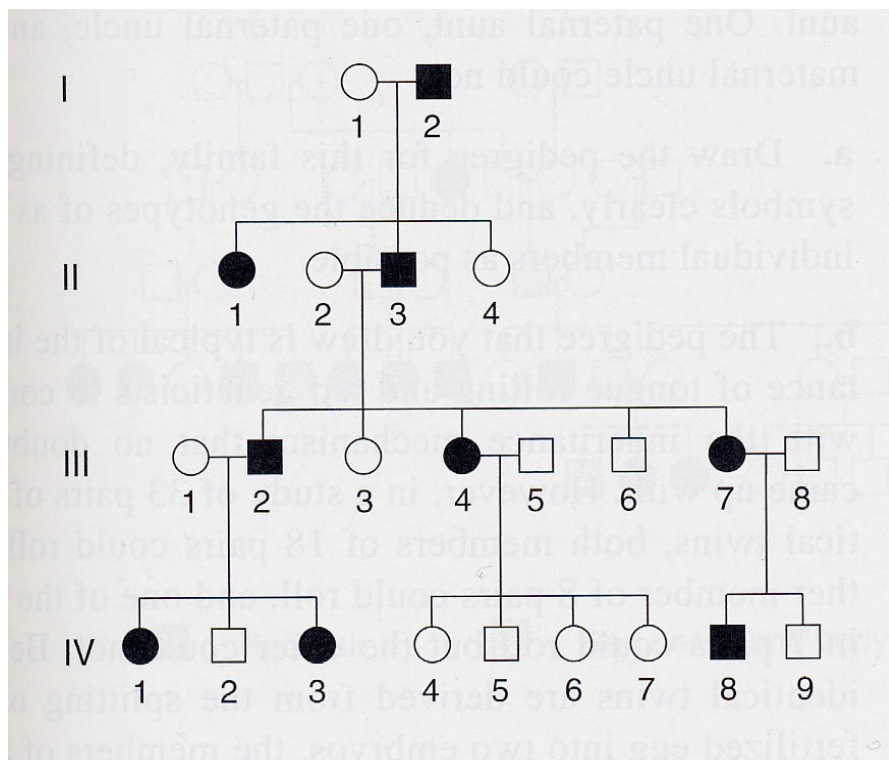
Year 9 TF14 “*Explain why a paper cup without water in it will burn but one with water will not*” - Explanation Rubric

Component	Level		
	0	1	2
Claim	Doesn't make a claim or makes an inaccurate claim.	Makes an accurate but incomplete claim. <i>The cup heats up more slowly.</i>	Makes an accurate and complete claim. <i>The paper cup with water in it never reaches its ignition temperature until the water boils away.</i>
Evidence	Does not provide evidence or inappropriate evidence	Provides appropriate but insufficient evidence. Provides one piece of evidence. <i>The water absorbs a lot of the thermal energy./A cup with water in it has a higher heat capacity.</i>	Provides appropriate and sufficient evidence. <i>Either, The temperature of the water increases slowly. Or Objects that are in contact with each other transfer heat. AND The temperature of liquid water doesn't go over 100°C or water evaporates/boils.</i>
Reasoning	Does not provide reasoning or only provides reasoning that doesn't link evidence to claim.	Provides reasoning that links the claim and the evidence and includes some scientific principles but not sufficient. <i>Links claim with one piece of evidence using a scientific principle.</i>	Provides reasoning that links evidence to claim and includes appropriate and sufficient scientific evidence. <i>Water is in contact with the paper cup so energy is transferred to the water as the particles try transfer thermal energy through collisions. The temperature of the water increases slowly as water has a very high thermal heat capacity so it absorbs a lot of energy to raise the temperature a little bit. The temp of the water never goes over 100 since at this temperature the energy is used to separate the molecules to form gas (latent heat of vaporisation). Therefore, the ignition temperature is never reached. (At least two of these explained. Must include the fact that the temp can't go over 100.)</i>

Grade 10 TF5 “*Explain why a car towing another car accelerates even though the force on car 1 on car 2 is the same as the force of car 2 on car 1.*” -
 Explanation Rubric (Mid-semester 1)

Component	Level		
	0	1	2
Claim	Doesn't make a claim or makes an inaccurate claim.	Makes an accurate but incomplete claim. <i>Recognises that there are other forces acting on the cars.</i>	Makes an accurate and complete claim. <i>There are other forces acting on car 1 which result in an unbalanced net force acting on the car. (Implicit understanding that each member of a Newton 3 pair acts on a different object.)</i>
Evidence	Does not provide evidence or inappropriate evidence.	Provides appropriate but insufficient evidence. Provides one piece of evidence. <i>Partially describes one other Newton 3 force pair type acting on the car.</i>	Provides appropriate and sufficient evidence. <i>Identifies two or more sets of Newton 3 force pairs types. Indicates the action/reaction pair. (Implicit understanding that each member of a Newton 3 pair acts on a different object.)</i>
Reasoning	Does not provide reasoning or only provides reasoning that doesn't link evidence to claim.	Provides reasoning that links the claim and the evidence and includes some scientific principles but not sufficient.	Provides reasoning that links evidence to claim and includes appropriate and sufficient scientific evidence. <i>Uses the Newton 3 pairs to determine that there is an unbalanced net force on the car. Hence since there is an unbalanced force, Newton's 2nd law applies – the cars accelerate.</i>

Grade 10 TF15 "Use this pedigree to determine the kind of inheritance of the characteristic shown in black" - Explanation Rubric (Mid-semester 2)



Component	Level		
	0	1	2
Claim	Doesn't make a claim or makes an inaccurate claim.	Makes an accurate but incomplete claim. <i>The characteristic cannot be sex-linked.</i>	Makes an accurate and complete claim. <i>The characteristic cannot be sex-linked. There is not enough evidence to determine whether it is autosomal dominant or recessive.</i>
Evidence	Does not provide evidence or inappropriate evidence.	Provides appropriate but insufficient evidence. <i>Provides one piece of evidence or doesn't elaborate.</i>	Provides appropriate and sufficient evidence. <i>Only one out of two girls in Generation II has the condition. AND Only one out of two boys from parents 7 & 8 in Generation IV has the condition. OR No situation where the students have the condition but the parents don't.</i>
Reasoning	Does not provide reasoning or only provides reasoning that doesn't link evidence to claim.	Provides reasoning that links the claim and the evidence and includes some scientific principles but not sufficient. <i>Links one claim with appropriate evidence using some scientific reasoning.</i>	Provides reasoning that links evidence to claim and includes appropriate and sufficient scientific evidence. <i>Links each of the pieces of evidence with the claim using scientific reasoning to support the claim eg Punnet squares.</i>

Appendix F: Semi-structured Interview Questions

Year 10 In-depth interviews:

Interview Protocol

1. How confident are you that you will be able to understand new concepts in science?
2. Why do you feel confident, why don't you feel confident? Has that changed over the past year/two years?
3. What kinds of activities in science help you to understand a topic?
4. Would you feel more confident giving your answer as pictures, spoken words or written words? Why did you choose that one?
5. Think back to last year. What do you think are the biggest differences about how you learned science last year to this year? Which things do you prefer? Why? Which things useful or not useful for learning science? Why?
6. What have you found helpful for your learning in science about using the Thinking Frames Approach?
7. What have you found difficult or unhelpful about the approach?
8. Would you say that your attitude towards learning science has changed?
9. Would you say that your belief in your ability to write explanations in science has changed?
10. Are you interested in studying science next year, in Year 11? Why or why not? Has your interest in studying science changed at all over the past two years?
11. Overall we have used TF to study physics, chemistry and biology topics. Which of these has TF been helpful for?
12. Year 10 topics and TF?
13. Do you find it easy to imagine/visualise what is happening when explaining scientific concepts?
14. Do you think TF helps in visualisation? How does it help you?
15. Does it help in writing explanations/ communicating? How does it help you?
16. When writing an explanation do you find it easy to find the right scientific words to explain with? Do you think that TF has helped you in knowing the right scientific vocabulary to use? Why or why not?
17. Do you find levelling your work at the end of doing TF helpful? Why or why not?
18. How useful is the feedback that you get in TF?
19. In your opinion, which topics were TF most helpful for you in understanding? (Atoms and bonding, Ecosystems, Respiration and Photosynthesis, Diffusion, Negative Feedback and homeostasis, reflex arc, the immune system, thermal physics and electricity). Why or why not? Elaborate on this.
20. Has TF helped you to remember concepts? For example in exams? How has it helped?
21. I want to get an idea of how to improve teaching using TF. Can you think of some ways in which my teaching could be improved?
22. How has working in groups gone? Are there things that are helpful or difficult about that?
23. Show them a TF that they did well on and maybe one from earlier to show the improvement. How did you feel about answering this question? Do you feel that you have improved in your ability to write a scientific answer?
24. What things about the teaching this year have helped you to improve? (It might not be just the TF!)

25. Look at the pre and post tests for particles and matter, thermal physics and electricity. What areas have they improved in? Why do they think they have improved? Not improved?
26. Did you find doing the pre- and post-tests helpful in learning the topics eg in thermal physics and electricity? If so what was helpful? If not, why not?
27. Overall, has your attitude changed to science? If so in what ways? Use their questionnaire data – highlight any areas where they were negative/positive and question them about these. Do you still feel the same? Why did you write that? Elaborate!
28. How important do you think it is to learn about science? Is it important for living in the modern world?
29. Can you tell me about some areas of science that you find easier/more interesting/ think that you can do well in? What is it that you find easier/ more interesting/ think you can do well in?
30. Are there some areas of science that you find difficult/ less interesting/ don't think that you can succeed in? What is it about these areas that you find difficult/less interesting/ don't think that you can succeed in?
31. Are there areas in your learning that you feel that you have improved in? Why?
32. Do you think that your writing has improved over this year? In what ways? Why or why not?
33. Would you be interested in doing more science later on, for instance in year 11 and 12?
34. What is something that you learned this year that you are pleased you learned/ think that you now understand well?

Appendix G: Feedback Given to Bronwyn's Response

Thinking Frame

Thinking Skills

THINK / SEQUENCE

What happens	→	Why
Car tows other car using the wheels	➔	the wheel move Earth backwards
the first car accelerates pulling the other car with it		The force is enough to pull it. It has to have

There is a net force acting on the cars. A Newton 3 pair of forces. The car pushes the earth back with a force exerted by friction of the tyres + the earth pushes the car forward with an equal but opposite force.

These forces don't cancel each other out as they act on different bodies.

PARAGRAPH

Write your answer to the problem as fully as you can. (HINT Use cause and effect words such as consequently, because, whenever, depending upon, eventually, since, until etc)

Car 1 pulls car 2 along with it since it has enough ^{net} force to pull the high mass object along. It has twice the inertia so it needs twice the acceleration. The reason it's able to move even because of the equal and opposite reactions stated in Newton's 3rd Law. ~~higher mass~~ Which ones?

Make sure you answer the question. ①

Appendix H: Feedback to Ven's Response

PARAGRAPH

Write your answer to the problem as fully as you can. (HINT Use cause and effect words such as consequently, because, whenever, depending upon, eventually, since, until etc)

When water is added to the cup they try to reach thermal equilibrium, so the cup's ignition point rises because of the water high thermal heat capacity. When the flame hits the cup it does not burn, because the water is taking ^{much of} all the energy. The cup will not burn until all the water has evaporated. The energy is used to heat up the water ^{+ the cup} not the cup. They are at the same temperature because they are in contact.

The cup's ignition point stays the same but this temp. isn't reached to thermal equilibrium

When water is added to a cup they try to reach thermal equilibrium, so they both are the same temperature.

When the flame comes in contact with the flame comes in contact with cup, the cup does not burn because of the water's high thermal heat capacity, so the ^{most of} all the thermal energy is taken by the water and is used to heat it up. The cup will not burn until all the water is evaporated through a phase change.

3.4

The temperature doesn't go above 100°C Why?