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The Role of Experiences in Learning to Design and Problem Solve in the Context of Hard Materials

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Abstract

Problem solving and design are key factors identified with technology education. Such attention has contributed to a curriculum shift from technical education to technology education. When hard materials are considered, practical experiences play a significant role in learning in technology education.

The purpose of this research project was to identify in what ways experiences contribute to learning to design and problem solve in the context of hard materials. This research asked five expert technologists who design and problem solve in the context of hard materials in what ways they considered experiences contributed to their learning. A similar question about learning through experiences was posed to five New Zealand secondary hard materials technology teachers in order to identify the ways in which experiences with hard materials contribute to their students' learning to design and problem solve.

This research used an interpretivist mode of inquiry and interviews to enable the research participants to share their knowledge and understanding that inform this research. Data were analysed to identify themes and theorised using four learning theories based on experiences - experiential learning theory, situated cognition theory, distributed cognition theory and activity theory.

Both experts and teachers identified that significant learning experiences involved: developing knowledge of materials; recognising the complexity of technological knowledge; providing feedback on the effectiveness of design, on-going development of strategic knowledge that is used to design and problem solve; and developing character traits relevant to design and problem solving.

The analysis identified a broadened construct of experience as a significant factor that contributes to learning to design and problem solve. This research showed that four learning theories could be used as a tool to analyse learning through experience as well as theorising a curriculum and pedagogy that focuses on experience as a significant and important component of learning to design and problem solve in the context of hard materials.

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Chapter 1: Introduction

1.1 Introduction to research

An emphasis on two areas—design and problem solving—has been identified as a key factor that has helped to distinguish the subject of technology as a separate curriculum area in education over the last two decades (Mawson, 2001; Mioduser & Dagan, 2007; Stein, Docherty, & Hannam, 2003). This coincided with technology being introduced into schools as a general and compulsory subject in primary, intermediate and secondary education in several countries worldwide, notably New Zealand, Canada, England and Wales, Northern Ireland, Australia, Israel and the United States (Mawson, 2001). It follows that technology curricula in these countries require students to be able to design and problem solve. A major justification for including design and problem solving in technology curricula is that these have been acknowledged as essential elements of what expert technologists do in their everyday work (Cajas, 2002).

In the context of hard materials, technology education has replaced technical or manual education that traditionally involved activities and experiences carried out in a metal or wood workshop. Nevertheless, practical experiences and activities remain common in technology education in the context of hard materials. To define this context, hard materials have been identified as resistant materials of wood, rigid plastic and metals (McNair & Clarke, 2007). Changes in technology education in the context of hard materials also require students to be able to design and problem solve. The pedagogy associated with learning to design and problem solve in technology education has not been presented in any easily accessible way for teachers. In many technology classrooms, instead of a pedagogy, a generic process identified as a sequence of steps has been offered to enable learning both design and problem solving (Johnsey, 1995). Consequently, students learning to design and problem solve in the context of hard materials remains a key area of discussion and focus in technology education for both teachers and curriculum planners.

1.2 Personal interest

My own learning to design and problem solve in the context of hard materials began through studying mechanical engineering and completing a 9,000-hour apprenticeship as a Mechanical Fitter with the New Zealand Electricity Department. In many ways, I entered

the field of mechanical engineering as a novice with extremely limited experiences or knowledge of either hard materials or the mechanisms made from such materials. My interest in studying mechanical engineering was initiated by the thought that it would be both interesting to find out how and why machinery worked and to know how to fix something if it broke. However, I grew up with traditional female toys (no Meccano sets or Hornby trains) and had no background in engineering from my education in an all-girls' secondary school. I did not follow the career pathway of either of my parents or older siblings although I did have a father who made many of our toys when we were young and always did most of his own home renovations.

After leaving secondary school, I commenced studying as a full-time student for a New Zealand Certificate in Engineering (NZCE). Initially this study provided me with a theoretical approach to engineering. An NZCE programme at the time (1971) required 1 year of full-time study and 2–3 years of part-time study at a New Zealand tertiary technical institute plus 3,000 hours of work-related experience. To meet the practical requirements of the NZCE and to get some experience in a practical engineering world, I decided to complete a 4-year apprenticeship as a mechanical fitter. Consequently, my technological learning began as an apprentice mechanical fitter situated within a practical engineering environment where I worked alongside skilled and experienced tradespeople in the general context of hard materials. At the time, I was the first female apprentice mechanical fitter that the government department supplying electricity to New Zealand had employed. During my apprenticeship, my learning also continued in a more theoretical direction as I studied papers towards my NZCE as a part-time student at night school and/or by correspondence.

My apprenticeship as a mechanical fitter included working on New Zealand power stations. My first power station learning experience was when I worked on projects and problems around a coal-fired power station under the guidance of tradespeople. A first impression of this environment was the impact of the continuous noise of six large boilers and turbines and related ancillary plant operating 24 hours a day. Another lasting impression was the immense size of the plant which in many ways added to the initial excitement of working in this environment. What struck me was the very real context of working on a power station that produced power for the national grid. My previous technological learning had centred on created *exercises* to support my learning but, in my eyes, had lacked any realness or authenticity.

I do not believe the experience of working in an environment such as a power station can be explained easily, it is something that has to be experienced to appreciate fully its impact. For me, working as a young female mechanical fitter, a power station presented a very exciting and interesting place to be. Essentially, a mechanical fitter tries to find out what the problem is when a component is not operating correctly and then fixes it. This may require designing a new part, modifying an existing piece of equipment or replacing a component part. Fitters also do general maintenance so they develop an understanding of how plant operates over substantial periods of time by pulling things apart, finding out what is wrong and putting them back together.

The skilled practitioners (tradespeople) that I worked with often related the practical work experiences to relevant theoretical concepts that could be utilised to solve the problems we were confronting. For example, when working on a power station, there were explanations as to how a pump operated, how steam turbines produced electricity, and the way different pumps worked and why they were suited to specific applications. Throughout this time, I accumulated an assortment of facts, knowledge and some understanding but I also began to appreciate the complexity of plant, its operation and how challenging it was to apply this knowledge. I became even more aware of how little I knew and my inability to apply this knowledge, compared with some of the tradespeople and the apprentices with whom I worked.

However, working on specific plant helped me to appreciate how plant and mechanisms operate. For example, when a boiler or turbine was out for long term survey-type maintenance, I was able to view inside the boiler or turbine and develop a better understanding of how various components interacted, fitted together and functioned. An understanding of the overall operation of a power station also developed as we apprentices worked for short periods of time in different gangs in specific areas (turbines, boilers, fuel processing, water pumps) within the power station. At this time, apprentices were required to study by correspondence or at a technical institute and sit for their Trade Examinations which were two 3-hour written examinations at the end of each year. The examinations included engineering theory, calculations and technical drawing based on mechanical engineering. This requirement realised the expectation and requirement to develop some theoretical learning alongside the practical hands-on learning experienced through physically working on the actual power station.

During my apprenticeship, my NZCE studies continued to provide me with a more theoretical approach to solving problems as well as an introduction to design. For example, my NZCE studies included some theoretical problem solving and design incorporated into written assignments based on activities in engineering laboratories or theoretical design scenarios. Often, they required using physical laws that applied scientific and mathematical knowledge. For me, there were limitations in this course work as we were never challenged with designing something and building it to find out whether or not our designs functioned effectively.

Occasionally, I did recognise the close relationship between the practical activities and knowledge acquired during my apprenticeship learning and the theoretical knowledge approach of my NZCE study but this transfer was not always apparent. One example I can recall was in one of my NZCE papers where we studied the energy efficiency of the coal-fired power station where I had worked for several months. Because I had worked on various component parts that contributed to the efficiency rating of the power station, I had prior knowledge and therefore a much clearer understanding and keener interest to participate in discussion before applying the scientific and mathematical formulae to find the efficiency rating. For me, there was a contextualisation of the problem because I had familiarity with aspects of the plant that contributed to and improved the efficiency rating of this power station. In other words, the theoretical problem was connected to something real and tangible that I had experienced. It was interesting to find out how low the efficiency rating was despite the many plant refinements that had been implemented to improve the power station's overall energy efficiency rating.

In contrast, when I first commenced my NZCE engineering studies, I would read a mechanics problem and have no conception of items such as shafts or pulleys that were presented in the problem. At first, even reading a problem referring to the size of a nut or a bolt diameter presented some difficulty for me (I knew what a diameter and a millimetre were from studying mathematics but had to think carefully to distinguish in my mind the nut from the bolt). At this stage, I had very few concepts to attach to the terminology used in many of the problems although I could do the mathematics and even get a correct answer. With my limited background, I simply had no point of reference and constantly felt I was in catch-up mode compared to the rest of my male class members. However, as I proceeded through my apprenticeship and studies, gradually I acquired basic knowledge and understanding but not enough to design and problem solve on my own.

After the completion of my apprenticeship, I had the opportunity to work for 6 months with professional mechanical engineers where my learning was focused more theoretically, even though the learning context remained centred around power generation. Most of the work focused on modifications of existing plant or analysis when something went wrong. At this stage, I worked under the guidance of mechanical engineers; consequently, I had no decision-making power or responsibility and the designing and problem solving were fairly mundane. However, because I had worked on some of the power plant we were modifying, I had a good understanding and was reasonably confident in contributing to the discussion that often involved the need for modifications. For example, one of the jobs I worked on was considering the modification of existing plant to “arrest” grit more effectively from going into the atmosphere, as a result of the burning of fossil fuels. As I had worked on this power station, I had some conception of the existing plant we were modifying and had witnessed first-hand the grit going up the chimney flues. This made the calculations more meaningful for me as I could attach it to my knowledge of the physical situation experienced.

A short time later, I had the opportunity to train as an operator on a large substation and gas-turbine power station. This training and work focused on power generation and supply from a completely different perspective than what I had experienced as either an apprentice or working in a mechanical engineering office. I remember the first time manually switching a 3-phase 33,000 KVA power line and seeing the massive electrical arc produced while the knife switch disconnected the 3-phase power line into the substation. After this experience, I had a great deal of respect for the high-voltage environment in which I was working.

Problems arose for me as a female which resulted in me not legally being allowed to do the night shift as it contravened an old factories act law. As a consequence, I investigated the possibility of using my engineering background and qualification to become a teacher. I was interested in learning because my own journey in engineering had been somewhat convoluted. This resulted, I believe, because I had no initial background experiences when commencing my own engineering learning. Often, I reflected on why both the practical and theoretical engineering learning had been so difficult for me including both the design and problem solving aspects.

In 1979, I completed a 1-year secondary technology teaching programme. During my teaching practicums and my pre-service teacher education, I encountered the craft-focused

programmes that had become prevalent particularly in intermediate and early secondary technology classrooms. During this time, subjects such as “technicrafts” had been introduced into some New Zealand secondary technical schemes of work. At this time, the emphasis in technicrafts was on craft design where students used hard materials and workshop processes to make objects such as sculptures and repousse pictures from copper that incorporated elements of their own design input. From my perspective, it incorporated very few of the elements of design or problem solving that I had encountered in my workplaces. The influence of art design seemed very apparent. At the same time, technical subjects such as engineering shopwork and technical drawing were still being taught in secondary schools. There seemed quite a gap between these traditional technical subjects and technicrafts. The former focused on quite prescriptive engineering related learning while technicrafts focussed more on design and crafts.

Some years later when I returned to teaching, I was living in a remote location with no local secondary schools. Consequently, I commenced teaching in primary schools and decided through part-time study to complete a Bachelor of Education (Teaching), a primary school teaching qualification. During this time, *Technology in the New Zealand Curriculum* (TNZC) (Ministry of Education [MoE], 1995) was being introduced into New Zealand schools replacing the *1986 Forms 1–4 Workshop Craft Syllabus for Schools*. The TNZC document established technology as a core subject in both New Zealand primary and early secondary schools. I found a significantly different emphasis in TNZC from my initial teacher education in 1979 as this new curriculum focused on students designing technological solutions to technological problems with less emphasis on outcomes or design of craft-type products (Harwood, 2002). I attended many of the professional development courses provided by the New Zealand Ministry of Education to implement TNZC and became excited about many of the changes in technical education. During this period, I taught technology at both primary and intermediate levels. As a result of my primary teaching qualification, I also became keenly interested in how students learn and the impact of effective pedagogy on student learning across all curriculum areas and, specifically, in the context of technology education.

Several years ago, I took up a role as a curriculum leader in the Year 8 (11–13 year olds) department of a Year 7–13 New Zealand secondary school. Currently, I teach several core subjects at Years 7–9. In this role, my focus and interest has been in how students learn and how educators can best facilitate this learning for their students.

In my current school, I have taught technology education at both intermediate and secondary levels and my specialist area in technology remains with hard materials. While I am very aware that students enjoy the practical activities of a technology classroom, my interest is in what they are learning and how are they learning through these practical activities and experiences. In particular, I am always questioning whether or not any of these experiences support their learning to design and problem solve.

In this thesis, I bring together my working background, including the challenge of entering the field of engineering as a complete novice; the parallel learning approaches to problem solving and design from both the theoretical and practical approaches that I had experienced as an apprentice and throughout my NZCE studies; my interest as a teacher in how students learn through effective pedagogy and learning experiences; and my background as a secondary-trained specialist technology teacher working in the context of hard materials. As a result of my background in engineering and current practice as a teacher, I am interested in student learning, pedagogy, design and problem solving in the context of hard materials and the role of experiences in learning to design and problem solve. From my own learning pathway, I consider that both theoretical and practical knowledge, skills and understanding have relevance when it comes to learning to design and problem solve. In this thesis, I have utilised my own learning, my background and current role in education to investigate and interpret the role of experience in learning to design and problem solve in the context of hard materials.

1.3 Organisation of the thesis

This thesis comprises ten chapters. In Chapter 1, a brief background to the introduction of design and problem solving in technology education is presented. The two key foci of this research, namely of experience and of learning to design and problem solve, are also introduced in this chapter. My background and personal history relevant to the research topic has been presented in this chapter to provide some insight to the interpretivist lens through which this research was conducted.

Chapter 2 presents an in-depth look at the literature that backgrounds and informs this research. In this chapter, the changing nature of technology education is presented and the introduction and subsequent issues relating to design and problem solving in technology education is discussed. This chapter also considers the types of knowledge and learning theories that relate to experiences and activity. The gaps in current research and literature

are identified and the resulting research sub-questions and overarching research question are presented.

In Chapter 3, the research design used to guide this research is described in detail. The choice of an interpretivist mode of inquiry, the ontology and epistemology are explained and the justification given for choosing a qualitative research approach. This chapter identifies the reason why two distinct groups of research participants were chosen to conduct this research. The selection process for research participants is explained, how the data were collected and the way in which the data were analysed is explained in detail. The chapter concludes with an examination of trustworthiness as it relates to qualitative research and the pertinent ethical considerations. A research timeline is included also in this chapter in Figure 3.1.

Chapters 4 and 5 present the research findings of the expert technologists. Chapter 4 provides an in-depth analysis of the expert technologists' data. This chapter presents the findings regarding in what way the expert technologists consider experiences contributed to their learning to design and problem solve.

In Chapter 5, the data findings of the expert technologists focus on strategic skills that enable effective deployment of knowledge and understanding relevant to design and problem solving. This chapter presents also the expert technologists' conceptions of design and the role of problem solving in the context of hard materials. Finally, the chapter provides detail of how the experts design and problem solve in their respective technological working environments.

Chapters 6 and 7 present the analysis of the teachers' data findings. Chapter 6 discusses the findings about technology teachers' conceptions of design and the role of problem solving in hard materials technology education. Second, the chapter reports the findings regarding the technology teachers' conceptions of key traits of successful novice student designers and problem solvers. The findings in Chapter 6 provide the teachers' conceptions relating to design and problem solving that influence their pedagogy analysed in Chapter 7.

Chapter 7 presents the findings from the analysed data of the technology teachers that contribute to students learning to design and problem solve through experiences. The issues identified in the teachers' findings which relate to students learning to design and problem solve also are presented in this chapter. This chapter concludes with a discussion

regarding the technology teachers' pedagogy relating to learning design and problem solving.

Chapter 8 analyses both the expert technologists' and the technology teachers' data using four different learning theories relating to learning through experience. As learning through experience is a key focus in this thesis, this chapter provides a further analysis that considers how learning through experience can be theorised utilising four existing learning theories.

In Chapter 9, the findings from the analysis chapters are discussed with reference to the literature review and the overall research question and sub-questions. This chapter begins with a discussion of the findings from the expert technologists' analysed data then considers the technology teachers' analysed data and findings. The chapter concludes with a discussion of how learning experiences may be analysed and how this relates to the overall research question and sub-questions.

Chapter 10 is the final chapter of this thesis and presents the significance and educational implications of this research. This chapter includes information about the relevance of this research for technology education, technology educators and future curriculum decisions. It characterises learning to design and problem solve and theorises this characterisation using four existing learning theories to inform a pedagogy based on experience. Finally, the limitations of this research are acknowledged and future relevant research possibilities presented. Chapter 10 finishes with a concluding statement identifying the key outcomes of this research into the role of experience in learning to design and problem solve in the context of hard materials.

Chapter 2: Literature Review

2.1 Introduction

This literature review considers key aspects in the development of technology education, specifically the introduction and relevance of learning design and problem solving. A key focus in the literature review is the connection of experience to learning technological design and problem solving in the context of hard materials technology education. Further, this literature review examines the current situation of technology education and identifies areas in which significant research needs to be conducted.

First, in Section 2.2, the literature review considers some of the historical influences that have contributed to the development of technology education. This section includes a brief history of technical education and seeks to identify some of the reasons for the evolution of a discrete technology curriculum both in New Zealand and in other countries. In this section, the changing nature of technical education is highlighted with the introduction and development of design and problem solving as part of technology education both in New Zealand and in other countries in which a technology curriculum has been implemented.

Section 2.3 presents relevant historical events and issues relating to the changing nature of technology education. Because it is argued that learning to design and problem solve constitute two key elements of change in technology education, Sections 2.3.1 and 2.3.2 examine in some detail the introduction of problem solving and design to technology education. Section 2.3.3 considers some of the ongoing issues of design and problem solving, which include the interrelationship of design and problem solving as represented in technology education and curricula. In Section 2.3.4, a selection of current literature and research relating to design and problem solving in technology education is presented.

Design and problem solving are activities in which many experts engage. Therefore, it is relevant to consider design and problem solving from their perspective. In Section 2.4, a general view of how experts are considered to problem solve, in relation to how novices problem solve, is discussed. Section 2.4.1 includes specific references to how experts and novices problem solve and design in technology-related activities where problems are ill-defined. In Section 2.4.2, significant research relating to both expert and novice designers and problem solvers is described.

Section 2.5 discusses the ways in which specific kinds of knowledge are relevant to learning design and problem solving with hard materials. This section presents an overview of technological knowledge, including some of its distinguishing features. Section 2.6 describes procedural knowledge relevant to technological activity, while Section 2.7 describes conceptual knowledge and its relevance to technological activity. In Section 2.8, the different categories of integrated knowledge required by both expert technologists, who design and problem solve with hard materials, and those thought relevant to technology education are presented. Sections 2.5–2.8 also identify some of the gaps in current literature concerning technological knowledge that relate to the research focus of this thesis.

Because an examination of how learning to design and problem solve with hard materials often includes experiences with hard materials, it is pertinent to consider those theories that seek to explain learning through experience and activity. A review of four major learning theories is presented in Section 2.9: experiential learning theory, situated cognition theory, distributed cognition theory and activity theory.

Technology teachers are the key providers of learning opportunities that enable students to learn design and problem solving in technology education. Therefore, it is applicable to address both teachers' content knowledge and their pedagogical knowledge relevant to teaching design and problem solving with hard materials. In Section 2.10, the influence and importance of pedagogical content knowledge of teachers is considered, and, in particular, how this is significant in the context of hard materials technology education.

The chapter concludes with a summary in Section 2.11 of key aspects presented in Chapter 2, including curriculum and research issues associated with several of these aspects. Section 2.11 also presents the key research question and sub-questions emerging from the literature review that guide this research.

Table 2.1 lists the various technology education-related documents/relevant organisations referred to in this literature review and, where applicable, their acronyms, abbreviations, synonyms, date of origin and country of origin.

Table 2.1: Documents and acronyms relating to technology education referred to in the literature review

Technology related document or relevant organisation	Abbreviation if used in literature review	Date of introduction of document where applicable	Country of origin
1904 Regulations for Secondary Schools		Board of Education, 1904	Great Britain
Workshop Craft		1977	New Zealand
Craft, Design and Technology	CDT	Early 1980s	England and Wales
Forms 1–4 Workshop Craft Syllabus for Schools		1986	New Zealand
Department of Education and Science/Welsh Office	DES/WO		England and Wales
Technology in the National Curriculum		1990	England and Wales
Key Learning Areas (in Technology for Australian Schools)	KLAs	1994	Australia
Australian Education Council	AEC		Australia
Department for Education	DFE		England
Design and Technology in the National Curriculum	D & T	1995	England and Wales
Technology in the New Zealand Curriculum	TNZC	1995	New Zealand
National Academy of Engineering	NAE		USA
International Technology Education Association	ITEA		USA
Design and Technology Curriculum		1998	England and Wales
Science, Technology, Engineering and Mathematics	STEM		USA England
The Standards for Technological Literacy: Content for the Study of Technology		2000 2002 2007	USA
The New Zealand Curriculum: Technology	NZC: Technology	2007	New Zealand
Constraints, Optimisation, Predictive Analysis	COPA		USA
Next Generation Science Standards	NGSS	2013 (Draft)	USA

2.2 The changing nature of technology education

In this section, the changing nature of technology education, and historical influences on it, are examined. The literature review identifies some key episodes and changing emphases in the history of technical and technology education. It describes the emergence of design and problem solving as two important curriculum elements and notes the changes associated with technical and manual subjects resulting from the introduction of these curriculum elements. The purpose of Section 2.2 is to consider the overall development of technology education internationally, beginning with the historical influences that contributed to schools being able to provide industrial-type workshops for their students to learn skills and make artefacts with hard materials.

Section 2.2.1 begins by looking at the historical context of students working experientially with hard materials to make artefacts and examines reasons why manual technical education was implemented as a school subject both in New Zealand and in other countries. As this research seeks to ascertain the connections of experiences with hard materials to learning of design and problem solving, it is pertinent to look to the historical roots of technology education in terms of students' experiences when working with hard materials. In Section 2.2.2, the shifting emphases in technology education are explored, including the introduction of design into technical education. In Section 2.2.3, the introduction of technology as a discrete curriculum subject, both in New Zealand and elsewhere is examined. Also in this section, reasons for the re-conceptualisation of technical education are discussed. In Section 2.2.4, the resulting problems of teaching technology are described, with a particular emphasis on the design and problem solving components of technology education.

2.2.1 Antecedents of technology education

The purpose of presenting this brief history of technical education is to provide an historical perspective of technical education in which experience using materials was a key focus. As illustrated in this section, learning through experiences with hard materials in technical education has been a component of education for many years. The historical influences presented indicate that the initial purpose of technical or manual education was not necessarily to prepare students for a blue-collar workforce. Rather, it was implemented, in part, to provide students with a unique form of learning in which a key element was experiences with materials, unlike other book-oriented school subjects of that period.

However, this contrast between hands-on learning and book learning led eventually to a significant difference in status for technical education. As secondary education became more available, technical subjects were accorded a lower status than more academic subjects were, particularly when these subjects became separated from general education for all students. Indeed, the low status of technical education resulted in the study of technical subjects being confined to a limited number of students in secondary schools.

Prior to the 1980s, technical and manual education curricula and work schemes, both nationally (New Zealand) and internationally, had stressed the need for students to work with hard materials using specific tools in order to acquire skills for the workplace, learn vocational competencies and develop craft skills (Cajas, 2002; Hill, 1998; Jones & Compton, 2009). As acknowledged by these researchers, early technical education is often perceived as skills training for industry although, historically, this was not its only intended function.

Interest in education that included a technical component began in Great Britain as early as the mid-18th century in response to the Industrial Revolution occurring at this time (1750s–1850s) (Dakers, 2006). Leading industrialists of that period promoted the relevance of education as it provided learning that was associated with specific occupations in industrial settings but also recognised the importance of everyone learning the principles of science and technology. As Dakers (2006) points out, an “industrial literacy” for all citizens was considered a necessity to engage and develop in an emerging industrial society (p. 149). By the end of the 19th century, Great Britain was declining as a powerful industrial world leader and the lack of science and engineering-type learning in education was sometimes blamed for this decline. Partly in response to Great Britain’s industrial decline, the *1904 Regulations for Secondary Schools, Manual Work*, based on industrial trade craft, was introduced as a compulsory subject for boys in their first 2 years of secondary education. Manual Work was studied alongside a broad range of academic and less academic subjects that included science. Although Manual Work involved working with metal and woodworking tools and therefore introduced students to workplace skills and attitudes, it became a component of a compulsory general curriculum for all English state secondary schools. At the time, it was considered relevant and significant for all male students to experience this component of the curriculum (Wakefield & Owen-Jackson, 2013).

From 1944, Great Britain introduced a *tripartite system* of secondary education. This was a three-tiered secondary state education system with Secondary Modern Schools and Secondary Technical Schools existing alongside Grammar Schools. After 1944, entry to the academic-focused Grammar Schools was gained through an examination taken by all students at the end of their primary schooling. Entry to Grammar Schools was allocated to those students whose marks were in the top 10–35 percentage, depending on the local education authority. Those with lower marks attended Secondary Modern Schools that provided a more general education. It was intended that Secondary Technical Schools would provide a third option for students who wished to study mechanical science, technical and engineering subjects in order to become technicians and engineers in industry. These students were more academically able than were the students attending Secondary Modern Schools. However, few Secondary Technical Schools were built because of their cost and the problem of finding teachers with appropriate qualifications (O’Sullivan, 2013). Until the age of 14, students who attended Secondary Modern schools did have the opportunity to take technical subjects such as woodwork, building and metal work (Wakefield & Owen-Jackson, 2013). As a consequence, during this post-war period in Great Britain, technical subjects became associated with schools that were attended by students who had failed to gain entry to an academic education via the state-funded Grammar Schools. This situation resulted in a lower status being attached to students taking technical subjects in secondary schools.

Post-1944, the failure of Secondary Technical Schools to be developed in any significant numbers was seen as a missed opportunity. Secondary schools missed the chance to provide a broader technology-type industrial focused curriculum for technically motivated and academically able students. It was also seen as a missed opportunity to increase the status, importance and value of learning associated with science, technology and engineering-type subjects (O’Sullivan, 2013; Wakefield & Owen-Jackson, 2013). Nonetheless, Secondary Modern Schools did provide a significant number of male students with an opportunity to study technical subjects using hard materials. Largely, these subjects were chosen by students who were perceived to be non-academic and better suited to learning pre-vocational skills as preparation for the blue-collar workforce (Wakefield & Owen-Jackson, 2013). As a consequence, in Great Britain, the status of technical subjects using hard materials declined from its early 20th-century position when technical subjects were perceived to be of value for all male students.

Technical subjects in the United States initially centred on Manual Training which is reflected in its title. This education was based on industrial crafts and provided students with opportunities to learn to process materials, study mechanical drawing and work with tools. However, in the late 19th century, Calvin Woodward (one of the subject's chief advocates) believed that the subject also could provide opportunities that other subjects could not. He considered it gave students the opportunity to work with, and engage in an imaginative way with real objects in their world (Lewis, 2004). This attitude to Manual Training reflected current thinking in Great Britain that manual work was a relevant and worthwhile subject for a broad cross-section of students to study. This thinking is reflected in the three reasons posited by Savage and Sterry (1990) for male students to study manual education (training) in the United States. These are: to keep boys in school; provide them with vocational skills; and to promote "leisure-time activities". Under the influence of Charles Richards (the author of *Arts in Industry*, an influential report for the National Society of Vocational Education), the title of Manual Training was changed in the early 20th century to Industrial Arts. The new title reflected more fully developments in industry at the time and the more general educational value of the subject (Dugger, 2009).

In the United States, during the 1930s, the notion of students obtaining educational value from being able to work practically, and to observe the real results of their work in Industrial Arts, was acknowledged and given substantial impetus by John Dewey (Lewis, 2009). Doolittle and Camp (1999) note that Dewey's vision regarding education through experience was thought to be liberating for students, and was not just a means to retain the "status quo" or perpetuate class distinction. Lewis (2004) notes that while the origins of technical subjects in the United States were "premised upon blue collar knowledge" (p. 21), they were never intended just to prepare students for a blue-collar industrial workplace. Instead, technical subjects were made available to all children as a legitimate practical learning area with perceived educational value beyond training students for industry.

In New Zealand, from the early 20th century up until the mid-1970s, students working with hard materials and learning to use tools appropriately were elements of intermediate and secondary school technical education (Harwood & Compton, 2007). An initial motivation for introducing manual and technical instruction into schools in the very late 19th century was to provide an alternative to traditional book learning. A second motivation at this time

was to provide opportunities for students to develop any natural aptitude they might have to work practically with materials (Harwood & Compton, 2007).

After 1901, secondary education was made available for all New Zealand students who passed a proficiency examination at the end of their primary schooling (Harwood & Compton, 2007). Because secondary education at this time was so strongly academic, an alternative was sought to provide for those students perceived to be less academically able with subject options that would encourage them to continue with their education. By 1910, the establishment of separate Technical High Schools in major centres filled this gap. These schools offered male students pre-vocational courses in engineering, building and agriculture (Reid, 2000). However, the Technical High Schools were thought to be stigmatised because they provided education for students who were academically less able. These students followed courses to prepare them for the blue-collar workforce. This stigmatisation made the schools less attractive, although there is evidence that some parents and students saw them as a worthwhile alternative to having no post-primary education (Reid, 2000).

After 1945, technical subjects such as woodwork and metalwork were brought back into mainstream education in New Zealand. While these were optional subjects in secondary schools, in intermediate schools (11–13 years old) they were compulsory subjects for all male students (Harwood & Compton, 2007; Reid, 2000). In secondary schools, students who opted to study technical subjects also generally studied core curriculum subjects that included English, mathematics and a science option.

In New Zealand, studying optional technical subjects was often a precursor for students upon leaving school to take up 4- or 5-year apprenticeships in trades such as carpentry, fitting and turning or automotive engineering (Harwood & Compton, 2007). It would appear that manual and technical education was not necessarily the training-ground for unskilled manual labourers who learned a few tool skills, as portrayed in some literature. Rather, it provided a pathway to become a skilled and certified tradesperson in the workplace. Nonetheless, the status of technical subjects taught in mainstream New Zealand secondary schools remained quite low in the eyes of many and continued to be associated with students perceived to be non-academic (Harwood, 2002).

Technical skills were taught to students in schools' specialist-built wood or metal workshops, largely through the process of making an individual product or artefact using

prescribed plans. The prescriptive nature of many of these early school technical courses suggests that students were not encouraged or required to use these experiences to develop either their design or their problem-solving skills. Indeed, Harwood and Compton (2007) argue that technical teaching was based largely on a behaviourist model of learning; in other words, the teaching and transfer to students of an identified body of knowledge and skills. Nonetheless, Fergusson (2008) notes that many New Zealand technical teachers argued that the theoretical element in technical subjects always had been important and that being capable of doing the practical element of the subject required “significant mental ability – you do not think with your hands” (p. 48). More recently, this thinking has been recognised by Claxton, Lucas, and Webster (2010) who note one of the reasons that “practical (and much vocational) learning is so undervalued” (p.vi) is the result of a failure to understand its complexity and the significant intelligence it demands.

As can be seen from this brief history, technical subjects the precursor to technology education, involved students working experientially with hard materials. Initially, this learning often was considered a rich experience for all students and its status remained relatively high. As technical subjects became separated from mainstream secondary education, these experiences became less available to more academically able students. This situation resulted in a lowering of status for technical subjects. Although technical subjects in New Zealand were brought back into mainstream state secondary schools after 1945, they continued to have a low status and were taken only by relatively small numbers of male students.

2.2.2 Shifts that include design prior to the 1990s

This section considers the shifting emphasis in technical education prior to the 1990s with the introduction of design. During the 1970s in New Zealand, manual and technical education began to change when design became a component of these subjects. This change in New Zealand reflected changes occurring in other parts of the world, particularly in England and Wales (Cave, 2000). During the 1970s, two education initiatives in England and Wales— *Project Technology* and the *Design and Craft Education Project*— began to reform the technical secondary curriculum and introduce elements of design. *Project Technology* aimed to introduce technology into the English and Welsh curriculum as a new and separate subject. In the early 1980s, the *Design and Craft Education Project* introduced Craft, Design and Technology (CDT) as a secondary subject to broaden

technical and craft subjects and include more intellectual organisational skills and a stronger design component (Benson, 2009).

As noted by Benson (2009), this shift in technical education centred on engaging students in their own learning by providing education that endeavoured to address the individual needs of students. As well, the shift provided opportunities for students to develop the broader skills needed for work in a changing technological world. Also, it could be argued these changes gave technical subjects more academic appeal and credibility. In support of these changes, a broader range of materials such as acrylic and polystyrene acrylic plastics and polyester resin were used in CDT. The introduction of these materials was an attempt to integrate a variety of materials that were perceived to be more appealing to students and would more readily facilitate design (Cave, 2000).

Likewise in New Zealand, the subject *Technicrafts* evolved from the *1977 Workshop Craft* technology scheme. This new emphasis provided opportunities for students to work with a wider range and mix of materials and introduced the concept of design in a more explicit form. At this time in New Zealand, there was a push for students to take more pro-active roles in decision making when planning their projects' design and function. This change in focus reflected curriculum moves to student-centred learning and away from the perceived behaviourist underpinnings of manual technical learning (Harwood & Compton, 2007; Jones & Compton, 2009) (see Section 2.2.1). However, this design focus often emphasised the decorative superficial aspects of design, rather than design in terms of developing a technological solution to a problem posed. In some situations, design had a stronger connection to art design than it had to solving technological problems. In fact, the design aspect often related to students' own likes and dislikes (Harwood, 2002). For example, art design projects such as sculptures were made using a range of materials, that included metal, wood and plastic (Jones & Compton, 2009).

CDT in England and Wales was also thought to have similar limitations. For example, many considered it failed to represent modern technological advancements and therefore was deemed intellectually inadequate for preparing students for a developing and rapidly expanding technological world (McCormick, 1992).

Work schemes in New Zealand (based on *1986 Forms 1–4 Workshop Craft Syllabus for Schools*) continued the shift to a stronger design focus. For example, in New Zealand secondary schools an internally assessed and nationally moderated School Certificate

subject called *Workshop Technology* was offered as an alternative to the two existing School Certificate technical subjects *Woodwork* and *Engineering Shopwork*. Woodwork and Engineering Shopwork used 3-hour end-of-year examinations to assess a student's woodwork or metalwork knowledge. By way of contrast, Workshop Technology was internally assessed throughout the year and contained a stronger design emphasis that related to the design, production and manufacture of a student's individual project (Harwood, 2002). As a result, students were able to input some of their own design ideas into their practical work, thus reflecting the trend towards a more student-centred constructivist learning approach occurring in general education. Students were also required to provide their own written research in support of their individual projects. Similarly, during this timeframe in New Zealand secondary schools, Technical Drawing was replaced by a new subject, Graphics and Design, which also had a much stronger emphasis on design (Jones & Compton, 2009).

In short, during the 1970s, technical subjects involving hard materials encapsulated a move away from the more traditional and disciplined vocational technical training focus in hard materials to one where students took greater ownership of the products they produced. In part, this change developed as a consequence of a wider range of materials being introduced. As well, the drive to provide opportunities for students to include some of their own design input reflected a shift to a more student-centred constructivist learning focus. These changes and shifts resulted in technical subjects appealing to a broader cross-section of students and, as a consequence, a possible change in status for technical subjects. A change of status can mean a subject acquires more academic credibility in the eyes of parents and consequently attracts more academically able students. However, there was the potential during this time to alienate those students who required a disciplined technical educational focus in preparation for careers as technicians and tradespeople.

The following Section 2.2.3 considers the shift of technical education to mainstream education through the introduction of a technology education curriculum.

2.2.3 Technology emerges as a discrete curriculum, incorporating design and problem solving

This section considers the introduction of technology as a discrete curriculum in England and Wales, New Zealand, Australia and the United States. It notes the emphasis in various curricula allocated to two key elements: design and problem solving. It is argued that the

introduction of design and problem solving as key elements of technology education continued to academicise, broaden the appeal and improve the status of technology education from its predecessor technical education.

In 1990, England and Wales were the first countries to introduce a new primary and secondary compulsory curriculum called *Technology in the National Curriculum* (Department of Education and Science/Welsh Office [DES/WO], 1990). The English and Welsh technology curriculum incorporated significant elements of design. However, it created much controversy at the time of its introduction associated largely with the emphasis on design. The controversy centred on the curriculum's perceived lack of any definable knowledge base that could be attached to designing (Wright, 2008). Partly due to this controversy, a later national curriculum for technology in England and Wales was published as *Design and Technology in the National Curriculum* (Department for Education [DFE], 1995), emphasising design, making and capability combined with knowledge and understanding (Benson, 2009).

The New Zealand situation echoed the development in England and Wales, in that New Zealand also acquired its own national technology curriculum, TNZC (MoE, 1995). Technology represented one of the seven essential learning areas in *The New Zealand Curriculum Framework* (MoE, 1993). Indeed, Mawson (2003) asserts that TNZC was based quite substantially on the 1990 English and Welsh Technology in the National Curriculum model (DES/WO, 1990), although TNZC maintained a focus on the design aspect in hard materials technology that had been a component of technical subjects since the 1970s. This new technology curriculum acknowledged also the process of technological problem solving. The introduction of both design and technological problem solving represented a radical shift in emphasis from individual students within a class producing the same pre-designed artefact that had been a key element in previous technical subjects using hard materials (Harwood, 2002).

Although achieving and developing students' technological literacy was the overall aim of TNZC (MoE, 1995, p. 5), there were repeated references in this document expressing the need for teachers to provide students with opportunities to solve practical problems by designing a technological solution (MoE, 1995, p. 8). In New Zealand, technology education also focused on studying how technologists functioned in the *real* world, including how technologists design technological solutions to problems. The belief was that students could adapt these processes to their own technological problem solving and

designing (MoE, 1995). It could be argued that TNZC, like other technology curricula elsewhere, attempted to intellectualise and academicise the subject in order to justify its place as one of seven essential learning areas, one that *all* students would access.

In the current *New Zealand Curriculum: Technology* (MoE, 2007), the overall key aim remains on building technological literacy. However, two of the three stands, Technological Practice and Technological Knowledge, include provision for problem solving and designing. Technological Practice is identified as the “know how” and includes brief development, planning for practice, outcome development and evaluation. These four aspects link to solving an overall problem (brief development) and developing and evaluating design ideas and outcomes (planning for practice, outcome development and evaluation). Technological knowledge is characterised as the “know that” and includes technological modelling, products and systems. Knowledge is identified as essential to enable technological practice, as identified and characterised above (Compton & France, 2007; MoE, 2007).

Technology as a learning area was developing also in other parts of the world. Although countries such as Australia and the United States vary their technology educational focus according to individual states, there are some federal guidelines and directives. In 1987, the Australian national goals for schooling stipulated technology as one of eight learning areas, each with an equal status (Banks & Williams, 2013). In 1994, the Australian Education Council developed Key Learning Areas (KLA) for technology for both primary and early secondary students with a focus on problem solving, designing and making (Middleton, 2009b). These KLAs were general federal guidelines from which individual Australian states were able to develop separate technology curricula. Currently, in Australia, there is an attempt to develop a national curriculum for all key subjects, with technology due for consideration in phase 3 of a three-phase project (Banks & Williams, 2013). At present, the Australian government is also promoting the establishment of a Vocational Education and Training (VET) centre in each Australian high school in response to the current emphasis on providing a skilled workforce for key industries such as mining (Jones, Bunting, & de Vries, 2013). The emphasis on problem solving supported by designing apparent in the federal guidelines for technology education may be in danger of becoming redundant in such initiatives. Middleton (2009b) notes that the vocational training focus appears to parallel a corresponding diminishing interest by the Australian government in technology education in general education.

In the United States, the recent key focus of technology education has been on developing technological literacy, with a greater emphasis on problem solving than on design helping to achieve it (Savage & Sterry, 1990). However, design features significantly in national standards. *The Standards for Technological Literacy: Content for the Study of Technology* (ITEA, 2000, 2002, 2007) state what students need to achieve to be technologically literate from early childhood through to Grade 12. These 20 standards are divided into five categories, two of which relate directly to design (design and the designed world), thus recognising design as a significant element for students to become technologically literate. The standards are recommendations laid out with support from the United States National Academy of Engineering (NAE). Although these standards still require curriculum development within individual states, in a survey conducted in 2006–07, 42 states (91.3%) indicated they had used the standards in one or more of the following ways: in state curriculum guides, state standards, or professional development workshops (Dugger, 2009). Currently, Science, Technology, Engineering and Mathematics (STEM) education continues to be promoted in the United States with a significant push for engineering to be introduced earlier into both primary and secondary education as a means of promoting economic development (Jones et al., 2013; Lammi & Becker, 2013). Because design and problem solving are key elements in many types of engineering, these aspects continue to have prominence in STEM education initiatives. The Next Generation Science Standards (NGSS) also give prominence to both science and engineering practices that all students should learn and for engineering includes defining problems and designing solutions.

STEM initiatives have received a somewhat mixed reception in England and Wales. A key element in the current English *Design and Technology* curriculum, as reflected in the title, is recognition that designing and making of purposeful products is important in developing students' problem solving and creative skills (Barlex, 2007; de Vries, 2012). While STEM education is supported and promoted, there are some doubts about its place alongside the Design and Technology curriculum, with concerns expressed that STEM is an initiative to prepare strongly academic students for professional careers such as engineers. In contrast, Design and Technology provides opportunities for all students to participate in technological design and to work with materials. Given that engineering has a strong practical design and problem-solving focus, Cowell (2013) believes Design and Technology could provide STEM education with examples of how students might learn to design experientially. Nevertheless, there remains uncertainty as to how STEM and Design and Technology might coexist in future technology education programmes in England.

STEM education appears to promote technology in a stronger academic context than technology education does and, as a consequence, seeks to increase its appeal to more academically able students.

From the brief summaries presented in Section 2.2.3, it is evident that design and problem solving were introduced as significant elements of technology education curricula in several countries. It is reasonable to conclude that design and problem solving were two key elements of technology education that distinguished it from previous technical subjects and remain as two key and important elements of contemporary technology education and worthy of continued investigation.

2.2.4 Problems of how to teach design and problem solving

In New Zealand, during the 1990s, difficulties in teaching design and problem solving emerged for both primary and secondary teachers charged with the responsibility of teaching the new technology curriculum (Mawson, 2003). This problem was also evident in other countries, such as England and Wales, where technology had been introduced as a core curriculum subject, commencing in primary school (Solomon & Hall, 1996).

Initially, the English and Welsh Technology in the National Curriculum (DES/WO, 1990) consisted of two parts: *Design and technological capability* and *Information technology capability*. Benson (2009) suggests that when implementing the 1990 technology curriculum, many primary schools perceived the subject primarily as learning about computers, as they had no understanding of what constituted the design and technological capability component of the document. Because primary school technology education had not been a part of primary teachers' own education, teachers had severely limited content knowledge of this new subject (Banks & Williams, 2013; Hill & Anning, 2001). As a consequence, it was difficult to find teachers to take charge of the subject either in schools or in teacher-education establishments (Benson, 2009; Jones et al., 2013).

Equivalent problems of skill and focus were apparent in New Zealand, as trained secondary and intermediate workshop technology teachers were required to shift their thinking and teaching away from the traditional skills and craft. Instead, they were required to emphasise designing and solving problems, where processes were to receive as much prominence as outcomes (Harwood, 2002). As Jones et al. (2013) comment, this lack of confidence and expertise among technology teachers remains an ongoing problem not only in New Zealand but also throughout the world.

2.3 Issues surrounding the introduction of problem solving and design in technology education

Because this thesis investigates the learning of problem solving and design, it is important to consider what influenced the inclusion of problem solving and design in technology education and how the problem solving and design processes have been presented and taught to students in technology classes. Also, it is important to identify the limitations associated with the generic problem solving and design teaching and learning models, and to note that the learning of problem solving and design in technology education, frequently, have been seen as separate processes rather than one integrated process.

Therefore, in Sections 2.3.1 and 2.3.2, the distinctive features of the problem solving and the design processes are described and their origins investigated. In Section 2.3.3, some key issues relating to design and problem solving are addressed. In Sections 2.3.4, two pieces of literature specific to the issues relating to design and problem solving in technology education are discussed. Section 2.3.5 summarises literature that has identified experience with materials as relevant to learning design and problem solving in technology education.

The introduction of design and problem solving into technology education was a key part of the academicisation of technical education and an attempt to give technology more status than technical education, specifically technical education using hard materials. If technology was to become a compulsory subject for all students in primary and secondary schools, it had to demonstrate that it was a subject worthy of study for all students and to be able to “override” old distinctions of low status associated with technical education (Herschbach, 1995).

Eggleston (1994) noted that when technology was first introduced as a subject in the United Kingdom, a major goal was to ensure that all students were provided with the opportunity to understand, develop and handle technology in all its aspects. He argued that if technology was to succeed as a subject, it had to create new attitudes to technological work. He surmised that if learning goals were to be achieved, input would be needed from both practical and academic quarters. To illustrate this point of view, he described technology education in terms of its likely contribution to economic development and its influence in shifting British attitudes to technological production, which he regarded as having been a major obstacle as far back as the industrial revolution in the middle of the 18th century:

If [technology] succeeds, it may achieve a major goal – to break down the status barriers which have so long impeded the economic development of England and Wales and many other Western Countries – the low status of actually making things in a system controlled by those who do not ... to achieve these goals it is vital that technology in schools does not suffer the same pitfalls and devalue sound practical capability (Eggleston, 1994, p. 25).

So far, this literature review has argued that design and problem solving are two important and key components in the shift to new learning offered in technology education, and particularly within the context of hard materials. These components are important developments of ‘technical’ education that have helped to ensure all students have greater access to learning technology, regardless of whether their intention is to become a tradesperson, a professional engineer or, simply, an informed citizen.

2.3.1 The problem-solving process

In this section, the origins and distinctions of a generic problem-solving process as utilised in technology education are examined. The emphasis on problem solving reoriented the subject in terms of a more constructivist learning model, in line with similar shifts occurring in general education during the mid-1980s. Likewise, problem solving helped to distinguish the new subject, “technology”, from its predecessor, “technical education”, which many perceived had developed on the basis of a behaviourist learning model where students replicated projects designed for them by their teachers (Compton & Harwood, 2003; Sutton, 2003).

However, problem solving as presented in technology education literature often reflected the general concept of problem solving that underpinned learning in other subject areas, particularly mathematics and science. For example, during the 1990s in New Zealand, problem solving was regarded as one of eight overall “essential skills” that students were expected to develop across all essential learning areas (MoE, 1993). As Middleton (2009a) notes, problem solving in general education was seen as a generalisable and transferable learning process for helping students achieve expertise in several different subjects. Indeed, at that time, the development of generic skills and models was a widespread and somewhat unfortunate trend in many subjects.

Generic problem-solving methods used in general education often were based on four steps originating in descriptions of problem solving by John Dewey (1933) and George Polya (1957), subsequently used as a means to solve problems in subject areas such as science

and mathematics. The four problem-solving sequential steps presented in Polya's description are: (i) understanding the problem; (ii) devising a plan; (iii) carrying out the plan; and (iv) looking back on the plan to evaluate how it could be improved (Carson, 2007; Karsnitz, Hutchinson, & O'Brien, 2013). The problem-solving sequence attributed to John Dewey comprised five steps: (i) confronting the problem; (ii) diagnosing or defining the problem; (iii) inventing several solutions; (iv) conjecturing consequences of solutions; and (v) testing consequences. As Carson (2007) notes, Dewey's problem-solving sequence often was applied to scientific investigation. In general education, these steps are summarised in terms of: (i) finding and clarifying the problem; (ii) devising a plan; (iii) executing the plan; and (iv) checking the solution (Petrina, 2007).

An alternative approach to problem solving developed from this four-step model was the "problem space" model devised by Newell and Simon (1972) to explain how people think when solving problems (Parkinson, 2007). It comprises three key elements: a *problem state*; a *search space*; and a *goal state*. In the problem state, everything that is known about the problem is stated; the search space is the phase where all the information relevant to the problem is gathered; the goal state is the solution phase. In this model, problem solving progresses from the problem state through the search space to a final solution or goal state. The movement through the process is forward and linear. The literature shows this model was based on strategies used by a primary student to solve a mathematical problem; it proved an inadequate model for representing the more complex and ill-defined problems that occur in technological-type problem solving (Middleton, 2009a).

The problem-solving process used widely in technology education, often referred to as the technological problem-solving process or the technological method (Savage & Sterry, 1990), developed from these problem-solving models that had originally been created for other subject areas such as mathematics and science. Problem solving developed as a more central focus in the early United States technology education literature where the term *technological* method originated (Savage & Sterry, 1990). The technological problem-solving process addressed problem solving as finding a solution to an overall global-type problem and generally was depicted as comprising four or five sequential steps (Middleton, 2005; Petrina, 2007). For example, in some technology education literature, early depictions of problem-solving processes included: (i) defining the problem; (ii) developing alternative solutions; (iii) selecting the solution; (iv) implementing and evaluating the solution; (v) redesigning the solution (Savage & Sterry, 1990).

When applied to mathematics education, the generic problem-solving descriptions and models of Polya and Newell and Simon depicted the solution of analytic-type problems that have a single correct answer. In mathematics education, the problem is “clear” and often defined in one way; and it is perceived that there are limited ways to solve the problem (McCormick, 2004; Middleton, 2009b). However, in technology education, the principal difficulty of using a generic problem-solving description or model is the inability of the approach to address the unique features of ill-defined technological problems. Middleton (2006) and Taylor (2000) point out that by the early 1990s, technology educators were realising there were very significant differences between technological problem solving and the approach used in other subject areas. For example, when solving technological problems, there is an undefined beginning point and there are often multiple possible solutions, rather than one singular correct solution. There are also multiple criteria regarding the acceptability of solutions. The reality is that strategies for effective problem solving vary widely, depending on the context or community in which the problem is located (Cordon, Williams, Beyerlein, & Elger, 2007). Problem solving in this sense is open-ended and exists in the context of a situation, not as a calculated answer (Woods, 2000).

Because technological problem solving is context specific, a general problem-solving process, as presented in much technology education literature, is problematic (McCormick, 2004) and any transfer of general problem-solving skills across domains such as mathematics and technology unlikely (McCormick, Murphy, & Hennessy, 1994). Put simply, problem solving in technology requires knowledge of the context, the materials and available facilities and constraints. It also requires experience and expertise.

The stepwise technological problem-solving process does not include any of the knowledge or actions required to enable real world technological-type problem solving, particularly by novice student problem solvers. This failure to acknowledge either the types of knowledge or the thinking required to design and problem solve in real technological situations led McCormick (2004) to describe the generic approach as a “ritual” with little purpose.

In recent years, several concerns have been raised in the literature concerning problem solving in technology education. While problem solving has been called a learning strategy at the centre of the technology education “ethos” (Turner, 2009), Zuga (2004) has noted the lack of empirical evidence to verify technological problem solving as a valid method

relating to learning technology in the classroom or in workplace technology. She also questions whether there is a learning theory underpinning problem solving as a suitable teaching method in general. Therefore, there seems a need for further research regarding the place of problem solving in technology education, including its connection to a relevant learning theory.

Issues associated with a general problem-solving process identify it as a heuristic model, with no knowledge base, represented by an abstract thinking process that, supposedly, can be applied to widely different situations (Carson, 2007). McCormick (1997) recognises that although problem solving is used in technology classrooms, there is little empirical evidence of actually what occurs in classrooms when it is being used. Some 15 years ago, Black (1998) noted that how students' cognition in technology links knowledge to provide solutions to complex problems is not understood fully and requires some "difficult" research.

Two other types of problem solving that occur in technology classrooms and that receive little attention in curriculum documents are: (i) solving the problems that occur during the making of a product, and (ii) troubleshooting or fault-finding problems. That is, the diagnostic trouble-shooting type problem solving used when something does not work (McCormick, 1997, 2004). There seems to be limited current literature regarding these types of problem solving.

There has been limited research that identifies the types of activities that support learning the complex problem solving that occurs in technology education and, specifically, problem solving associated with hard materials. The role of problem solving in technology education, as Zuga (2004) points out, also requires investigation, including its relevance and how it contributes to learning in technology education. There appears to be a gap in the literature regarding problem solving as it relates to design with hard materials from the point of view of both expert technologists and technology educators.

2.3.2 The design process in technology education

In this section, the features of a technological design process as distinct from those of a technological problem solving process are explored. As noted previously, a key part of the academicisation of technology education was the introduction of design. In technology education, design, like problem solving, often was presented as a sequential set of steps to support teachers who had limited previous knowledge or experience of technological

design. In the English and Welsh *Design* curriculum, these supposed steps were the attainment targets for design and technology: (i) identifying needs and opportunities; (ii) generating a design; (iii) planning and making; (iv) evaluating (DES/WO, 1990). Predictably, teachers viewed these targets as a linear set of steps, so they became very quickly a process by which to teach and assess design (Benson, 2009). Elsewhere in the world, learning to design was often presented in technology classrooms as satisfying a series of steps similar to those presented as attainment targets in the English and Welsh Design curriculum.

A key difference between the technological problem-solving process and the technology education design process lies in the first step. In the problem-solving process, step 1 *defines or identifies the problem*; in the design process, step 1 *identifies needs or opportunities* (McCormick & Davison, 1994). While the problem-solving process requires an initial problem to begin, the design process may commence with recognising a need or opportunity, not necessarily a problem.

From an engineer's perspective, design includes both the plans of the design and the production processes associated with the design to produce a realised outcome (Vincenti, 1991). Mital, Desai, Subramanian, and Mital (2010) consider engineering design as the application of scientific concepts, mathematics and creativity that will produce a machine, system or artefact to perform a specified function. The design steps envisaged in technology curricula often reflect the design processes represented in university-level engineering textbooks. For example, many engineering design textbooks include the following as representing an engineering-design process: (i) stating the problem (clarifying and defining the task) and thinking about design concepts; (ii) writing specifications; (iii) developing a conceptual design; (iv) developing a detailed embodiment (detailed expression) of the design; (v) making and evaluating; and (vi) obtaining stakeholder or customer approval (Jack, 2013; Mital et al., 2010). In contrast to the attainment targets for *Design* (above), the first step is depicted as identification of a problem. As noted by Mital et al. (2010), an "unfulfilled need" in design can result in the formulation of a problem. In fact, they state that engineering design is a form of problem solving because many of the steps in engineering problem solving are included also in engineering design. Although presented as a set of design steps, the design models identify a designer's iterations between steps and acknowledge the necessity to anticipate and consider several steps simultaneously throughout the process. The steps described in the engineering-design

process define essentially the process of taking an abstract engineering-design concept through to a concrete designed outcome (Jack, 2013). These steps present a rationalisation of the components required in a complex design carried out by a professional engineer. Like the technology education design process, the complexity of knowledge, experience and learning inputs into each of these steps is not apparent necessarily in such a model.

Both Middleton (2005) and Savage, Miles, Moore, and Miles (1998) regard design as one of the most cognitively demanding activities in which people become involved. It follows that technology education should not simply define how to design as a set of four or five abstract steps. Rather, the issue for technology education should be to ascertain in a meaningful and purposeful manner the knowledge, thinking, types of experiences and prior learning that students need as input into each of the design steps to be able to make necessary design decisions and judgements.

Teaching design throws up some major problems for teachers. Given the complexity of tasks involved in the cognitive aspects of design, it is difficult to identify contributing aspects in isolation. However, these contributing aspects need to be identified broadly if students are to be provided with opportunities to learn how to design in technology classrooms. Consequently, there is a need to unwrap the complexity of design to try to make it more explicit for students. In fact, there has been a widespread and unfortunate assumption that students learn how to design without specific planned programmes or support, often referred to as the “osmosis” approach to learning design (Stein et al., 2003). In other words, students are assumed to learn by engaging in a variety of ad-hoc unplanned or unstructured activities. In response to this seeming impasse, Norman (1998) has argued that the skills, knowledge and values that constitute what expert designers do are, in fact, difficult to transfer into any sort of generic model that can be used effectively in technology education. Consequently, there is a gap in current technology literature regarding what planned and specific activities may contribute to students learning to design. If technology educators wish to replace their reliance on the stepped process of design, they need to know what types of activities they can provide for their students and how effectively they might support their students’ learning in order to design. This is particularly relevant in the context of hard materials—an area where usually a design concept can become a realised artefact that addresses a need or opportunity, or solves a problem.

2.3.3 Issues in design and problem solving in technology education

The first of three key issues identified from the introduction of design and problem solving into technology education is the overlap between the design and problem-solving processes. When generic design and problem-solving processes were introduced into both secondary and primary school technology programmes, often there was little distinction made between them. The two terms were used simultaneously or interchangeably, with little recognition of any distinctive meaning (McCormick, 1997; Mawson, 2001). Even official curriculum documents often alternate between the terms without any recognition of a distinction. As explained previously in Sections 2.3.1 and 2.3.2, these processes were presented in technology curricula and support documents as a series of steps implying students should follow them sequentially.

In a review undertaken in the United Kingdom, Johnsey (1995, 1998) found little distinction between the described design and the problem-solving processes. He considered 17 different models of the design and problem-solving processes published between 1970 and 1995, including those specific to the development of the National Curriculum for *Design and Technology* for England and Wales. Johnsey acknowledged that most of these 17 design and/or problem-solving models fitted a four-stepped linear outline, which he summarised as investigation, invention, implementation and evaluation. It is evident that Johnsey's design and problem-solving outline has significant parallels with the general problem-solving models of Dewey (1933) and Polya (1957) (see Section 2.3). Internationally, these stepped design and problem-solving processes have been summed up in various ways. In Australia, "design-make-appraise" (Australian Education Council, 1994) was the preferred construct of technological design and problem solving (Mawson, 2001). In the United States, it is described as the technology process: define problem; generate ideas; model; test (ITEA, 2000), which reflects a greater emphasis on the problem-solving component. In England and Wales, where there was, and still is, a stronger emphasis on the design component in technology, it was seen as: identify; generate design; plan and make; evaluate (DES/WO, 1990).

As noted previously, the two processes do cover much of the same ground. However, the design and problem-solving processes may also appear as two distinctive and sometimes conflicting aspects. Thus, Barak and Goffer (2002) recognise a major challenge in technology education as it seeks to find the best combination and balance between nurturing design activity based on openness and disorder, on the one hand, and employing

systematic methods for innovative thinking and problem solving, on the other. Hill and Anning (2001) have characterised this tension in technology education as a requirement to use the “divergent traditions of art and design” (p. 118) to develop interesting, innovative and creative solutions to problems while, at the same time, requiring a functioning crafted product that has employed the “convergent traditions of technology” (p. 118). Mioduser and Dagan (2007) discuss this conflict in terms of design having to be creative and “branching” using multi-disciplinary knowledge yet, at the same time, having to meet the requirements of products and production processes when creating solutions to problems. Fergusson (1993) identifies effective design as a combination of formal knowledge and experience that usually involves decision making relying on judgement more than “certainty”. In summary, although design and problem solving are often sandwiched together as an interrelated process in the technology education literature, they represent two important distinctive and sometimes conflicting aspects of technology education, particularly in the context of hard materials.

A second key issue relating to design and problem solving was the simplified nature of the “steps approach” which supposedly made the rather abstract nature of designing and problem solving in technology more ordered and constituted “a helpful guide” for teachers in planning various technology teaching experiences (Johnsey, 1995; Mawson, 2001). While these models became an accepted and tangible way internationally for design and problem solving to be taught in technology classrooms, there was little research evidence to establish their validity as either effective teaching approaches or descriptions of how students in technology classrooms work when designing and problem solving (Johnsey, 1995). Although McCormick (2004) reminds us that the steps of “clarifying the problem, thinking of alternatives, implementing it and evaluating it” remain the steps associated with problem solving rather than design, the terms “design” and “problem solving” continue to be used interchangeably by many teachers, as noted by Middleton (2005).

In recent years and as argued previously (see Sections 2.3.1 and 2.3.2), the linear design and problem-solving processes have been discredited as artificial representations of design, problem-solving and technological activity that neither professional designers nor students engage in when designing (Barak & Goffer, 2002; Mawson, 2001; Parkinson, 2007; Petrina, 2000; Stein et al., 2003; Williams, 2000). One of the inherent weaknesses of such models lies in the attempt to represent the internal “opaque workings of cognition” that

occur when a person designs and problem solves as a structured set of simplified linear steps (Savage et al., 1998).

It would appear that further research is required to investigate the types of experiences that might support the learning of problem solving and design in technology education. To date, there has been limited research investigating what shapes an expert's ability to design and problem solve in situations that use hard materials. Likewise, there seems to be little research investigating what types of learning experiences teachers believe support and develop students' design and problem-solving skills in areas such as hard materials, where designing and problem solving produce realised outcomes in the form of artefacts.

A third key issue associated with design and problem solving is identifying in what ways design and problem solving are interrelated in technology education. The interface of design and problem solving has been expressed in many different ways both in technology education literature and in technology curricula. For example, Morrison and Twyford (1994) state that design arises from problems and issues and its function is to change things for human purposes. Stein et al. (2003) define design in technology education as a form of problem solving, though different in several respects from problem solving in other curriculum areas. Indeed, design is often seen as a defining component of *technological* problem solving (Middleton, 2005; Taylor, 2000). It is the multifaceted nature of design that enables the generation of multiple solutions to a problem. Similarly, because design is often described as a process employed to provide a solution to the problem posed, design is sometimes considered a process within *technological* problem solving (Taylor, 2000). McCormick et al. (1994) express this interconnection in the early technology curriculum in England and Wales as design being the “manifestation” of a problem-solving process (p. 5). In other words, design encompasses the thinking, knowledge, ideas and outcome that can solve a problem. However, there are many situations where design creates an artefact because someone has perceived a need or opportunity, not a problem, recognising that design often occurs when there is no overarching problem to solve (McCormick & Davidson, 1996).

The Australian technology document, *Technology for Australian Schools* (1994), identifies technology as a key learning area and acknowledges the relationship between problem solving and design as “the problem-solving based design process” (Middleton, 2009b). A contrasting view, presented by Johnsey (1995), distinguishes the design and problem-solving processes as two separate processes: (i) when the end requires a solution to a

practical problem, then the problem-solving process has been used; (ii) if the end has produced a designed product that has satisfied a defined need, then the design process has been used. This view restricts design to the production of a product and not the process producing a solution to a problem.

What and how to teach design and problem solving within technology education, coupled with how students can learn to develop their ability to design and problem solve, have become ongoing areas of interest in technology education research. Although technology programmes have focused on design and problem solving, there has been limited research about what types of experiences, associated with these activities, are effective in developing students with the attributes to become skilled problem solvers and excellent designers (Kelley, 2008).

In summary, the research literature presents disparate views of the interconnectedness and differences between design and problem solving in technology education and seeks to identify reasons for the confusion about what constitutes problem solving and what constitutes design in technology education. It is evident from early representations of both these procedures that, in fact, they share much in common. Although there has been limited research regarding design and problem solving in technology education per se, some research and literature that relate to the issue of design and problem solving as *processes* in technology education are presented in the following section.

2.3.4 Research literature addressing the issues in the design and problem solving processes

In this section, research and literature relating to the issues associated with the design and problem-solving processes in technology education are presented. First, is an Israeli research project utilising an alternative *functional* approach to teaching and learning design and problem solving in technology education (Mioduser & Dagan, 2007). Second, is an alternative model of problem solving developed by Middleton (2009b) that incorporates characteristics of both linear problem solving and design processes discussed in Sections 2.3.1 and 2.3.2.

The Israeli research project investigated an integrated design and problem-solving “functional” approach as an alternative to teaching design and problem solving as linear processes. This alternative functional approach teaches students a variety of design functions and encourages the use of one or more of these design functions at any time

when students are problem solving. The “functions” include: issues identification and definition of gaps that require filling; exploration and investigation; planning, making and evaluation (Mioduser, 2009; Mioduser & Dagan, 2007). Each function can be applied repeatedly to different stages of the design process. For example, the exploration function can be used for identifying the issue and problem, defining constraints and reviewing prior solutions to previous problems.

To investigate the effectiveness of this functional design and problem-solving approach, 80 grade 7 students were divided into two groups. One group was instructed in technological problem solving using a functional approach, while the other group was instructed in the linear-steps design process. Students taught by the functional approach showed significantly more design capabilities than did students taught via the linear-steps approach. Significantly, it seems also that the functional approach to teaching design had a positive impact on students’ ability to develop mental models of the technological design process. As Mioduser and Dagan (2007) note, skilled problem solvers, including experts, are considered to have powerful, dynamic and flexible mental models and therefore it is an important skill for technology students to develop. This functional problem-solving/design process is more cyclic, iterative and flexible than linear-step models, and enables students to suit the process to a particular problem, its context and their own way of working through a design to solve a problem.

Second, this section considers a problem-solving model devised by Middleton (2009a) that accommodates the characteristics of design in the problem-solving process, based on Newell and Simon’s (1972) three element problem space model described in Section 2.3.1. While Newell and Simon’s model represents a start point and moves through a search space to a finishing point or goal state, Middleton’s model acknowledges that ill-defined complex design problems do not always have a precise beginning or defined end point. In the first of three key changes incorporated into Middleton’s model, the problem state becomes the *problem zone*, in order to recognise that a design problem may be represented in several different ways. Second, the goal state changes to the *satisficing zone* to account for the many different yet valid solutions possible to solve a design problem. Satisfactory and sufficient (*satisficing*) solutions represent early possible solutions generated by the problem. Third, the search space changes to the *search and construction space*, acknowledging that design solutions to problems use existing and new knowledge and may utilise several different strategies to solve a problem. These zones are presented with two-

way arrows indicating as much iteration as necessary between the three zones (Middleton, 2002). This model attempts to characterise how people may attempt to design solutions to problems and therefore is relevant to contemporary approaches in technology education (Middleton, 2009a). It recognises that technological problem solving requires reflective thinking and requires students to interact with many different sources of information in the process of solving a problem (Middleton, 2009a; Twyford, & Jarvinen, 2000).

2.3.5 Research indicating experiences with materials supporting learning to design and problem solving

This section presents previous research and literature that acknowledges the value of practical experiences with materials contributing to students learning to design and/or problem solve in technology education. Meaningful design and problem solving in technology education has been discussed by Hill and Smith (1998) in terms of beginning as a lived bodily experience rather than a mental process. Hill and Smith's research investigated the learning of senior secondary students in a manufacturing technology class working on practical community problem-based projects. Students learned to solve a real-world problem through an authentic physical design experience working experientially with materials producing an artefact. Hill (1998) concluded that through these types of purposeful practical experiences, students were able to be involved where "theory is learned and confirmed through practice" (Hill, 1998, p. 216). Technology education research also has recognised that some form of experiential learning develops knowledge that proves influential in students' later abstract design processes, including their realisation of ideas in 2- or 3-dimensional drawing models (Hill & Smith, 1998). Wiener (1993) acknowledges that further modification of a design idea occurs almost always during production of a design using available materials and processes to produce an actual artefact.

Parkinson (2007), for example, acknowledges that the cognitive growth and development required in design does not occur in isolation; rather, it requires a range of "things" that support its development. He argues that it requires sensory input and this sensory input is obtained through practically making and modelling design ideas that allow young children (5–11 years) to build up experiences on which they can draw when designing. Both Middleton (2005) and Parkinson (2004) consider that the complex activities required in design require higher order thinking and are supported by the manipulation of materials in relevant and meaningful situations and contexts. Petrina (2007) also notes that introducing

students to designing may be achieved through an initial experiential project, that is, teachers taking students collaboratively through the experience of imagining, designing and building an artefact with actual materials. This may be through a scaffolded step-by-step process for younger students, or with the teacher acting in a more facilitating role, if working with older students (Petrina, 2007).

Producing working models, purposeful artefacts and hands-on experiential approaches in technology education provide a framework for developing concepts into broader generalisations and applications that stimulate and develop students' thinking skills in terms of their design capabilities (Barak & Williams, 2007; Parkinson, 2007). However, there is little research that investigates specifically in what ways experiences in the context of hard materials influences the learning of design and problem solving with hard materials.

2.4 Novice to expert designers and problem solvers

Investigating how expert designers and problem solvers work could provide information to educators that enable them to recognise significant differences between experts and novice student designers and problem solvers. Once the differences are recognised, educators can consider how they might go about bridging the gaps through the learning experiences they provide for their students. Daly, Adams, and Bodner (2012) note that understanding differences in how designers approach the design task could inform and help novice designers become more expert-like in their own design endeavours.

2.4.1 Distinctions between novices and experts

Expert technological problem solvers and designers carry out a specialised form of problem solving that utilises design. Some of the characteristics that distinguish these experts from novices include the following. First, experts have been identified as having powerful, dynamic and flexible mental models which they are able to adapt to different situations (Mioduser & Dagan, 2007), while novice learners are thought to have difficulty transferring knowledge and thinking skills to new contexts or situations (Barak & Williams, 2007). Second, most experts are able to integrate large amounts of related information, whereas novices focus and tend to get stuck on details (Petrina, Feng, & Kim, 2008). Novices often suffer from information overload, whereas experts manage to organise information in more effective ways and have learnt to integrate concepts into networks of knowledge (de Vries, 2005). Third, decisions in engineering-type design

require judgement after consideration of many aspects relating to a design problem. Design experts in engineering engage in forward thinking, that is, they try to evaluate design concepts before implementing them because utilising a strategy such as trial and error is like reasoning backwards (Ahmed, Wallace, Lucienne, & Blessing, 2003). In contrast, novices often resort to trial and error design methodology.

Other findings from expert-novice research indicate that expert designers focus more on design solutions and do not get absorbed or bogged down in the problem, as do novice designers. However, while experts frame the problem and scope the problem, they do not fixate on too deep an analysis of the problem (Cross, 2001). In his overview of expert and novice problem solvers and designers, Cross (2004) acknowledges that studies have shown that experts are able to develop some type of solution relatively quickly. This is helpful because they are able to look at the problem and potential solution together. In contrast, novices, with their limited expertise and frames of reference, don't do this. Another characteristic of experts is that once they have developed a design concept to solve a problem, they appear very reluctant to abandon it (Cross, 2004). From this literature of the characteristics of experts, it is apparent that experts are able to move relatively quickly to the design stage when solving technological problems. It seems that novice designers and problem solvers are not.

It could be argued that in general problem solving, the abilities and strategies used by experts and novices vary considerably. Experts have developed their expertise from practising problem solving and building an extensive and organised body of knowledge which they can utilise and further develop over time. New information is processed and formed from the experts' existing body of knowledge and this enables them to see patterns and connections. Consequently, the expert problem solver identifies key principles and applies them to a range of problems, while a novice memorises how to solve specific problems. Novices focus on surface aspects of problems, unlike experts, who identify quickly principles they can utilise to solve problems even where the surface aspects may be quite different (Sutton, 2003).

In terms of beliefs, the novice often believes that new problems are too difficult for them to attempt, whereas experts have personal belief in their capacity to solve problems. Their confidence enables them to persevere, even if they cannot immediately find a solution to the problem. Experts are able and motivated to evaluate their thinking; in contrast, novices tend not to evaluate how previous problems were solved and therefore tend to move onto

new problems without any transfer of concepts used from previous problems. Experts can access “chunks” of their long-term memory relatively quickly, with this kind of instant accessibility developing further through repetition (Schunn & Silk, 2011).

It is proposed that the way experts learn or practise design and problem solving could help technology teachers to identify aspects that may be adapted for their technology classrooms to help students become more expert-like as designers and problem solvers. This thesis seeks to identify what expert designers and problem solvers do that involves, or relates to, experiences with hard materials in developing expertise.

2.4.2 Research on experts and novice designers

This section presents detail of three research projects (Hill & Anning, 2001; Merrill, Custer, Daugherty, Westrick, & Zeng, 2008; Newstetter & McCracken, 2001) that have investigated how experts’ design practices and ideas have been utilised to compare or inform novice designers in their learning. These research projects provide insight into how it is often valuable to look to experts and seek to adapt findings to support students in their learning.

Hill and Anning (2001) investigated and compared a broad and general understanding of design within three different groups. The three groups included teachers ($n = 4$), students as novices ($n = 8$) and expert workplace designers ($n = 6$). Four different workplace design fields were considered: graphic design, apparel design, mechanical engineering and architecture. With respect to their current practice, the workplace designers described designing in different ways, both within and across their different design fields. These workplace designers’ concepts were compared to teachers’ design knowledge. How these teachers perceived that design should be taught in their technology classrooms, and students’ ideas about design, then were compared to the workplace designers’ views. The research also compared whether or not relationships existed between the school-situated design and the workplace design that was investigated.

A mechanical engineer, one of the four workplace designers, worked with hard materials and therefore his comments are relevant particularly to this research project which also looks to such experts. He argued the power of visualising different design outcomes, then sketching these ideas on paper and working with them. He emphasised working in groups and the value of having experience with materials and knowing the physical properties of materials. As well, he acknowledged the value of hand skills in turning a design idea into a

material object because the “practicalities” from idea to prototype were better understood. However, Hill and Anning’s (2001) research emphasises the need for further research to identify the skills and knowledge used by workplace designers and to link this deeper understanding of what is termed workplace “designerly” activities to learning design in similar school design contexts. Importantly, the research established the value of looking to the experiences, learning and behaviours of “real expert workplace designers” in their respective design fields and the relevance of these when considering school learning and teaching of design that involves novice student designers.

Hill and Anning’s (2001) research provides a very broad overview of how various groups consider and carry out designing in different contexts. However, their research did not focus in depth on the ways in which any specific aspect contributed to the mechanical engineer’s expertise. Rather, it presented an overview of how he carried out design and compared it to other groups of expert designers, teachers and students. It did not compare designers’ ideas within a specific context or domain to obtain more detailed insight into their learning to design, or investigate the role of problem solving in design.

In recent years, programmes in American secondary and primary technology classrooms have been developed to facilitate students learning engineering. Three core engineering principles, *constraints*, *optimisation* and *predictive analysis* (COPA), have been identified from the field of engineering design expertise and recently have been included into some American secondary school technology programmes. These three principles developed as a result of partnership with the engineering community resulting in technology teachers’ professional development and students’ hands-on activities. COPA are considered the key elements that expert engineer designers utilise. The first principle of COPA, constraints, defines the parameters around the design solutions while the second, optimisation, aims to find the best solution to a problem after all “trade-offs” have been considered. The third, predictive analysis, involves the use of scientific or mathematical equations to help to predict a situation before developing a solution.

A study by Merrill et al. (2008) investigated how to facilitate 114 secondary students’ learning about COPA. Focus groups with 54 students provided the researchers with a detailed picture of what students had learnt about the COPA principles. Encouragingly, these students were able to identify the three core engineering principles and the interrelationships among them. The focus groups provided opportunities for these students to discuss the learning programme, including the activities they found most motivating in

terms of their own understanding. Particularly, the students found the application of scientific and mathematical knowledge using hands-on, situated and contextual technological activities beneficial and their preferred means of learning and applying this knowledge.

One important conclusion from this research project was that secondary technology education would benefit from incorporating activities for students that simultaneously develop conceptual knowledge that is activity based (Merrill et al., 2008). This result contradicts previous notions that “skills” and hands-on activity-based technology programmes only develop students’ procedural knowledge. It provides also encouraging results of how a technology education programme focused on teaching design to novices has included learning that reflects how experts (engineers) perform in a particular domain (Merrill et al., 2008). In other words, there is value in looking to experts in specific domains (such as engineering) to find out information that also may be influential in developing and supporting student learning.

A research project with 290 freshmen in Atlanta, Georgia, investigated novice designers’ conceptions of design as they entered a generic design class. By means of a questionnaire, students were asked to rank 16 terms associated with designing from *most important* to *least important* (Newstetter & McCracken, 2001). Students ranked terms such as creativity, visualising and brainstorming in the top five, and making trade-offs, decomposing the problem, synthesising, generating alternatives and sketching (identified by experts as crucial for design) in the bottom five. That is, those terms seen by expert designers as critical to design were ranked by the students in the bottom five.

The students considered that designing was aligned strongly with having good ideas, although they lacked a concept of design as activity. In response to a further question asking students to define design in their own words, few students considered engineering as a design domain, although they were attending an engineering learning facility. A significant number of students (163) identified design domains such as fashion design, architecture and interior design.

Not surprisingly, Newstetter and McCracken (2001) concluded that significant numbers of freshmen had major misconceptions of design compared with expert designers. Indeed, the significance of this research is its identification of the considerable gap between novice students’ conceptions of designing (at a college/university entry level) and those of expert

designers. There appears to be a need to research how secondary technology educators could provide meaningful learning experiences that ensure students have an understanding and conception of design that reflects that of expert designers, rather than the impoverished view in this research study that these freshmen had upon entering university.

2.5 Technological knowledge in design and problem solving

Technological knowledge, or the learning of knowledge relevant to technology, is not an end in itself, but a means that enables people to design, problem solve and produce artefacts that meet the specific needs of society. As Herschbach (1995) states, a key characteristic of technological knowledge is that it is evolved from activity and, therefore, has purpose and meaning through activity. Because this thesis is specifically about the learning of design and problem solving with hard materials through activity and experiences, it is important to consider the types of relevant technological knowledge that have been identified in the research and literature.

As both Faulkner (1994) and Lewis (2005) observe, design cannot occur in a vacuum disconnected from some form of a knowledge base. Likewise, Norman (1998) comments that designers in the “real world” require knowledge bases to be able to perform as designers:

Designers in the real world are trained in distinct approaches to designing in relation to the different technologies of their fields and different knowledge bases about materials, processes, values and practical skills (p. 71).

The major value of this statement is recognition that because expert designers in the real world design in specific ways relevant to, and within, particular domains and contexts, they require specific types of knowledge that are relevant to the particular field in which they are designing. Similarly, Vincenti (1991) recognises that specific types of knowledge are essential components of what an expert engineer designer requires and utilises.

The types of knowledge that experts must draw on to design and problem-solve with hard materials are many and varied. In fact, expert technologists may be drawing on a wide range of knowledge types at any one time. In a sense, this is what their expertise enables them to do, to integrate different types of knowledge and apply them to design and problem solving. It seems that these knowledge types need to be identified if technology educators are to provide learning opportunities that enable novice student designers and problem solvers to access them, use them appropriately, and integrate them into their

overall repertoire for designing and problem solving. In other words, we need to ascertain what it is that experts know and, therefore, what students need to learn.

Knowledge in technology education has been identified as a key component underpinning learning to design and problem solve, just as it is a key component in designing itself (Lewis, 2005; McCormick, 2004). Clearly, it is important for technology educators to identify and know about the types of knowledge that relate directly to design and problem solving if they are to create meaningful learning opportunities that support students learning this knowledge. Likewise, it is important to distinguish these types of knowledge so that curriculum documents may acknowledge them as important learning foci. As presented earlier in this thesis (see Section 2.4.1), one way to find out the types of knowledge relevant to design and problem solving with hard materials is to analyse the types of knowledge experts utilise when doing so.

A first step in identifying relevant knowledge is identification of some of the distinguishing characteristics of technological knowledge as a distinct body of knowledge. Establishing technological knowledge as a body of knowledge separate from scientific knowledge recognises that technology is not simply applied science (de Vries, 2006; Herschbach, 1995; Vincenti, 1991). While scientific knowledge predominantly is generalised knowledge and deals primarily with abstractions that tend to strip away the context, its technological knowledge equivalent is much more context specific (de Vries, 2012; McCormick, 2004; Ropohl, 1997). As technological knowledge is applied to technological activities that have purpose and meaning in specific contexts, a generic technological knowledge is difficult either to categorise or codify (Herschbach, 1995). Although technological knowledge may, when appropriate, utilise knowledge from learning domains such as science and mathematics (McCormick, 1997; Solomon & Hall, 1996), in utilising such knowledge technologists and engineers often adapt and modify it.

Vincenti (1991), a historian and engineer, has provided valuable insights into the nature of technological knowledge, particularly associated with designing in aeronautical engineering with a specific range of hard materials. He presents designing as a central activity of engineers' practice and points out, like Herschbach (1995), that design can in some circumstances build bodies of technological knowledge rather than just utilise them. For example, aircraft design began as a series of trial and error design activities and after 50 years resulted in a specific and accumulated body of specialised technological knowledge. This links with notions that the artefact (aeroplane) embodies technological

knowledge that is later detailed and identified (Compton & France, 2007) and that new technological knowledge often develops from activity (Herschbach, 1995).

Among six categories of technological knowledge associated with engineering design identified by Vincenti (1991), four are distinctly technological while two (theoretical tools and quantitative data) are associated with science and maths. These six knowledge categories comprise: fundamental design concepts (includes fundamental operating principles associated with the device being designed); criteria and specifications (layout, configuration of components, embodiments, sizes, materials); theoretical tools (scientific laws of nature); quantitative data (use of descriptive and prescriptive knowledge); practical considerations (how best to make a component part, identify clearances so assembly can occur, knowledge of production, use of mock-ups or prototypes, reliance on feedback from designer's previous design experience); and design instrumentalities (how to go about design, deconstruct the problem into subsidiary problems, ways of doing things, judgement and optimisation). However, Vincenti's identification of technological knowledge, while relevant to this thesis, represents only the perspective of a professional engineer. His identification of distinctly technological knowledge does not constitute the broader understanding of technological knowledge used by technologists who design and problem solve with hard materials who are not professional engineers. While these categories provide an outline of knowledge relevant to expert designers' practice, they require much distillation in terms of how technology educators might use this information with their novice student designers and problem solvers.

The following views identify the artefact as a distinguishing and key factor of technological knowledge. Faulkner (1994) described science as "understanding" the natural world by producing knowledge and technology as "controlling" the natural world by producing artefacts. The artefact in technology not only integrates a wide range of necessary knowledge but also embodies knowledge in its own right (Compton & France, 2007). Custer (1995) points out that the production of a designed artefact is a distinguishing component of technological knowledge that represents activity, experience and practice. Baird (2002) recognises also that a functioning artefact contains knowledge that distinguishes it from other forms of knowledge.

Herschbach (1995) argues for the centrality of activity in technological knowledge and states that *through* activity, technological knowledge can be defined. In other words, activity provides a "framework" for technological knowledge to be utilised and from which

new technological knowledge often is developed, as was the case in aeronautical design (Vincenti, 1991). Both artefacts and activity (experiences) are central to designing and problem solving with hard materials as most often the goal of design and problem solving is to create a purposeful functioning artefact. The perspective that experience, activity and practice build technological knowledge is central to this thesis as it aims to identify the key role experiences (activity) have in building technological knowledge that contributes to learning to design and problem solve.

Building on Vincenti's identification of specifically technological knowledge used in design, Faulkner (1994) also identified and conceptualised a range of technological knowledge that expert designers draw on when engaged in innovative technological activity. Her typology of knowledge, based on expert designers engaged in industrial innovation, incorporates information from three empirical studies: Vincenti (1991), Gibbons and Johnston (1974) and Faulkner's (1994) own study. Faulkner groups 15 knowledge types under five titles related to technological innovation. While all five titles relate to designing and problem solving with hard materials, two of the titles with particular relevance to the context of this thesis are knowledge related to the natural world and knowledge related to the final product. Knowledge of the natural world identifies the importance and relevance of designers having knowledge and understanding of the properties of materials (links also to Vincenti's *theoretical tools* and incorporates scientific knowledge). Knowledge related to the final product recognises that designers have knowledge and understanding about the performance of materials, production and processing competencies and the design requirements enabling manufacture.

While recognising that these knowledge types are what professional designers and experts use, McRobbie, Stein, and Ginns (2001) note that reflection on what knowledge professional designers use can provide a suitable base to analyse the types and "nature" of knowledge student designers might need also when designing and solving technological problems. Research has indicated already that both experts and students often acquire knowledge relevant to design and problem solving through practical experiences that includes handling and working with actual materials (Davies, 1996; McCormick, 2004). However, there is little current research based on expert designers' and problem solvers' practice focusing on the types of specific experiences that develop technological knowledge to enable design and problem solving that could translate into learning experiences for students in technology classrooms.

As noted previously, it is important to build up an understanding of what constitutes knowledge relevant to learning design and problem solving with hard materials so that technology educators can provide learning opportunities that enable their students to access such knowledge. Because this thesis investigates the ways in which learning to design and problem solve with hard materials is developed through experiences, the knowledge types utilised by expert designers and problem solvers that are both considered important to design and problem solving with hard materials in technology education and that could be developed through experiences, are therefore identified and described briefly in the next section.

Two overarching categorisations that have been used to describe technological knowledge are *procedural* knowledge and *conceptual* knowledge (McCormick, 2006). *Procedural* knowledge is often explained in terms of *knowing-how*; it is implicit and non-propositional. In contrast, *conceptual* knowledge is explained as *knowing-that*; it is explicit and propositional (Ryle, 1949). For example, procedural knowledge often concerns the performance of a skill or process, while conceptual knowledge involves the understanding and integration of ideas and concepts (McCormick, 1997).

Sections 2.6 and 2.7 break down conceptual and procedural knowledge into further sub-categories. Section 2.8 presents knowledge that integrates both conceptual and procedural knowledge. The integration of conceptual and procedural knowledge includes: qualitative knowledge; prescriptive knowledge; device knowledge; and knowledge of constraints. Finally in Section 2.8.5, strategic knowledge is discussed. That is the knowledge that enables the best choice and application of procedural and conceptual knowledge.

Table 2.2 provides an overview of the various types of technological knowledge considered relevant to experiences and design and problem solving with hard materials that are described in Sections 2.6–2.8.

Table 2.2: Technological knowledge categories relevant to design and problem solving with hard materials

Strategic knowledge	Technological knowledge	
	Procedural knowledge <i>Knowing-how</i> Non-propositional Implicit	Conceptual knowledge <i>Knowing-that</i> Propositional Explicit
	Tacit knowledge	Descriptive knowledge
	Qualitative knowledge	
	Prescriptive knowledge	
	Device knowledge	
	Constraint knowledge	

2.6 Procedural types of knowledge

Prior to the introduction of technology as a common learning area, educators often perceived technical education, and certainly technical subjects using hard materials, as a place where only procedural knowledge was learned (McCormick, 1997). Partly, this was the result of an erroneous distinction drawn between technical learning as requiring *know-how* (procedural knowledge) and science as requiring *know-that* (conceptual knowledge). In other words, technical learning was perceived to be solely about “how-to-do” procedures, while science was concerned with learning and understanding theoretical concepts and conceptual structures (theories).

As stated above, procedural knowledge is concerned with the knowing-how in technological design and problem solving. Because designing and problem solving with hard materials are centred on producing a product or artefact, procedural knowledge is involved intimately with these activities. Procedural knowledge is often non-propositional and, as described by Jones et al. (2013), includes technological knowledge that uses drawings, models and mock-ups to convey the complexity of design ideas and the technological task. These authors note that this knowledge is not something that can be learnt from a textbook and, therefore, the implications for teaching entail transfer by “showing and doing” activities.

2.6.1 Tacit knowledge

Middleton (2005) identified three representations of knowledge when technologically designing as *tacit*, *visual* and *verbal* knowledge. The tacit aspect of knowledge includes

both the visual and verbal aspects but also the “perception of physical action” involved. The visual knowledge aspect involves developing a realistic mental 3-dimensional image of an object. The verbal knowledge aspect relates to describing the processes involved. Physical action that develops tacit knowledge has been linked to the handling, viewing and using of existing products. As a result, new products are often designed using *tacit* forms of knowledge based on products already in existence. As Carlson and Gorman (1992) note, inventors such as Bell and Edison used (tacit) knowledge acquired from experimenting with existing inventions to design their new products. While it is uncertain how these experiences impacted on the inventing process, it has been assumed that it is connected to inventors acquiring tacit knowledge from these physical experiences. As Middleton (2005) notes, now tacit knowledge is established firmly as an essential part of the inventing process and likewise a key factor in technological design.

Tacit knowledge is most often knowledge associated with experienced and skilled craftspeople and therefore is linked to activity, physical practice, immediate recall and working with materials (Custer, 1995; Herschbach, 1995; Solomon & Hall, 1996). Ropohl (1997) considers that tacit and implicit knowledge, which he calls technical know-how, results from an expert’s successful and failed experiences and remains as both conscious and unconscious forms of knowledge on which an expert may draw. He recognises it as knowledge that builds over long periods of time; and accessing it takes much practise. McCormick (1997) describes tacit knowledge as informal and implicit and notes that, in technology education, it is the knowledge that is used to understand how things work and are made and therefore, is critical to design and problem solving.

Because of its implicit nature, tacit knowledge is difficult to separate from other types of knowledge, either to pinpoint it or to teach it to students. As a consequence, it has been referred to as “indwelling”, absorbed and intuitive (Custer, 1995; Solomon & Hall, 1996). Therefore, McCormick (1997) points out, a different approach to “textbook” learning is required if students are to acquire tacit knowledge in a school technology situation. When students design and problem solve in technology education, practical activities including the manipulation of materials in meaningful contexts has been shown to contribute to students’ tacit knowledge (Fleer, 2000; Middleton, 2005). If tacit knowledge is gained through experience and practice, and is knowledge used by experts to design and problem solve, its acquisition should be considered useful for technology students. It is therefore pertinent to investigate in more specific ways how this knowledge develops in experts so

this information may inform strategies for developing technology students' beginning tacit knowledge.

2.7 Conceptual types of knowledge

In contrast to procedural knowledge, conceptual knowledge relates to understanding that links and builds on ideas and understanding. It requires technology students to be able to link different pieces of relevant knowledge and ideas in a coherent and purposeful way (McCormick, 1997). Currently, conceptual knowledge is understood to be a crucial and key area of importance that supports understanding of technological ideas and processes that include designing and problem solving (Jones et al., 2013). The key step in developing conceptual knowledge is to understand concepts. Petrina (2007) describes design concepts in technology education as organised but ever-changing groupings of thoughts or ideas to understand, classify and to manage interrelationships of knowledge and skills. It is postulated that technological concepts that students have acquired or understand already can act as frameworks to which further concepts may be attached (Jones, 1997). However, as Schunn and Silk (2011) note, often engineering and science students may not have appropriate or relevant conceptual frameworks or they may have such limited frameworks that it is difficult to attach new concepts and learning. Knowledge that develops students' technological concepts and builds their conceptual knowledge requires students to think about the technological "activity" that is involved in technological designing and problem solving, and not just to carry it out (McCormick, 1997). Zuga (2004) states that students need to internalise technological concepts to build understanding that can be engaged and utilised when designing and problem solving. Currently, there is little research detailing the ways in which experiences with hard materials may contribute to the developing and internalising of conceptual knowledge that is useful for designing and problem solving.

Because technological activity is found in so many areas of peoples' lives, it is difficult to define one generic body of technological conceptual knowledge. As noted earlier, the specific contexts and domains of different technological activities are crucial and therefore determine the overall body of technological conceptual knowledge (Fox-Turnball, 2007; Herschbach, 1995; McCormick, 2004; Solomon & Hall, 1996). However, research is required to find out in what ways students might develop conceptual knowledge to understand technological concepts (Hennessy & Murphy, 1999; McCormick, 1999) within these specific technological contexts, including the context of hard materials design and problem solving.

Rossouw, Hacker, and de Vries (2011) identify five key general concepts and 16 sub-concepts important to Engineering and Technology Education (ETE) developed from an international Delphi study involving educators and expert technologists. These five key general concepts are relevant to design and problem solving with hard materials. They are designing, systems, modelling, resources and values. Fourteen sub-concepts developed from this Delphi study are: optimising, trade-offs, specifications, invention, artefacts, function, structure, materials, information, innovation, sustainability, social interaction, technological assessment, and risk/failure. It could be argued that these are identified key concepts that should be a part of students learning to design and problem solve in a context such as hard materials.

2.7.1 Descriptive knowledge – a conceptual form of knowledge

Expert designers, including engineers, identify *descriptive* knowledge (a conceptual form of knowledge) as relevant to designing and problem solving with hard materials. As it has a defined body of knowledge (knowledge that can be written down and learnt), descriptive knowledge is a type of formal knowledge and is central to many technological activities (Herschbach, 1995). Technology educators often refer to descriptive knowledge as theoretical knowledge as it is factual information concerned with describing things as they are—including the physical properties and strengths of individual materials (Anderson & Felici, 2012; de Vries, 2012; Ropohl, 1997; Vincenti, 1991). For example, expert designers regard knowledge about the physical properties and the strength of materials as crucial because this knowledge enables them to predict how a material will perform when used in a design (McCormick, 2004). Descriptive knowledge often states the relationship between different pieces of information. For example, the failure of particular materials under specified loadings is factual, in that it identifies the relationship between a force applied and the resulting strain on individual materials.

As Herschbach (1995) notes, descriptive knowledge states factual information and presents a type of “framework” that experts operate within. Although details of the strength of materials and properties of materials can be found in books that expert technologists consult regularly (Pitt, 2001), this research is interested in the ways in which this knowledge may be developed through experiences with hard materials and how experiences can be designed to help students develop and deepen their understanding of theoretical and descriptive-type knowledge.

2.8 Integration of procedural and conceptual types of knowledge

When technology was first introduced as a separate learning area (see Section 2.2.3), researchers highlighted the importance of students developing an understanding of both procedural and conceptual knowledge and the integration of these knowledge types so that technology could develop as a legitimate learning and teaching area (Custer, 1995; Jones, 1997; McCormick et al., 1994). A key interpretation of the integration between *know-how* and *know-that* knowledge considers that conceptual knowledge enables the appropriate choice of procedural knowledge to be used when solving problems in a specific context (Glaser, 1984; McCormick, 1997). Petrina (2007) regards procedural knowledge, on its own, as inadequate to enable design, making or other technological activities, and points to the need for procedural knowledge in technological design to be integrated with propositional (conceptual) forms of knowledge. Although the integration of conceptual and procedural knowledge has been recognised as relevant to problem-solving and design activity in technology education, there is little research seeking to investigate how procedural and conceptual integrate when designing and problem solving. Neither is their research identifying what integration entails when deployed by either expert technologists or student designers and problem solvers.

2.8.1 Qualitative knowledge integrates conceptual and procedural knowledge

McCormick (2004) provides an example of the integration of conceptual and procedural knowledge in technology education when he acknowledges that technological concepts are supported by practical technological knowledge within specific “situated” contexts. He calls this contextual knowledge *qualitative* and recognises it as a unique type of knowledge relevant in technology education. Qualitative knowledge is relevant to classroom designing and problem solving as it enables students to think as technologists (McCormick, 2004). McCormick notes that it is both conceptual and procedural. In other words, technological problem solving is not a general skill that can be applied unless the problem solver has some experience in a specific domain and understands the context in which a problem is presented (McCormick, 1997).

An example of practical, situated qualitative knowledge would be students finding out how a model mechanism works and how this could be modified. Through practical physical experiences working with the mechanism and guided by a teacher, students develop their qualitative knowledge about machines, mechanisms and their function. McCormick (2004)

sees a key role of technology educators as trying to get students to think as they are doing and reflecting about the doing in order to inform their ongoing thinking. This, in turn, informs their design and problem-solving capabilities. Identifying the kinds of qualitative knowledge used by teachers in technological problem solving is clearly an area in need of further research.

2.8.2 Prescriptive knowledge integrates knowledge types

Prescriptive knowledge is prescribed or stated by an expert designer and reliant on their informed judgement to make suitable decisions (Vincenti, 1991). Quantitative data in engineering design, as described by Vincenti, utilises prescriptive knowledge (see Section 2.5). The application of safety rules and regulations and technical specifications (dimensions/tolerances) are examples of prescriptive knowledge in that they are created bodies of knowledge that serve specific and important functions in design with hard materials (Mokyr, 2002). Although prescriptive knowledge when prescribed by a designer is explicit, it is knowledge that results from continuous efforts to achieve better results in design, such as more effective procedures or functions, and continues to be adapted and modified over time, depending on the specific context and application (Herschbach, 1995; Mokyr, 2002). Therefore, prescriptive knowledge and its adaptation are influenced to a large extent by the tacit knowledge developed from the previous experiences and practice of the expert (Mokyr, 2002). Consequently, it represents an integration of both conceptual and procedural forms of knowledge. As stated, this prescriptive knowledge is utilised by expert designers but the types of specific experiences that develop this knowledge require investigation to make the same or similar experiences available for students so they are able also to access prescriptive knowledge.

2.8.3 Device knowledge integrates knowledge

An expert utilises *device* knowledge, that is, practical understanding of how various components act in relation to each other within a device or mechanism (Gott, 1989). Device knowledge also represents an integration of conceptual and procedural knowledge. For example, an understanding of the operating principle of a device requires a conceptual understanding. However, Vincenti (1991) notes that this develops through experience and therefore device knowledge is also an implicit form of knowledge for those familiar with the device. Likewise, a device (machine or tool) in a real world context may require procedural knowledge to operate it or to dismantle it and fix it (McCormick, 1997). Device

knowledge, utilised by experts in technological design, is relevant for technology students who require knowledge of how devices operate (mechanisms and tools work), including the operating principle of such devices. For example, design and problem solving with hard materials often includes mechanisms such as a gear train as a component within an overall design concept.

2.8.4 Knowledge of constraints, materials and design

Recognition and evaluation of constraints have long been acknowledged as necessary knowledge considerations when designing and problem solving. Consideration of constraints when solving a problem is significant because it reduces the size of the problem and its solution; it helps novice designers confine ideas within more manageable chunks of information (Merrill et al., 2008). Constraints such as time and cost have been researched in relation to design in technology education, but little of this research has been materials specific (Merrill et al., 2008; Morrison & Twyford, 1994; Savage et al., 1998).

Design always occurs in a specific context and a key part of that context is the type of materials the designer intends to use (McCormick, 2004). An understanding of the constraints imposed by the materials used in design and problem solving requires an understanding of the properties of those materials, how and why they are used and both their potential and their limitations (descriptive knowledge). It is important to know how the material behaves in various situations, including its strength and rigidity, because these properties contribute to key design constraints. Thus, when a technologist is dealing with design constraints, the laws that predict the behaviour of materials also can be a key factor to consider (McCormick, 2004). It is clear that consideration of constraints requires extensive procedural and conceptual knowledge.

2.8.5 Strategic knowledge

It has been argued in Section 2.4 that experts are able to integrate many different types of knowledge and ultimately this is what educators want their students to do. Sections 2.6–2.8.4 considered those specific knowledge types pertinent to developing expertise in design and problem solving and that are understood to develop through experiences with hard materials. The identification of these types of knowledge has also indicated the complexity of knowledge required to design and problem solve with hard materials. A final significant category of knowledge described by Gott (1989) is *strategic* knowledge. It is described as knowledge that enables a designer and problem solver to know “how to decide what to do

and when” (p. 100). Ultimately, it would seem that is what an expert designer and problem solver is able to do, to draw on many different types of knowledge and know-how and know when to apply them to new situations (Shulman, 1986). However, there seems to be little research that identifies how experts acquire and learn to utilise effectively different types of knowledge. It is what technology education teachers strive to enable novice student designers and problem solvers to do through suitable curricula and effective learning programmes; that is, to learn and then be able to utilise types of technological knowledge in new situations. There seems to be little research that identifies clearly the types of experiences teachers might provide for students to enable them also to access this complex array of technological knowledge.

As technology education provides a unique opportunity for students to learn through experiences, the following section considers four learning theories developed to explain learning through experiences.

2.9 Learning theories and technology education

While this section considers learning through experiences in general, this thesis utilises these learning theories as theoretical frameworks for analysing experiences specifically pertinent to develop the learning of design and problem solving. According to Stevenson (2004), how students in technology education learn generally is under-theorised and at the very least, should include an examination of the transformations that students experience within themselves, their technological activities and their technological knowledge development. It follows that students must be presented with learning opportunities that enable those transformations.

Holistic theorists acknowledge that learning, particularly in school contexts, often is associated with a range of different learning theories (Miller, 2007). Therefore, in Section 2.9, relevant established theories of learning are examined in terms of their value in providing a tool to analyse in what way learning occurs through experience. Section 2.9.1 considers *experiential learning theory*, Section 2.9.2 considers *situated cognition theory*, Section 2.9.3 examines *distributed cognition theory* and Section 2.9.4 considers *activity theory*. These theories link practical learning experiences to the development of knowledge, concepts and understanding, components considered relevant to learning design and problem solving (Lewis, 2005; McCormick, 2004; Middleton, 2005).

Significantly, three of these learning theories; situated cognition theory, distributed cognition and activity theory also acknowledge that learning through experiences is a very interactive social activity. Therefore, these three social cognitive learning theories not only enable an analysis of experiences pertinent to developing learning to design and problem but also enable the identification of the specific social nature of many of these technological learning experiences. That is three of these four learning theories allow the social nature of technology learning through experiences to be explored.

2.9.1 Experiential learning theory

Experiential Learning Theory (ELT) describes how learning develops from an initial physical concrete experience. As design and problem solving with hard materials often are linked to physical experiences with materials and processes in workshops, it is a particularly relevant learning theory for considering learning through experiences.

ELT is a four-stage cyclic theory of learning that first considers an experience, then perception and cognition, and finally behaviour. It regards learning as an overall process that creates knowledge through transforming experiences. Knowledge and the modifying adaptation of knowledge are recreated through what the learner already knows (D. Kolb, 1984). Experience is the key component that develops through thought and discussion into concepts that can be applied to new and different situations. Learning through experience is what links ELT to John Dewey's argument that education should be conducted on the basis of experience and that this process requires a learning theory to support it (A. Kolb & D. Kolb, 2005). Other educators who regard experience as central to learning, and on which ELT is based, include Kurt Lewin and Jean Piaget (Demirkan & Demirbas, 2008; A. Kolb & D. Kolb, 2005).

The cyclic learning process identifies two opposing ways of perceiving experiences: Concrete Experience (CE), likened to doing, and Abstract Conceptualisation (AC), likened to thinking. The two ways of transforming or processing these experiences are: Reflective Observation (RO) (or reflecting); and Active Experimentation (AE) (or acting) (A. Kolb & D. Kolb, 2005). These modes of perceiving experiences enable the whole person, body and mind, to take part in the function of learning. During this learning process, people are required to move in and out of the somewhat conflicting modes of reflecting and acting, and doing and thinking. Doing occurs during the initial experience and acting is a consequence of new experiences. The four modes in this experiential learning cycle have

been related to the structure of how the human brain functions. CE relates to the sensory cortex in the human brain. RO involves the integrative cortex at the back of the brain, AC the frontal integrative cortex and AE the motor brain (A. Kolb & D. Kolb, 2005). Design has often been defined using these four modes (Demirkan & Demirbas, 2008).

ELT identifies learning occurring through an initial concrete experience that involves the senses or whole person in the experience (Moon, 2001). However, for experiences to be transformed into knowledge and therefore learning, reflection and thinking about the experiences also must take place. For experiences to transform into learning that develops knowledge and enables students to design and problem solve more effectively, reflection and thinking have to form a part of the process. ELT theorises how concrete experiences are transformed into more than just “doing” exercises. Nevertheless, it does not account for how concrete experiences become abstracted or how the reflective or thinking processes function. It is important to note that ELT is an individualised theory of learning and does not take into account the physical setting or the cultural and social constructs of learning (Petrina, 2007).

Teachers and researchers using ELT sometimes employ a Learning Style Inventory (LSI) to assess how individuals can best fit four identified approaches or styles associated with learning: *diverging*, *assimilating*, *converging* and *accommodating* (A. Kolb & D. Kolb, 2005). These learning styles are associated with learning abilities or modes on the experiential learning cycle. Divergent thinkers, for example, prefer CE and RO learning modes. The divergent thinker is able to see a range of ways to deal with something and benefits from brainstorming when generating ideas in designing. An assimilating learning style relates to strengths in AC and RO learning modes; learners are better able to draw on a broad range of information and find a concise final design. Learners with converging styles have stronger AC and AE learning abilities. These learners have been identified as particularly effective in technology activities as they are able to solve problems relating to technical tasks. The accommodating learner has strengths in CE and AE learning abilities and prefers hand-on experiences (A. Kolb & D. Kolb, 2005). The LSI has been acknowledged in higher education as a useful tool to explore design education (Demirkan & Demirbas, 2008).

Because ELT is a theory linked to both experience and learning, it is highly relevant to this thesis which investigates ways in which learning design and problem solving with hard materials may link to experiences in the context of hard materials. The theory is useful to

explain how learning occurs through experiences for the individual. Experiential learning has sometimes mistakenly been associated with students simply having physical experiences, often referred to as busy-happy-good activities with little evidence of learning occurring. ELT points very clearly to the other necessary steps for learning to occur following an initial concrete sensory experience (Moon, 2001).

2.9.2 Situated cognition theory

A second learning theory based on experience is situated cognition theory—a theory that considers that knowledge gained through a practical experience is a consequence of participating in the activity. It recognises that an activity occurs within a specific context that often has a particular culture attributed to it and a set of associated values. Consequently, learning is embedded not only in a physical world, but also in a social world. An authentic situation or context is considered to co-produce the knowledge and learning, with the learner and context being central and key components of learning. As this thesis considers learning design and problem solving through experiences in the specific context of hard materials, situated cognition provides a valid learning framework to utilise in understanding the ways in which experts learn through experiences with hard materials in authentic workplace situations. In this learning theory, both procedural *know-how* knowledge and conceptual *know-that* knowledge are component parts of the whole learning and considered to be integrated and inseparable (Brown, Collins, & Duguid, 1989).

Situated cognition is based on Lev Vygotsky's (1978) socially mediated theory of learning and includes three key elements: the social nature of learning, the physical environment and learning within a Zone of Proximal Development (ZPD) (Petrina, 2007). Students are in the ZPD when they occupy a cognitive space in which they can act and develop understanding successfully with teacher support and encouragement but could not do so unaided (Hodson & Hodson, 1998). This facilitation by a teacher is called scaffolding learning (Wood, Bruner, & Ross, 1976). For example, when students are participating in a physical activity, they are often operating in the ZPD, but with teacher support they can learn to extend their understanding from the activity into the type of knowledge that supports learning. Eventually the support of the teacher fades as the student builds knowledge and confidence, gradually being able to take more control of their own learning.

Situated cognition incorporates and builds on Vygotsky's learning theory, developing the concept of "situatedness" and the context of an activity as central components of learning (Petrina, 2007). First, an activity or experience is a key element of the knowledge being learnt and should not be separated from it. Second, as in ELT, the experience is important but the context and situation of the experience is also central to the learning process (Brown et al., 1989; Hendricks, 2001). Lave and Wenger (1991) recognise that cognition (learning and understanding) is shared when learners enter a Community of Practice (CoP), which develops through social sharing and participation in activity as individuals become enculturated into the specific environment/context in which the learning occurs.

In the beginning, the key focus for a learner is the activity which may build their procedural knowledge. However, conceptual understanding and knowledge also develop from, and as a result of, the activity or experience in a specific context. Once conceptual knowledge is able to be abstracted by the learner as a result of experience within a specific situation and context, it may be applied in other situations (Brown et al., 1989; Case & Jawitz, 2004). Apprentices, for example, enter the culture of their practice or trade (CoP) by physically working in a real workplace alongside others who are qualified and experienced tradespeople. In apprenticeship, learning emphasises the relevance of activity and social interaction in learning relevant knowledge. It also highlights the inherently context-dependent, situated and enculturated nature of learning. Apprenticeship learning reflects and links the social and situated modelling (scaffolding), teaching and fading of Vygotsky's ZPD but also the relevance of activity, experiences and a context where learning is situated (Collins, Brown, & Newman, 1989).

Lave and Wenger (1991) further note that in the early stages of engagement within a CoP, a novice learner such as an apprentice may obtain access only to the periphery, but as they gain in confidence and proficiency they will work towards greater involvement and eventual full participation. This notion of situated cognition as Legitimate Peripheral Participation (LPP) further develops the concept of situated learning to include the interconnectedness of people, activities and knowledge in the lived world (Lave & Wenger, 1991).

Situated cognition recognises that knowledge gained through practical circumstances is a consequence of participating in the activity, in the specific context, and being part of the culture where it is deployed. In other words, knowledge is contextualised. This contrasts sharply with much school learning where knowledge often is stripped of its context (Hill &

Smith, 2005). It follows that learning to design and problem solve with hard materials requires much contextualised knowledge and requires technology educators to find out in what way this knowledge may be learnt through experiences with hard materials. Thus, situated cognition learning theory provides a tool for analysing such learning.

2.9.3 Distributed cognition theory

Distributed cognition learning theory disputes the notion that learning or cognition only takes place in an individual's mind and highlights the importance of interaction with artefacts and other individuals (Vvidis, 2002). McCormick (2004) identifies the importance of technology students being able to do and "to think through their doing, and for the feedback from this doing to affect their thinking" (p. 23). In distributed cognition, cognition is not limited just to an individual's "skin and skull"; rather, it involves the whole system within which a person operates, including their tools, artefacts and the surrounding community (Hutchins, 2001). In other words, distributed cognition relates to learning distributed across the individual mind, the tools that help to mediate the learning and other people who also may contribute to the learning experience. The physical object develops and stimulates the mental activity and, vice versa, mental activity makes use of the physical object. The social context is the use made of other people to support the cognitive activity and often the learning will depend also on this social context (Vvidis, 2002).

With respect to learning design and problem solving through experiences with hard materials, this learning theory provides an analytical tool to describe learning by doing. For example, the cognitive resources of the learner (memory, attention, skill) co-ordinate with external factors to develop knowledge and understanding relevant to design and problem solving. The external factors may include experiences utilising materials, processes and artefacts (technologies) and other people. The internal factors include the cognitive knowledge, skills and attributes that individuals bring to the activities.

The use of materials, technologies and interaction with others does not occur without cognitive input and knowledge. A key aspect of distributed cognition is that it considers there to be no gap between the internal (mind) and the external (materials, processes, artefacts, technologies and other people). The internal and external aspects work in parallel and collaboration to enable learning (Petrina, 2007). In other words, technologies and other

individuals are not seen as mediating the learning but as essential elements in helping an individual to construct knowledge and understanding.

2.9.4 Activity theory

A fourth learning theory that is centred on learning through activity is activity theory. It is considered in this thesis because it explains learning that occurs through experience within a social structure. Activity theory provides a framework that enables an understanding of how the cognitive, physical and social aspects contribute to support learning (Engestrom, 2001). It acknowledges how learning occurs through activity that is supported by a complex social network. A range of actions, groups and their social and cultural rules contribute to the learning environment and contribute to the entire activity system. The processes of design and problem solving, for example, rely on an activity system that is both complex and multifaceted.

In an activity system, there is a *subject*—in this situation, the learners and teachers. There is an *object*—in this thesis, learning to design and problem solve for a purpose. As well, there is an *outcome*—being able to design and problem solve in new and different situations. The learning or object is mediated through tools, artefacts, activities, knowledge and experiences and governed by a community, rules and a division of labour. An activity system requires all these factors to come together to transform and provide the network to support the activity. These factors include the subjects (people), the rules of an organisation, the community, the instruments, tools or technologies, the object (the problem being worked on), the outcome or goal and the division of labour (Engestrom, 1991). In other words, the social and cultural aspects, the organisational systems, the history and backgrounds of people and the environment, all input to the system for learning to occur (Engestrom, 2001). As a result of the whole activity system, knowledge and learning is continuously revised by utilising and refining previous knowledge and expertise. Thus, an activity system provides opportunities for change and innovation.

Activity theory differs from other learning theories insofar as the community and the learner interact in a more significant way. In activity theory, learning requires an experience (like ELT), a context (like situated cognition), an interaction with artefacts and other individuals (like distributed cognition). However, its point of difference is that the learning is embedded within a wider community in which all participants are actively involved and supported in their learning by the community. In terms of learning to design

and problem solve with hard materials, activity theory provides a tool to analyse learning that includes experiences and activities that occur and rely on a community of learners.

A key aspect of this thesis is to find out in what ways experiences with hard materials can influence the development of learning to design and problem solve with hard materials. As these four learning theories are based on learning through activity or experiences, they provide a useful tool to analyse how learning design and problem solving may occur through activity and experiences of both expert designers and problems solvers and novice student designers and problem solvers.

2.10 Technology teaching and pedagogical content knowledge

Often in technology education, technology teachers have practised as technologists prior to becoming teachers. Therefore, they bring distinctive domain-specific subject knowledge to their technology teaching practice. Jones and Moreland (2003) acknowledge that teachers' knowledge of a discipline impacts on what they discern as important and relevant for students to learn. Consequently, they argue that knowledge of a discipline also influences a teacher's individual pedagogy in a classroom. In other words, the pedagogy of technology teachers is likely to be influenced by their own experience and consequent knowledge and understanding about aspects such as design and problem solving. Often, the combination of content knowledge of a subject and delivery of such knowledge to students in a classroom is referred to as *Pedagogical Content Knowledge* (PCK) (Shulman, 1986).

PCK offers a framework to analyse the learning experiences teachers provide for their students. It refers to teachers being able to combine their subject and content knowledge of a particular subject with their pedagogical knowledge in order to be an effective teacher (Shulman, 1986). In other words, to enable students to learn, teachers with specific content knowledge related to their subject specialities also require pedagogical knowledge about how to transfer this knowledge to make it accessible and comprehensible to students through the learning experiences they provide for students (Ball, Thames, & Phelps, 2008). Van Driel, Verloop, and de Vos (1997) refer to transfer as "interpreting" and "transforming" knowledge to make it accessible to learners (p. 673). According to Shulman (1987), skilful teaching is developed through seven key classifications of teachers' knowledge: subject matter; PCK; pedagogical knowledge; curriculum knowledge; knowledge of learners and their abilities; knowledge of contexts in education; knowledge of educational aims, purposes and values.

Cochran, DeRuiter, and King (1993) identify PCK as *Pedagogical Content Knowing* (PCKg), recognising knowledge as changing and developing. Like Shulman (1986), they recognise PCKg's importance to effective teaching and subsequent learning. However, their model encompasses the integration of only four elements or components:

- Subject matter and content
- Characteristics of students (knowledge about students as learners)
- Environmental context of learning (knowledge about the specific school community)
- Knowledge of pedagogy (appropriate teaching and learning strategies for a classroom).

Barnett and Hodson (2001) have elaborated on PCK with three additional and interconnecting components that they identify as *Pedagogical Context Knowledge* (PCtK) to make knowledge and understanding relating to a subject accessible to novice student learners.

The four key components of PCtK are summarised below:

- PCK (content knowledge, how best to present concepts in sequence of lessons, theoretical elements, how to motivate students, management of students)
- Classroom knowledge (knowledge of students in class, best practice for specific group of students, verbal interactions and delivery for specific students, adaptations for particular classes of students)
- Professional knowledge (teachers know intuitively what to do, gained through conversations amongst peers, is tested through practice, includes academic/research knowledge, sometimes pertinent to specific schools, referred to as teacher lore)
- Academic and research knowledge (includes content knowledge, cultural and historical knowledge relevant to subject, obtained through in-service and professional development courses, how and why students learn, requires teacher's personal reflection on teaching).

PCK in the PCtK model is relevant particularly to technology education because the context-specific background experiences and knowledge of many technology teachers is

considered relevant alongside teachers' understanding of how best to transfer this knowledge and understanding to students.

Classroom knowledge is pertinent to technology teaching as technology is a compulsory subject in many countries in middle secondary schools. Consequently, it is reasonable to assume student bodies from individual schools will be very different and this is likely to influence the types of programmes that teachers provide for students. Also within each individual school, there will be particular groups of students with quite different needs, for whom technology teachers must provide relevant technology learning programmes.

Professional knowledge referred to in PCtK refers to teachers knowing how to teach through practice and experience, which includes discussion with peers. As technology teachers have quite specific roles in schools that are quite distinct from other departments, often they form teacher associations specific to their area of teacher expertise.

The last component of PCtK is academic and research knowledge. Because many technology teachers have learnt to be technologists prior to becoming technology teachers, they bring particularly rich perspectives of how technological knowledge might be transmitted to students based on their own prior learning. They have experienced learning technology in a specific cultural and situated way as technologists in various industries and they bring these backgrounds to their technology teaching. As acknowledged by Barnett and Hodson (2001), PCtK provides a straightforward yet effective way to analyse teachers' perspectives and the knowledge they utilise when discussing their teaching and pedagogy. Therefore, it is considered a useful tool to analyse pedagogical practice of teachers in technology education. There appears to be little research enabling hard materials technology teachers to reflect on their pedagogical practice.

2.11 Summary

First, the literature review considered the introduction of design and problem solving as part of an attempt in many countries to academicise and broaden technical education in the process of introducing it as a compulsory school subject accessible to all students. As the literature review highlighted, problem solving and design became interchangeable terms and presented problems for many teachers who had little previous exposure to these concepts, resulting in a limited understanding of what constitutes either design or problem solving in technology education (Johnsey, 1995; Mawson, 2001; McCormick, 1997). Therefore, what constitutes design and problem solving, how to go about teaching design

and problem solving and how students might learn to design and problem solve became ongoing problematic issues for many teachers in technology education (Jones et al., 2013).

Following the introduction of technology education, many students continued working in activity-based programmes with hard materials in purpose-built technology classrooms and workshops, as they had in previous technical and craft programmes. As stated previously (see Section 2.2.3), the introduction of technology education established a major focus on design and problem solving as two key elements. Since students continue to work in these specialised learning environments, it seems pertinent to investigate in what ways students' learning of design and problem solving in the context of hard materials technology education might be supported through experiences that includes activities in purpose-built classrooms such as workshops.

It could be argued that a key way to find out about design and problem solving with hard materials is to consult expert technologists. Indeed, it has been argued that a key way to find out about novice designers in engineering education is to consult expert designer technologists (Daly et al., 2012). While there have been several studies identifying how expert designers operate, there has been little research that focuses on the first-hand accounts of the role experiences play in developing designers' and problem solvers' expertise (Hill & Anning, 2001).

As the field of mechanical engineering provides a broad spectrum of expertise, that includes skilled tradespeople, technicians and professional certified engineers, it provides a suitable domain from which to draw a range of opinion and expertise for this study. Therefore, a sub-question in this research emerging from the literature review is: **In what ways do expert technologists consider experiences with hard materials developed their expertise (knowledge and understanding) to design and problem solve with hard materials?**

As well, expert technologists' conceptualisations of design and problem solving are considered important in this research as these conceptions may help to build a more comprehensive understanding of what constitutes design and problem solving with hard materials. There has been little research that has included experts' views regarding the role of problem solving in relation to designing with hard materials. Therefore, a further sub-question arising from the literature review guiding this research is: **In what ways do**

expert technologists conceptualise the relationship between design and problem solving in the context of hard materials?

Likewise, it is relevant to establish how teachers conceptualise design and problem solving and how that conceptualisation might identify relevant learning experiences to support students learning design and problem solving. While there is some research in which teachers have identified types of problem solving (McCormick, 2004), there is limited research of how teachers or indeed experts actually conceptualise design and problem solving or their interrelationship in the context of hard materials. As a result of this lack of research, a key sub-question in this research emerging from the literature review is: **What are technology teachers' conceptions of design and the role of problem solving in hard materials technology?**

Because teachers play a pivotal role in developing students' learning, this research considers it important to consider their views concerning the traits of successful novice student designers and problems solvers. By establishing the traits of such students, teachers and technology educators may be able to focus learning programmes to develop such traits in all students. Teachers' learning programmes that may utilise experiences to develop these traits are pertinent to this research. Therefore, a further research sub-question in this research is: **What are teachers' conceptions of the key traits of successful novice student designers and problem solvers working with hard materials?**

Teachers' views relating to the role experiences with hard materials play in students learning to design and problem solve with hard materials are, likewise, key to this research. As an aside, there is some recent speculation that experiences with materials and working hands-on in terms of *actual* making in general technology education may disappear from technology education if its relevance cannot be justified (Martin & Owen-Jackson, 2013). In particular, this research aims to investigate how such activities and experiences, including making in the context of hard materials, may contribute to students' learning design and problem solving. Although there has been some research that has linked experiences with materials to students developing their design expertise, these have not been in the context of hard materials and have not involved secondary school students' learning (Fleer, 2000; Middleton, 2005). Therefore, as a result of the review of literature, a further research sub-question in this research is: **In what ways do teachers consider learning experiences with hard materials can influence and support students'**

knowledge, understanding and learning to design and problem solve with hard materials?

Technology education literature acknowledges the importance of context in learning design and problem solving, including how these concepts link to learning theories such as situated cognition (Fox-Turnball, 2012; McCormick, 2004; Petrina, 2007). It would seem the social nature of learning in the context of both technology and technology education is very apparent. That is technologists and technology students interact with each other to construct their knowledge and understanding. However, there appears to be little research that investigates actual experiences that are analysed using relevant learning theories to identify how learning design and problem solving might occur through experiences, including the social nature of that learning, in specific contexts such as hard materials. Therefore, a final sub-question guiding this research is: **In what ways can experiences with hard materials be theorised regarding learning to design and problem solve with hard materials?**

In summary, the six sub-questions emerging from the literature review will be used to guide this research. As a result of these six sub-questions, the overall key research question guiding this research is: **In what way can experiences with hard materials influence the development of learning to design and problem solve in the context of hard materials?**

Chapter 3: Research Design

3.1 Introduction

The purpose of this research was to investigate the ways in which experiences with hard materials influence the development of learning to design and problem solve in the context of hard materials. As a result of the examination of literature and research presented in Chapter 2, the overall research question that emerged and guided this research is:

In what ways can experiences with hard materials influence the development of learning to design and problem solve in the context of hard materials?

In this chapter, the research design that enabled the overall research question to be investigated is explained and justified. In Section 3.2, the mode of inquiry and the philosophical principles that underpin and guide this research are described. This includes the identification of the ontology and epistemology in Sections 3.2.1 and 3.2.2. Section 3.2.3 argues the justification for choosing an interpretivist methodology using a qualitative approach. Section 3.3 provides a timeline of the research including a summary of the timeline presented in Table 3.1. The selection and recruitment of the research participants is presented in Section 3.4. In Section 3.5, the data collection through semi-structured interviews is described and the ways in which the data were analysed is presented in Section 3.6. Section 3.7 examines the issues of trustworthiness and in Section 3.8 the ethical considerations pertinent to this research are discussed. A summary of the overall research design is presented in Section 3.9.

3.2 Interpretivist mode of inquiry

An interpretivist mode of inquiry was used to conduct this research. This mode of inquiry assumes that the world is interpreted subjectively through the minds of individuals in their natural social settings and meaning is generated from lived human experiences (Cohen, Manion, & Morrison, 2007). This research is described best as using an interpretivist mode of inquiry because it enables expert technologists' and technology teachers' understanding of concepts, knowledge and interpretations about understanding and learning to inform the research (Cohen et al., 2007; Davidson & Tolich, 2003a; Neuman, 2003). Expert technologists and technology teachers were given a voice that has enabled the researcher to build a detailed picture of the ways in which experiences in the context of hard materials influenced and developed the experts' design and problem-solving skills and teachers

consider experiences help students to learn design and problem solving. Design and problem solving are complex cognitive activities. Choosing an interpretivist mode of inquiry provided the opportunity to investigate these complexities through the eyes of two groups of research participants.

An interpretivist mode of inquiry has a particular ontology and epistemology that guides the way in which research is conducted (Davidson & Tolich, 2003a; Punch, 2005). In Sections 3.2.1 and 3.2.2, the choices of ontology and epistemology are identified and justified in relation to this research. Section 3.2.3 presents the methodological decisions and how these complement the interpretivist mode of inquiry chosen for this research.

3.2.1 Ontology

Ontology is a way of viewing the world and is concerned with the assumptions all forms of research make about the nature of knowledge and reality (Davidson & Tolich, 2003a; Denzin & Lincoln, 2000). It is defined in terms of the knowledge claims constituting the assumptions, both theoretical and procedural, with which a researcher begins the research (Creswell, 2003). It informs the researcher about how and what he/she will learn during the research and how knowledge is claimed through a particular process and set of assumptions (Creswell, 2003). The theoretical perspective in this research is interpretivism; the procedural foundation or ontology is social constructionism (Sarantakos, 2005). Social constructionism focuses on the ways in which research participants construct subjectively and in detail their interpretation of reality and their personal experiences (Babbie, 2007; Creswell, 2003; Sarantakos, 2005). An interpretive mode of inquiry is underpinned by social constructionism in that this research relied on the research participants' subjective interpretation of their knowledge and understanding acquired as a result of their interaction with the world (Bryman, 2004; Sarantakos, 2005).

In this research, a social constructionist ontology enabled the research participants to provide subjective meanings of their experiences about particular things or concepts and these subjective meanings were seen to provide valid research data (Creswell, 2003). Two participant groups in this research shared their subjective meanings and perspectives of their reality, specifically, the way in which experiences with hard materials have influenced their own and others' understanding and ability to design and problem solve using these same materials.

3.2.2 Epistemology

Epistemology is the framework on which knowledge is verified, substantiated or refuted. It is concerned with what knowledge is and how we know what we claim to know. This includes how knowledge is obtained and how this knowledge may be shared with others (Cohen et al., 2007). Epistemology underpins the kind of knowledge the researcher seeks to investigate and their interpretation of how people make meaning (Babbie, 2007; Sarantakos, 2005). A social constructivist epistemology underpins an interpretivist mode of inquiry. A social constructivist epistemology was chosen for this research because it enabled the research participants (both experts and teachers) to share their individual understanding and the meaning they make as a result of social interactions and their interactions with their respective environments. A key assumption in an interpretivist mode of inquiry is that reality is constructed by the people who are involved in the research as they struggle to make sense of their experiences in the world (Denzin & Lincoln, 2000; Merriam, 1998; Neuman, 2003). As Cohen et al. (2007) note, this requires the researcher to have direct involvement with the research participants and also to struggle with sense-making, for “knowledge” does not exist separately from the social contexts in which it is situated.

Education viewed through an interpretivist mode of inquiry is thought of as a “process” and school as a “lived experience” (Merriam, 1998). From a technology teacher’s viewpoint, knowledge is obtained through developing an understanding of both the educational processes and the lived school experiences (Merriam, 1998). Likewise, an expert technologist’s knowledge is interpreted through reflection, construction and reconstruction based on experiences in real contexts (Sarantakos, 2005). Both groups of participants have developed and constructed their knowledge through beginning and ongoing participation in CoPs, each with their own distinctive cultures and histories (Lave & Wenger, 1991). The expert technologists belong to technological CoPs and the technology teachers belong to educational CoPs that have helped shape their constructed knowledge. Four of the teacher participants also belonged to technological CoPs prior to becoming teachers. In this research, the constructed knowledge of the research participants therefore informs this research hence the justification for choosing a social constructivist epistemology.

3.2.3 Qualitative

Qualitative research aligns with an interpretivist mode of inquiry (Cohen et al., 2007; Davidson & Tolich, 2003a; Neuman, 2003). Because the mode of inquiry underpinning this research is interpretivist (see Section 3.2.1), a qualitative research methodology was chosen to collect and interpret data (Punch, 2005). A key purpose of qualitative research is to find out the detail and wholeness of an experience, phenomenon or understanding, allowing an in-depth investigation from small groups of participants (Creswell, 2003; Davidson & Tolich, 2003a; Merriam, 1998).

This research involved an in-depth investigation of two different but related groups' views about learning to design and problem solve through experiences with hard materials. In other words, the focus in this research was learning to design and problem solve through experiences with hard materials. Qualitative research focuses on interpreting participants' conceptions and understandings and for this reason it is suited particularly to obtaining knowledge about educational practice and learning (Merriam, 1998). In addition, this research aimed to find out how knowledge is constructed and how learning occurs through experiences, from the perspectives of expert technologists and technology teachers.

Five key characteristics of qualitative research that make it appropriate for this research design are: (i) the researcher collecting and analysing the data; (ii) the research focus being seen from the perspective of the research participants; (iii) the researcher exploring within the participants' context when conducting the research; (iv) data being used to build theory not to test existing theory necessarily; and (v) research that is heavily descriptive in reporting the findings (Merriam, 1998). In this research, these five characteristics are apparent. First, the researcher personally collected and analysed the data. Second, the data collected were from the perspectives of 10 participants belonging to two different groups associated directly with technological design and problem solving as related to the overall research question. Third, the research participants worked within relevant contexts pertinent to this research (educational and/or technological). Fourth, the overall question has been informed and further developed by the analysis of the data (see Chapters 4–8) and the resulting discussion (see Chapter 9). Fifth, the data analysis chapters (see Chapters 4–8) and the discussion chapter (Chapter 9) in this thesis are both analytical and heavily descriptive.

As Merriam (1998) notes, when qualitative research is carried out there is acknowledgement of how all the parts work together to form a whole and through an analysis of the information provided, there is focus to find out the depth of research participants' understanding and knowledge. By choosing an interpretivist mode of inquiry, a social constructionism ontology, a social constructivist epistemology and a qualitative methodology, the views of reality of the research participants were able to be interpreted. The research participants shared their subjective knowledge and understanding about their learning and/or their experiences and its relationship to learning to inform the research questions (Creswell, 2003).

3.3 Timeline of the research

The timeline of this research comprised three phases. Phase one of the research involved the expert technologist research participants. This phase included the recruitment of expert technologists, data collection through interviews with five expert technologists and analysis of this data. Phase two of the research involved hard materials technology teachers. This phase included the recruitment of teachers, data collection through interviews with five hard materials technology teachers and analysis of this data. Phase three of the research involved the writing of this research thesis. Table 3.1 provides a timeline and summary of the three phases of this research and the research sub-questions pertaining to each research phase.

Table 3.1: Timeline of research project

Time Line	Research Questions	Research Description	Data Collection
Phase 1 2010 May	Sub-Questions 1, 2 and 6 <ul style="list-style-type: none"> In what ways do expert technologists consider experiences with hard materials developed their expertise (knowledge and understanding) to design and problem solve with hard materials? In what ways do expert technologists conceptualise the relationship between design and problem solving in the context of hard materials? In what ways can experiences with hard materials be theorised regarding learning to design and problem solve with hard materials? 	Obtained ethics approval for Phase 1 of research Contacted IPENZ Chairperson Advertised in IPENZ newsletter for engineers	
Phase 1 2010 May– 2011 August	Sub-Questions 1, 2 and 6 (See above)	Recruited and conducted interviews with expert technologists	Visited experts' workplaces Individual interviews
Phase 1 2010 June– 2011 December	Sub-Questions 1, 2 and 6 (See above)	Analysis of expert technologists' data	
Phase 2 2011 April–May	Sub-Questions 3, 4, 5 and 6 <ul style="list-style-type: none"> What are technology teachers' conceptions of design and the role of problem solving in hard materials technology? What are teachers' conceptions of the key traits of successful novice student designers and problem solvers working with hard materials? In what ways do teachers consider learning experiences with hard materials can influence and support students' knowledge, understanding and learning to design and problem solve with hard materials? In what ways can experiences with hard materials be theorised regarding learning to design and problem solve with hard materials? 	Obtained ethics approval for Phase 2 of research Advertisement TENZ newsletter	
Phase 2 2011 May– December	Sub-Questions 3, 4, 5 and 6 (see above)	Contacted school principals, recruited and conducted interviews with secondary hard materials technology teachers	Visited teachers' schools Individual interviews
Phase 2 2011 July– 2012 December	Sub-Questions 3, 4, 5 and 6 (See above)	Analysis of technology teachers' data	
Phase 3 2013 January– 2014 August	Overall research question In what way can experiences with hard materials influence the development of learning to design and problem solve in the context of hard materials?	Writing of thesis	

Note. Technology Education New Zealand: TENZ; Institution of Professional Engineers New Zealand: IPENZ.

3.4 Sampling and selection

The ten participants for this research were selected using purposive sampling. Purposive sampling was chosen because it ensured the research participants met a predetermined criterion and had the specific characteristics related to the research (Cohen et al., 2007; Merriam, 1998). In other words, the participants were chosen for a particular purpose. They were chosen because they were “knowledgeable people” and had “in-depth” understanding about specific issues (Cohen et al., 2007). Purposive sampling enabled two groups of participants with specific knowledge and qualities to be recruited. However, some participants in this research were also recruited using convenience sampling. Convenience sampling makes use of participants who are readily available to the researcher (Bryman, 2004; Cohen et al., 2007). Wherever convenience sampling of research participants was used, the research participants were also required to meet the purposive sampling criteria. In this research, the two different groups (experts and teachers) were required to meet two different sets of criteria. These criteria are detailed in Sections 3.4.1 and 3.4.2.

3.4.1 Expert technologists

Because mechanical engineering provides a broad area of design and problem-solving expertise in the context of hard materials, it was chosen as the domain from which to select the expert technologists. As the researcher, I had some knowledge through prior work experience within the domain of mechanical engineering, so wanted to ensure the recruitment of experts was representative of the broad spectrum of expertise available in this domain. To do this, expert technologists were recruited from three distinctive groups within the domain of mechanical engineering: New Zealand Certificate in Engineering (NZCE) or diploma-level qualified engineers; certified trade-qualified engineers; and professional mechanical design or product engineers. In this way, the expert technologists were “information rich” and therefore able to describe their pathways and identify relevant experiences to becoming expert and developing their current expertise (Creswell, 2008). A random sample using any expert technologists would be of little use to this research as they would be unable to provide responses relevant to the specific nature of the research questions (Cohen et al., 2007).

Therefore, the first group of research participants, the expert technologists, were recruited using purposive sampling. The purposive sampling criteria required the experts to have

expertise in design and problem solving using hard materials. They had to be practising currently as designers and problem solvers in the context of hard materials, with 5 or more years of experience beyond their training or study years. Four of the expert technologists were recommended to the researcher by other people, or were technologists approached because of both their known expertise and the specific type of hard materials engineering they perform. Consequently, four of the expert technologists were recruited using convenience or opportunistic sampling (Bryman 2004; Cohen et al., 2007; Neuman, 2003; Punch, 2005), at the same time meeting the purposive criteria for expert technologists. A detailed description profiling the technical backgrounds and the current occupations (at the time of the data collection) of each expert technologist is provided in Section 4.2, p. 91.

3.4.2 Technology teachers

The second group of research participants comprised five teachers who teach hard materials technology in five New Zealand secondary schools. All five of the technology teachers were recruited using purposive sampling (Cohen et al., 2007). The purposive sampling criteria for technology teachers required the teachers to be teaching a current hard materials technology programme that involved students' experiential use of hard materials. They had to be engaged in teaching in New Zealand secondary education and to be widely recognised as exemplary teachers within their specialist disciplines. Other criteria for the five teachers included having 5 or more years of teaching experience in technology education and being involved in teaching Year 10 students (14–15 year olds) or above so they had experience of students likely to be involved in design and problem-solving activities with hard materials. Three of the teacher participants were recruited because they were recommended by subject moderators/advisors and other technology educators as exemplary teachers. Therefore, three of the teacher research participants were selected using convenience or opportunistic sampling (Bryman, 2004; Cohen et al., 2007; Neuman, 2003; Punch, 2005), at the same time meeting the purposive criteria for technology teachers.

By restricting the teaching group involved to these criteria, it was possible for those involved in the research to be positioned to contribute their views to the research questions. Detailed information profiling the five technology teacher participants is provided in Section 6.2, p. 154.

3.5 Data collection

The principal data collection technique used to collect information was interviews with the expert designers and problem solvers and the technology teachers (Bryman, 2004; David & Sutton, 2004). Interviews complement an interpretivist mode of inquiry and a qualitative methodology as they enable the research participants to speak directly about how they make sense of their world. As Merriam (1998) states, data collection is deciding the type of information that will inform the research questions and the best technique to obtain such information. Sections 3.5.1–3.5.3 describe and justify the way in which data were collected for this research.

3.5.1 Interviews

In qualitative research, interviews are one of the most common data collection techniques (Merriam, 1998; Punch, 2005). This research used individual semi-structured interviews, also known as open-ended or qualitative interviews, to collect data to inform the research questions, the data analysis and the research outcomes (Brenner, 2006). A semi-structured interview is suited specifically to finding out people's understanding of their reality (Punch, 2005). Likewise, it enables research participants to share their knowledge and understanding from their own perspectives using their "own words" by answering "how" and "what" type questions (Brenner, 2006). The data obtained through interviews in this research is constructed in the words of the participants: the expert designers and problem solvers, and the technology teachers. With each participant, a rich insight into their understanding, knowledge, opinions, views and attitudes about the ways in which experiences with hard materials influence and contribute to learning to design and problem solve was shared with the interviewer. Therefore, semi-structured interviews provided an appropriate method of finding out about the overall question and sub-questions guiding this research.

Interviews have the advantage of being flexible enough to enable interviewees to respond in their unique ways to questions and contribute rich detail in their own words (Brenner, 2006; Bryman, 2004). Also, they allow the interviewer to probe or prompt with further related questions for more in-depth information and to elaborate and clarify interviewees' initial responses (Brenner, 2006; David & Sutton, 2004; May, 2001). Consequently, interviewers need to listen, to think and be responsive to the interviewee in order to probe questions effectively (Babbie, 2007; Bryman, 2004). It is also important that the probe

questions do not take the interviews in a particular direction favoured by the researcher (Brenner, 2006). In this research, the probe questions used in early interviews in this research often elicited rich information that resulted in similar probe questions being added to subsequent interviews (Brenner, 2006). Therefore, the skills required by the interviewer include asking pertinent questions, but also being a listener who is adaptive and flexible so that quality information is obtained (Yin, 2003).

Although an interview is a conversation between two people, it is the interviewer who determines the general direction of the conversation by the use of questions (Babbie, 2007). It is here that guide questions play a key role. A deep understanding of what is being studied is important as a researcher should be mindful of gathering pertinent information during the interview and keeping it to manageable sized proportions for later analysis.

3.5.2 Questions

In an interview, a list of guide questions is used that relates to the key themes of the overall research questions. The guide questions structure and differentiate the interview from a casual conversation (Babbie, 2007; David & Sutton, 2004). The guide questions (interview guide), ensure information relevant to the research remains the focus of the data collected throughout the interview process (Bryman, 2004). Guide questions also ensure the same core questions are asked of all research participants (Brenner, 2006). Questions constitute a key component of semi-structured interviews, as the participants' responses are dependent on how they have interpreted the questions (Tolich & Davidson, 2003). Therefore, it is important that the initial guide questions elicit the type of information that will help to inform the overall research questions, yet remain open-ended enough to ensure participants' unique responses will be recorded (Tolich & Davidson, 2003). In this research, guide questions found out participants' views of design and problem solving and the role they considered experiences have in learning to design and problem solve with hard materials.

The two sets of guide questions used in this research include the expert technologists questions (Appendix A) and the technology teachers questions (Appendix B). The questions were developed from the literature review carried out prior to the interviews taking place. The literature review considered information relating to design and problem solving using hard materials and experiential learning. It considered relevant research that

has already been conducted in technology education related to this topic. Therefore, the literature review not only shaped and informed the overall research question and sub-questions but the nature of the questions used in the semi-structured interviews of both the expert technologists and the technology teachers.

3.5.3 Conducting the interviews

The guide questions (Appendices A & B) were distributed to all the participants prior to the interviews taking place. This ensured all participants were fully informed of the questions guiding the interviews (May, 2001). The five workplaces of the expert technologists had been visited either during the data collection process or on a previous occasion. This familiarity with the expert technologists' respective workplaces enabled some of the shared information to be contextualised. Likewise, the schools and technology workshops of the five teacher participants were visited either during the data collection process or on an occasion prior to the data collection. Again, this familiarity with the technology teachers' respective teaching environments enabled the information shared to be put in context. Each semi-structured interview took 1–2 hours and was audio-taped and subsequently transcribed into text data by a professional transcriber.

Throughout the interviews, interviewees' responses were listened to and evaluated in order to probe effectively for more detailed information. With a background as a technologist in the context of mechanical engineering, completion of initial teacher education as a secondary technical teacher and current work as a technology teacher in a Year 7-13 secondary school, I brought relevant knowledge and understanding to the interview process with both the expert technologists and the technology teachers. This core of knowledge and understanding helped enable sense to be made of both the expert technologists' and the teachers' responses during the interviews and to probe some questions in more depth.

3.6 Data analysis

The analysis of both the expert technologists' data and the technology teachers' data occurred through the interpretivist subjective lens of the researcher. The researcher's task is to interpret the constructed subjective knowledge of the participants as clearly as possible to gain an understanding of their world and its contribution to the research questions.

3.6.1 Analysis of transcribed data

In qualitative research, the analysis of the data begins while it is still being collected. This initial or preliminary analysis, sometimes referred to as the informal analysis stage (Creswell, 2008), enables the researcher to use data gathered to inform and “illuminate” ongoing data collection (Merriam, 1998). Analysing data simultaneously with data collection enables the researcher to manage more effectively the large quantities of data that can occur in qualitative research.

Initial analysis of a semi-structured interview transcript can sometimes show that the guiding questions have failed to elicit enough pertinent information from the interviewee. By slightly altering the questioning technique and/or questions this problem may be addressed in any subsequent interview. Therefore, an early data analysis of each interview enables identification of aspects that could be probed in more depth to improve the interview process (Merriam, 1998). In spite of some modest adaptations, the initial guide questions for both the experts and teachers (Appendices A & B) were used for all of the interviews.

After each interview, the digital recording was checked before it was transcribed into text data. A professional transcriber transcribed the digitally recorded semi-structured interviews into text data. When each text data transcript was returned, the digital audio-taped interview was listened to again then an initial reading of the interview text transcript to obtain a “general sense” of the data collected from each interview (Creswell, 2003).

After an initial reading of the interview text, an important first stage in the analysis of qualitative data is to reduce and organise the large quantity of transcribed text data (Davidson & Tolich, 2003b). During this early stage of the analysis, each semi-structured interview text was read through several times to ensure the wholeness of the data was considered before breaking it into parts. Coding was then used to classify and identify key pieces or segments of text (Babbie, 2007; Creswell, 2008; Punch, 2005). At this stage of coding, tags or codes were allocated to particular pieces of text interpreted as relevant to the sub-questions guiding the research (Neuman, 2003). Related codes from the text were colour coded, which helped to begin the process of classifying the many different codes identified in the data. After re-reading the colour-coded pieces of text, they were classified further into themes or major ideas that related to the research questions (Creswell, 2008). At this stage, headings were assigned to these themes. Patterns were identified from the

semi-structured interview text data, and where applicable connecting themes established. The text data were revisited several times throughout the coding process. This “cycling” back and forward between data collection and analysis describes how in qualitative research both these processes may occur simultaneously (Creswell, 2008).

Memoing was used in the analysis process alongside the coding process to develop and identify concepts from the text (Punch, 2005). During the memoing process, the analysis moves to a more inductive phase by making notes about the text, reflecting and conceptualising about the codes developed from the text (Babbie, 2007; Neuman, 2003; Punch, 2005). Memoing brings together the researcher’s own perspectives and worldview; the information identified in the literature review; and reflection on the research questions guiding the research (Merriam, 1998). It supports the inductive processing of the data and the transition from general coding of data to the creation of themes identified and interpreted from the data (Merriam, 1998). In this thesis, once the coding and memoing were completed, identification began of the themes and general findings that could be linked to the research sub-questions and the overall research question. An example of coding and memoing used to interpret data in this thesis has been included (Appendix G).

3.6.2 Key words and phrases tabled

An additional tool utilised to analyse the transcribed data was identifying key words to support concepts or ideas interpreted from the data. Key words generated from text data analysis were tabled to provide evidence supporting a key idea or concept (see Section 6.4). For example, words and phrases generated from the five teacher participants’ text data analysis such as “questioned, attuned” were tabled as evidence of “awareness and curiosity” identified from the data analysis as a key characteristic of a successful novice student designer and problem solver (see Table 6.4, p. 176). These words and phrases have been underlined in each of the technology teachers’ quotations presented in Section 6.4.

Likewise, key phrases were tabled from analysis of several of the participants’ data within each group to indicate similarities and differences in understanding of concepts and ideas related to the research questions. For example, in Table 6.3, p. 175, a key point was tabled from the analysis of data summarising each technology teacher’s individual conception of design and problem solving. An example of one of these key points as presented in Table 6.3, p. 175 is: *Design requires some original input usually based on synthesising existing design ideas* (Andrew, TT, 1).

3.6.3 Learning theories as an analysis tool

The final stage in the data analysis includes an interpretivist discussion that summarises in detail the findings from the data analysis. The discussion of the analysis includes making critical comparisons with the literature and identifying how the data has informed the research sub-questions and the overall research question (Merriam, 1998). At this stage, the critical comparison of the data analysis with the literature indicated four learning theories based on experience could be utilised to provide another level of analysis of both the expert technologists' and the teachers' data. In particular, utilising four learning theories provided another level of analysis that related specifically to how and in what way learning occurs through experience and therefore could be used to identify the nature of learning to design and problem solve. The four learning theories used in this analysis were ELT, situated cognition theory, distributed cognition theory and activity theory.

In particular, three of these four learning theories (situated cognition theory, distributed cognition and activity theory) not only recognise learning through experiences but, also, the socially mediated nature of such learning. Therefore the social nature of both the technologists' situated learning experiences and the learning experiences that teachers provide for their students could also be identified. This analysis included utilising situated cognition theory, distributed cognition and activity theory to link the ways in which technologists learn both by experiences in context and through socially mediated experiences. Likewise, it is hoped that this analysis will explain and theorise teachers' pedagogical practice as the teachers recognise the social nature of both technology and technology education.

To develop these learning theories into theoretical analysis tools, the characteristics of each learning theory described in the literature review were bullet pointed into key points. The key bullet points of each of the four learning theories are presented at the beginning of each analysis section in Chapter 8. For example, in Section 8.2, the key bullet points of ELT are presented, then selected quotations recounting expert technologists' and technology teachers' experiences are analysed, utilising the key bullet points of ELT.

This process of analysis utilising key bullet points from each of the other three learning theories was repeated each time using different selections of the technologists' and the teachers' data relating to experiences (see Sections 8.3–8.5). The analysis utilising four learning theories based on learning through experience helped to inform one of the

research sub-questions and the overall research question. Specifically, it enabled the learning through the experiences described by the experts and the teachers to be analysed and later theorised including both the contextualised and social nature of this learning.

3.7 Trustworthiness

Qualitative research identifies “trustworthiness” as an alternative term to validity and reliability that enables more appropriately the quality of qualitative research to be assessed. In qualitative research, trustworthiness is about the reader being confident in the results because of the manner in which the research has been conducted and explained (Brenner, 2006; Merriam, 1998). Four key strategies and criteria that help to ensure the trustworthiness of qualitative research are: credibility; transferability; dependability; and confirmability (Bryman, 2004; Lincoln & Guba, 1985; Merriam, 1998).

3.7.1 Credibility

A key factor in establishing trustworthiness is ensuring credibility (Lincoln & Guba, 1985). Credibility provides an alternative in qualitative research to internal validity and is achieved by ensuring a research has been conducted according to “good practice” (Bryman, 2004; Merriam, 1998). In this research, good practice included making sure the semi-structured interviews were conducted in a manner that respected the research participants and that their responses were recorded accurately, transcribed and checked. This included using “member checks” on all transcribed interviews (Brenner, 2006; Bryman, 2004; Neuman, 2003; Punch, 2005). Member checks provide research participants with an opportunity to check the transcriptions of their interviews and thereby confirm that what they said was what they intended. At this stage, participants are able to request any changes or deletions to their interview transcripts.

A further use of member checks is to share outcomes of the analysis with some research participants to ensure the analysis of identified themes is shared with the participants and reflects the meanings they intended (Brenner, 2006; Merriam, 1998; Shenton, 2004). Early themes and outcomes identified from an analysis of two of the expert technologists’ data were shared with these same two expert technologist research participants via emails. Neither of these research participants disputed or requested changes to these outcomes resulting from this early sharing of data analysis.

Good practice also includes a comprehensive data analysis using coding and memoing to develop themes and concepts based directly on the transcribed text data of interviews (Silverman, 2003). The data analysis based on excerpts from the transcribed text data of both the experts and teachers is presented in Chapters 4–8 of this research thesis. Themes and concepts originating from the data analysis informed the findings and conclusions of this research and are presented in Chapters 9 and 10 (Bryman, 2004; Merriam, 1998). The findings and conclusions were discussed and critiqued with doctoral supervisors as they developed.

A final strategy used to enhance the credibility of qualitative research is establishing the researcher's credibility by presenting their theoretical perspective, worldview and knowledge background at the beginning of the research (Merriam, 1998; Shenton, 2004). The researcher's background was described early in the introduction chapter of this thesis (see Section 1.2, p. 1).

3.7.2 Transferability

Transferability is a further criterion of trustworthiness and relates to whether or not the findings and conclusions from a research can be transferred or generalised to other groups in society (Bryman, 2004; Merriam, 1998; Punch, 2005). In qualitative research, this is left to the reader who is dependent on the detail and quality of the research report to inform his/her decision. The rich or thick description in this thesis should enable readers to make their own decisions as to whether or not this research is transferable to other educational groups, contexts or settings. Thick or rich description includes a narrative and detailed description which often includes information about the research participants, their activities relevant to the research and the participants' own transcribed words used to support research findings and conclusions (Merriam, 1998; Shenton, 2004). Thick description is used extensively in the analysis and findings of this research that includes using participants' direct quotations to support how concepts and themes have been identified and interpreted from the actual data. Also, relevant information about the background of each of the research participants has been presented (see Section 4.2, p. 91 and Section 6.2, p. 154).

A further strategy supporting transferability is to use participants who represent some "typicality" of what is being researched (Merriam, 1998). By using expert technologists from three different domains within mechanical engineering and from five different

engineering workplaces, this research endeavoured to use participants who represented typical expert technologists. Likewise, by using technology teachers with various backgrounds from five New Zealand secondary schools, the teacher research participants were also representative of a typical group of secondary hard materials technology teachers.

3.7.3 Dependability

A third criterion of trustworthiness in qualitative research is dependability. Dependability parallels with reliability used to assess the quality of quantitative research (Sarantakos, 2005). Qualitative research, unlike quantitative research, is unlikely to produce the same data if repeated but still requires strategies to establish its dependability (Bryman, 2004). Therefore, qualitative research establishes dependability by creating an “audit trail” that presents the entire procedure of the research clearly recording and making the links between the data, the findings and the conclusion and implications (Merriam, 1998; Yin, 2003). This includes presenting the research design, how data were collected and reflecting on the inquiry mode chosen for the research (Shenton, 2004). The dependability of associated findings and the conclusions and implications then can be assessed with respect to the data obtained and analysed as presented in the research (Bryman, 2004; Merriam, 1998).

In this research, the data findings are presented (see Chapters 4–8), as is the discussion relating to the data findings (see Chapter 9), and the implications and significance of the data findings argued (see Chapter 10). A full account of the research procedure and design is presented including the way in which research participants were selected, the data were collected and justification made for the mode of inquiry (see Sections 3.2–3.5) that further uphold the dependability of the research. This includes a timeline of the research in Section 3.3 (see Table 3.1, p. 73).

Two research supervisors from the University of Auckland monitored this research throughout its duration. This monitoring included ongoing discussion and critiquing of the findings, conclusions and implications based on the analysed data. In the early stages, the research was monitored by two additional supervisors also from the University of Auckland.

3.7.4 Confirmability

A fourth criterion assessing trustworthiness is confirmability. Confirmability requires the researcher to conduct the research in an honest and unbiased way with concern that personal beliefs or theoretical positions do not *unduly* sway the research procedure, findings or conclusions of the research thesis (Shenton, 2004). However, Bryman (2004) acknowledges that complete objectivity is unachievable in social research. As this research uses an interpretivist mode of inquiry, it is important to present the researcher's worldview and background information in the initial stages of the research as these factors will inevitably have some impact on the interpretations made in this research (Sarantakos, 2005). In this research, the background and worldview of the researcher is presented in some detail in Section 1.2, p. 1.

3.8 Ethical considerations

Ethics approval was obtained for each of the two data collection phases of this research. The first phase of the research was approved by The University of Auckland Human Participants, Ethics Committee on 12 May 2010, reference number 2010/173. The second phase of the research was approved by The University of Auckland Human Participants, Ethics Committee on 4 April 2011, reference number 2011/122. Because social science humanities research involves collecting data from people and about people, ethical issues of any research are of particular importance (Punch, 2005). Every effort should be made to ensure participants are fully informed about issues and their rights respected at all times prior to, and throughout, the research process (Snook, 2003). Principal among these ethical issues is the relationship between the researcher and participants, particularly relevant in qualitative research (Merriam, 1998). In an interpretivist mode of inquiry, the participants put their good faith in the researcher representing them fairly and honestly. The ethical considerations in this research include authenticity, informed consent, anonymity and confidentiality, power relationships, honesty and truthfulness and researcher bias.

3.8.1 Authenticity

Authenticity is often linked to trustworthiness and focuses on whether the research has represented fairly the voices that exist in specific social settings (Bryman, 2004). In this research, authenticity was concerned with whether the two participant groups' voices had been truly represented in the analysis, findings and conclusions (Bryman, 2004; Neuman, 2003). In Section 3.4, p. 74, the participant selection process is explained indicating that

the research participants are representative of the two different groups, with relevant knowledge and/or experience required for this research. In this chapter, the methodology has clearly informed the reader of the procedures utilised to ensure that all participant voices have been represented truly and fairly in the analysis, findings and conclusions.

3.8.2 Informed consent

The two key considerations of informed consent include participants being fully and accurately informed about the research and voluntarily agreeing to participate in the research (Christians, 2000). Snook (2003) reminds us that practically it is not possible for research participants to be informed completely and fully about the research or they would know as much about the research as the researcher. However, informed consent ensures all participants are told in extensive detail about the overall research project and what they will be required to do should they agree to participate. In this research, several steps were put in place to ensure that all relevant parties were informed appropriately before signing their respective consent forms.

To recruit participants from the mechanical or product engineers' group of experts, the researcher emailed the chairperson of the Institution of Professional Engineers New Zealand (IPENZ), provided him with a copy of the chairperson of IPENZ Participant Information Sheet and Consent Form and asked his permission to approach members of IPENZ who met the purposive sampling criteria. In response to this email, the IPENZ chairperson signed the Consent Form that gave the researcher permission to advertise for research participants in the IPENZ newsletter. IPENZ members were invited to email the researcher directly if interested in being a research participant, in order to lessen any coercive pressures to participate in the research. As a result of this advertisement, the researcher was contacted by a professional mechanical engineer who provided his Curriculum Vitae profiling his background and current expertise. As he met the expert designers' and problem solvers' purposive criteria, he was provided with an expert designers and problem solvers Participant Information Sheet and Consent Form, which he signed and emailed back to the researcher, thereby agreeing to participate in the research.

Subsequently, contact was made either personally or by email with the four other expert designers and problem solvers who met the purposive sampling criteria for expert technologists and they were provided with an expert designers and problem solvers Participant Information Sheet (Appendix C) and Consent Form (Appendix D). This

enabled them to be fully informed and to freely consent to participate in this research should they wish to do so. Four expert designers and problem solvers who belonged to the two other mechanical engineering groups (certified trade-qualified and NZCE or Diploma qualified) agreed to participate in this research and signed and returned the expert designers and problem solvers Consent Form. Consequently, the expert designer and problem solver research participants included one professional engineer, three certified trade-qualified engineers, and one engineer with a NZCE qualification, all of whom had consented freely to participate in this research after they had been informed fully of the research details.

One means of recruiting the five technology teacher participants was to advertise in the Technology Education New Zealand (TENZ) monthly newsletter. In response to this advertisement, several email enquiries from technology teachers were received. However, access to research participants and sites often involves obtaining permission firstly from the so-called “legitimate gatekeepers” (Creswell, 2008; Seidman, 2006). The initial legitimate gatekeepers when recruiting school teachers as research participants are school principals of teachers’ respective schools. Therefore, to recruit the technology teacher participants, their respective school principals were contacted and provided with principals’ Participant Information Sheets which fully informed principals about the research, its purpose and the implications for their schools and their teachers. Each principal contacted signed a Consent Form granting site access to teachers in their respective schools. Site access enabled specific teachers at each of the respective schools to be invited to participate in the research including those who had made contact via the TENZ advertisement.

The five teacher research participants were all provided with teacher Participant Information Sheets (Appendix E) informing them about the research, the procedures and the time commitment of participating in the research. The teachers also had the opportunity to email the researcher regarding any further information they might require about the research. Both steps insured that all teacher participants had been informed properly and fully about the research before consenting to participate in it. Teacher participants were asked to email or post their signed Consent Form (Appendix F) back to ensure that participants had consented freely and voluntarily to participate after being informed fully about the research.

All participants were informed fully of the purpose of the research through their respective Participant Information Sheets. Representative samples of the Participant Information Sheets (Appendices C & E) and Consent Forms (Appendices D & F) are included to show the way participants were approached and consented. By informing the participants fully about the purpose of the research, they were kept informed honestly and truthfully so that the intentions of the research remained transparent (Snook, 2003).

3.8.3 Anonymity and confidentiality

Anonymity ensures that information provided by the participants should not be able to reveal their individual identity. Teacher participants and their respective schools' privacy were preserved throughout this research. Likewise, the workplaces and projects of the expert designers and problem solvers were not referred to by name in this research. To maintain anonymity, pseudonyms were assigned wherever the participants have been referred to or quoted (Neuman, 2003).

Confidentiality ensures that whoever participated in the research does not have their identity publicly disclosed. The transcriber signed a confidentiality agreement which helps to maintain participants' confidentiality. All participants were informed of this confidentiality agreement in their respective Participant Information Sheets (Appendices C & E). In this research, there was no necessity to refer to research participants' specific schools, individual workplaces or their localities. In other words, all identifying details of research participants have been removed.

The research participants' school types, background notes and occupations have been described in the data analysis chapters (see Section 4.2, p. 91 and Section 6.2, p. 154). Any school or workplace connection remained anonymous and confidential.

3.8.4 Power relationships

To recruit the teachers for this research, it was necessary to contact their respective principals (as gatekeepers) and provide them with a principal Participant Information Sheet to explain the research and the ethical issues pertaining to the research for their respective schools and their potential teacher research participants. The ethical issues relating to power relationships included the assurance that the employment status of teachers within their respective schools would not be affected in any way whether or not teachers chose to

participate in this research. As there were no gatekeepers for the expert technologists, the ethical aspect of employment status was not relevant for these research participants.

A further ethical issue for both groups of participants relating to power relationships was the risk that participants might feel coerced into or obliged to consent to participate in this research (Snook, 2003). To address this issue, participants were asked to email or post their signed Consent Forms to ensure they freely made their own decisions whether or not to participate in this research.

Inevitably, there is a possibility that research participants may feel anxious that they might say things that could be misinterpreted during the digitally recorded interviews. To address this concern, all research participants were emailed a transcription of their interview, with an invitation to delete or make changes to any part of the transcription. All research participants were informed in their respective Participant Information Sheets (Appendices C & E) that they could ask that the digital recorder be switched off at any time during their interviews. Likewise, all participants were informed of their right to withdraw their information from this research up until the time of data analysis. None of the ten research participants withdrew any of their data information provided through the semi-structured interviews.

Verification of the transcribed interviews was sought from each of the research participants by emailing their transcribed interview data to them. The full transcript of their respective interviews enabled participants to check that the transcript was a true and accurate record. All ten participants verified the transcripts as an accurate and true record via email before analysis of the data began.

3.8.5 Researcher bias

When using an interpretivist mode of inquiry in qualitative research, the researcher makes decisions as to what information and data to collect from research participants. Data that is collected is later “filtered” through the interpretivist eyes of the researcher when analysed and presented as part of the findings that inform the conclusions and implications of the research (Merriam, 1998). It is crucial that researchers are conscious of the possibility of their own biases infiltrating the research process and particularly which parts of the research process may be affected by this bias. However, as Sarantakos (2005) points out, in interpretivist research, including personal views in interpretations is often desirable as well as acceptable.

A key concern relating to bias is if the researcher develops interview questions that support their preconceived understandings (Yin, 2003). To minimise this problem, the semi-structured interview guide questions for both technology teachers and expert designers and problem solvers (Appendices A & B) were critiqued carefully in this research by doctoral supervisors and peer reviewed by fellow doctoral students. This helped to ensure that the interviewees could set their own agenda and were not led to agree with any of the researcher's own preconceived notions.

When probing questions to elicit more in-depth data, the interviewer may still create bias or emphasis (Cohen et al., 2007). During the interview process, there was continuous awareness of the possibility of bias and efforts made to ensure that any probing related to participants' responses rather than preconceptions about the research. Likewise, in selecting data and illustrative quotations to include in this thesis, every endeavour was made to ensure these represented what was intended by the participants (Cohen et al., 2007).

3.9 Summary

This research was conducted through an interpretivist mode of inquiry, a social constructionism ontology and social constructivist epistemology. Given the exploratory nature of the research topic and questions, plus the choice of an interpretivist mode of inquiry, a qualitative methodology was chosen as the most appropriate way to conduct this research. In interpretivist and qualitative research, it is important that researchers are aware that their interpretations of data will be influenced by their own ideas, which have been shaped by the range of factors that they bring to the research (Creswell, 2003). Therefore, the overall research design, the data collecting process and analysis, including the ethical issues associated with this research, have been described in detail in this chapter. This detail helps to ensure that this research project is as authentic and trustworthy as possible given that the research data has been collected and analysed through the interpretivist lens of the researcher.

Chapter 4: Data Findings: Expert Technologists

4.1 Introduction

This research phase comprised interviews with five expert technologists who currently design with hard materials. These five research participants design within the context of mechanical engineering. The sub-research question guiding this component of research is:

In what ways do expert technologists consider experiences with hard materials developed their expertise (knowledge and understanding) to design and problem solve with hard materials?

In Section 4.2, the background and detail about the five research participants in this research phase is provided. In Sections 4.3–4.8, the analysis of the experiences that the expert technologists recognise as contributing to their becoming expert technologists is considered, and how these experiences contribute to their current role as designers with hard materials. These sections include the technologists' informal learning experiences (Section 4.4), experiences developing their knowledge and understanding of materials (Section 4.5), experiences of processes that develop practical understanding (Section 4.6), experiences that provide feedback on effectiveness of design (Section 4.7) and learning through direct sharing of others' experiences (Section 4.8). In Section 4.9, the key points are summarised from the analysis of the five expert technologists' data.

4.2 Five expert technologists

The term “engineer” in New Zealand is a loose term used to define different categories of people associated with engineering. In this thesis, the term engineer is defined in three ways. In the first category, the term engineer defines someone who has completed an engineering degree at a university or accredited poly-technical institute to become registered as a certified engineer. In the second category is someone who has completed a NZCE. An NZCE qualification requires a combination of theoretical and practical work experience with more emphasis on theoretical study than an engineering trade apprenticeship model has. The third category of engineer defines someone with an engineering-related trade apprenticeship background. The five expert technologists interviewed in this research phase met the sampling criteria identified in Section 3.4.1 and each belonged to one of these three identified engineer categories. The intention was to

select expert technologists representing as broad a cross-section of mechanical engineering as possible.

In this research, one participant belongs to the first category of engineer and one has an NZCE qualification and belongs to the second category of engineer. Both these participants have had practical experiences with hard materials during their pathways to becoming expert designers and problem solvers. However, their training and current roles require them to design and problem solve primarily using engineering calculation and engineering drawing on a solid works 3-dimensional “modeler” type computer programme. In other words, they are not currently involved in the “hands-on” manufacture of their designed products.

The other three participants became expert via the pathway of a New Zealand trade apprenticeship and belong to the third category of engineers. This pathway requires a person to work practically for a period of time (8,000 to 9,000 hours over a period of 4 to 5 years), learning a trade alongside a qualified experienced tradesperson or technologist. Such an apprenticeship focuses on working in authentic situations and learning through work experience. It is invariably accompanied by some theoretical part-time studies that support the practical learning but its key component is work experience. The apprenticeship for these three participants included sitting end-of-year examinations several times during their apprenticeship.

In Sections 4.2.1–4.2.5, the five expert technologists, George, James, John, Brian and Peter describe their backgrounds and current roles as expert technologists by identifying their particular areas of expertise within the overarching context of hard materials and mechanical engineering. Because of their various technological backgrounds and expertise, their design expertise with hard materials varies considerably. This research phase provided an opportunity for the five participants to consider in what way the role of experiences with hard materials had contributed to their current expertise and practice.

4.2.1 George, Expert Technologist 1 (ET, 1)

George (ET, 1) is a marine engineering designer and belongs to the second category of engineers having an NZCE qualification. His work involves overseeing the mechanical and structural designing of a vessel from a customer’s design brief through to having it accepted into a marine class by a classification society such as Lloyds. Most vessels he has designed are less than 60 metres long.

We're mechanical engineers primarily in the marine field. So we would ... take a design brief from a customer on vessels usually under 60 metres and we are capable of doing ... all the mechanical and structural design for a whole ship (George, ET, 1).

The vessels are designed from the initial concept right through to a drawing and a “cut file” that provides technical details such as sizes, how to bolt pieces together and the required tolerances that enable each of the pieces of the vessel to be machined and manufactured.

We work right down to the machine cutting code that you press the button and the machine starts cutting the steel ... we provide a drawing ... we'd call that a cut file, so from the concept right through to working out all of the sizes and how to bolt it down, the tolerances and the rest of it (George, ET, 1).

George started his engineering career as a mechanical engineering cadet which, at times, required him to study and work simultaneously. He had spent significant portions of his early years in a drawing office making plans for different components. Later in his career he worked at a shipyard. He has the qualification NZCE in mechanical engineering.

I started originally... then it was called the Ministry of Works and did an [engineering] cadetship with them for about two years ... [then] I went down the road to the engineering company and started in a drawing office ... and finished my NZCE working in [name supplied] engineering where I stayed for 14 years before I came ... to the shipyard (George, ET, 1).

Currently, George is also involved in overseeing the designing of modifications to existing vessels. In his design work, mostly he uses different grades of steel including various grades of stainless steel and the specific marine grades of aluminium.

4.2.2 James, Expert Technologist 2 (ET, 2)

James (ET, 2) is a certified mechanical engineer who belongs to the first category of engineers identified in Section 4.2. He describes himself as a machine designer. When deciding on a career, James carried out an aptitude test which identified engineering as a suitable career choice to pursue.

Why did I become an engineer? I didn't know what I wanted to do ... I finished up seeing a career analyst ... who put you through a series of aptitude tests. ... The career analysis service ... said the technical side, engineering was probably a good career choice and so from there ... I did a diploma in technology and then a Bachelor's in mechanical engineering, a Masters and a research project in machine design and off I went into the world doing engineering (James, ET, 2).

James has adapted his engineering design skills to various working environments in different countries. He has designed laser chambers, tea harvesters, and bulk bagging machinery. James works mostly with metals, plastics, technical ceramics and some elastomers.

The work I've done in the past has mostly been structural and machine design. I'm a mechanical engineer. That's a fairly broad definition of what I do. ... I've designed electrodes for light sources, I've designed tea harvesters ... fire engines, laser chambers, so I call myself a machine designer... I'm currently designing bulk bagging machinery (James, ET, 2).

When describing himself, James said that as an engineer he looked at the world through the lens of an engineer.

It's everything I see and everything I do you sort of live it really (James, ET, 2).

As a result of his university training, qualification and engineering experience, James is a certified professional engineer.

4.2.3 John, Expert Technologist 3 (ET, 3)

John (ET, 3) belongs to the third category of engineers (see Section 4.2) and has a trade apprenticeship qualification. He completed an adult apprenticeship as a boilermaker in the late 1960s.

How I got to all of this is I started as an adult apprenticeship. In fact as a boilermaker. ... probably late 60s, and it was with a big [work] shop in Auckland (John, ET, 3).

As a qualified tradesperson he worked on the construction of hydro-power schemes which involved working on a wide range of engineering fabrication (making of parts) tasks that often provided John with an opportunity to design and then make a jig (a type of fixture often used to secure specific workpieces) to make a job easier.

I finished the apprenticeship and went and worked for ... with the power scheme [name supplied]. ... We had a big fabrication shop ... you got a range of things to do and it was always a bit of a challenge for me to sort of try and think outside the square ... so I used to make little jigs and things to make stuff easier (John, ET, 3).

He later started his own engineering business specialising in aluminium fabrication. This business was a jobbing-type workshop where he ended up designing all sorts of

engineering “bits and pieces”. In addition, he developed and maintained specialist equipment for people with disabilities.

Currently he has merged his business with a larger engineering company and refocused his work within the “niche market” that is centred on equipment for people with disabilities. His work involves using stainless steel, aluminium and mild steel. John designs and makes one-off parts that provide solutions to specific engineering problems associated with specialist equipment for people with disabilities.

4.2.4 Brian, Expert Technologist 4 (ET, 4)

Brian (ET, 4) belongs to the third category of engineers identified (see Section 4.2) and he has a trade apprenticeship qualification. He is the director and owner of an engineering company that was started by his father and uncle 60 years ago. He completed a technical course at secondary school before taking up an apprenticeship. He remembers having to make a choice at the end of his first secondary school year between taking either a metalwork or woodwork technical course.

At the end of the third form I had a terrible choice to make. I had to choose between metalwork and woodwork. I loved working with wood ... [it] was the material I had worked with mostly at home. ... I did enjoy metalwork as well and my father had an engineering business so metalwork ... was the choice (Brian, ET, 4).

His current work involves managing people but he still gets into the workshop to help sort out “trickier” engineering jobs. He did an apprenticeship as a fitter and turner and has a New Zealand Trade Certificate then graduated to machine shop foreman. Later he purchased the engineering business where he had done his apprenticeship.

After leaving school I completed an apprenticeship in fitting, turning and machining and gained a Trade Certificate. I graduated to machine shop foreman ... and later purchased the business ... I’m [currently] the director and owner of the engineering company my father and uncle started (Brian, ET, 4).

His engineering business is a jobbing workshop which involves designing solutions in many instances to one-off engineering problems. Brian works mostly with mild steel in the general engineering work in which he is engaged.

As a general engineering workshop we work with a wide range of materials. ... Most of our work is done using mild steel which is a relatively soft version of steel.

... we don't get involved with heat treating, preferring to send it to people with the correct equipment to carry out this process (Brian, ET, 4).

4.2.5 Peter, Expert Technologist 5 (ET, 5)

Peter (ET, 5) belongs to the third category of engineers (see Section 4.2) and has a trade apprenticeship qualification. He completed an apprenticeship as a boilermaker and welder in the 1980s with a company that specialises in heavy engineering construction in the petrochemical and marine and ship repair industries. Peter is currently the general manager of the same company, following a period working overseas in engineering-related industries.

I started my apprenticeship here. ... I came down here and asked and got [an apprenticeship] as a boilermaker. ... I didn't even know what a boilermaker welder was. ... Dad said get a trade and then you've got something to fall back on so that's pretty much how I started. ... I just went through the apprenticeship side of things (Peter, ET, 5).

Peter's company has trained several hundred apprentices and actively supports the promotion of personnel who have trained on the workshop floor as tradespeople. This training has developed into roles associated with overseeing designing and problem solving within the company. His company builds (fabricates) large heavy steel structures that include "difficult one-off" projects.

We're probably what you'd call a heavy specialist fabrication workshop, we do structures but we also do one-offs that are difficult (Peter, ET, 5).

Peter's current role involves identifying and solving problems with engineers in the initial design phase of a project. He designs solutions to problems associated with the manufacture, transportation and installation of very large engineering structures. Peter referred to this as the "buildability" of a project such as a railway bridge which he describes.

For me it's about buildability ... How am I going to make this [bridge] moving it the least amount as I can and to be competitive in the market... how are we going to transport it. ... That [railway bridge] is 36 metres long, that weighs 40 tonne. ... Once we get it there how do we get it into position? (Peter, ET, 5).

Peter's focus is on designing solutions to the problems associated with the practical aspects of a project which he described above.

All five expert technologists' past and current work is in the area of mechanical engineering which requires them to work with hard materials. Collectively, the five expert technologists have over 170 years of experience in the context of mechanical engineering working primarily with hard materials.

4.3 Becoming expert

A key focus of this chapter is to find out in what ways the expert technologists consider experiences with hard materials developed their expertise in designing and problem solving with hard materials. The relevance of finding out about these experts' experiences is to find the potential for enriching technology education pedagogy and learning through experience. In response to the experts' interview questions (Appendix A), these five expert technologists identified the experiences with hard materials that had contributed to their learning and expertise. In the following analysis of the expert technologists' data, five over-riding themes were identified that are associated with the experiences that built these technologists' expertise. The five overarching themes and subthemes identified from the analysis of the expert technologists' data about experiences developing their expertise are presented in Sections 4.4–4.8.

4.4 Informal learning experiences

The five expert technologists' informal learning experiences with hard materials included experiences that were separate from their structured formal learning experiences. All five technologists' initial informal learning experiences occurred during their childhood and teenage years prior to their taking up their formal study or training (Sections 4.4.1–4.4.6). James and Peter also identified how, as experts, they analyse informally the designed products of others in the world around them, particularly when hard materials are used (Section 4.4.7).

4.4.1 Early experiential learning with hard materials

The five technologists described many early experiences that enabled them to play around with hard materials to produce some purposefully designed objects. Their experiences involved pulling things apart, fixing things, building things, and using tools. As well, some of the experts tried to identify personal qualities that they felt may have initiated or sustained their interest in these early activities with hard materials.

4.4.2 Pulling things apart to find out how they work

George remembered when he was given a clock.

I pulled it to pieces to find out how it worked (George, ET, 1).

Likewise, John and James remembered wanting to find out how things worked as children and by pulling things apart, they were able to see how others' designed outcomes worked.

I always [pulled things apart] ever since I was a kid. Wondered how it worked ... starting to pull things apart when you're a kid is probably not a bad place to start (John, ET, 3).

I was the sort of kid who took things apart and chopped up my bicycle and played around with motorcycles when I was a teenager (James, ET, 2).

4.4.3 Fixing things

Peter remembered as a child wanting to fix things when they broke. This required pulling the item apart to discover how it was made and to consider why it was made that way. Peter wasn't sure why he could fix things but he could.

Once it did break I could fix it and I don't know why that is. ... I wouldn't call it a gift ... You methodically pull it apart that's broken, okay so what does that do and go from there (Peter, ET, 5).

4.4.4 Building things

By the time James was ready to commence his engineering studies, he had already built a car and had "played around" or tinkered with mechanical items as a child and teenager. James felt that to do this he must have had a mechanical ability which he identified as "mechanical aptitude and inclination".

I had built my own car ... and so I suppose I had this mechanical aptitude, this inclination I suppose you'd call it (James, ET, 2).

John described having an inquiring mind that initiated interest in mechanical objects.

I suppose you've got to have that inquiring mind to start with (John, ET, 3).

George also recalled wanting to build things, and this sometimes included testing the final product to check its effectiveness in-situ.

I built a water wheel when I was about fourteen ... and took it down the creek ... always made something (George, ET, 1).

Like James and George, Peter recalled building things and pulling motorbike engines apart which had derived from his interest in motocross as a teenager.

Mechanical stuff ... that was always a passion pulling motors apart and building things ... I liked motorbikes (Peter, ET, 5).

4.4.5 Learning to use tools

Brian described his first experience with hard materials as mucking about in his father's shed where he was introduced to working with tools. The tools provided him with his initial experiences of learning to manipulate, change and eventually being able to make things using hard materials. Learning to work with tools provided him with an initial skill that later enabled him to design and make his own artefacts using hard materials.

My path where I started was mucking about in my dad's shed. It was here that I gained a passion for working with tools. ... Christmas or birthdays, tools were often the presents given. ... When I got to intermediate school and tech classes teachers, who were all ex-tradesmen, showed me how to sharpen and care for tools ... they also showed me how to use tools correctly (Brian, ET, 4).

4.4.6 Imagining how an object could be made

Brian also recalled in his teenage years imagining how particular artefacts would be made, and the processes involved that produce them.

I can remember before I ever went to work I would look at an article to try and imagine how it would be made and the process. I still do that (Brian, ET, 4).

These five expert technologists' early experiences enabled them to think about how things were made. Such experiences contributed to their learning about materials as they made things, used tools and discovered how designed products worked. All five expert technologists considered these informal, yet real, experiences with hard materials had been both an initiator and influential to their becoming experts.

4.4.7 Informal experiential learning from designed world

James considered that engineering designers found out about materials in many instances by "looking around" at what other people had done. This informal "looking around" includes looking at how things are made and the materials from which they are made.

You get knowledge of how materials are used from all over the place ... everything I see I look at as an engineer. Any piece of machinery or structure I always pay close attention. I'm the guy that stops and looks at the hinges on the aircraft when I'm getting on board and looks at the conveyor on the baggage line. ... When I look under the bonnet of a car or I walk around somebody else's factory ... I almost certainly have a keener eye than a non-engineer for what they're doing how they're doing it what they're using and what some of the nuances are (James, ET, 2).

Likewise, Peter observed that he obtained ideas informally from looking at the world around him. This occurs whenever he comes across objects made of steel. His engineering focus is often associated with access, that is, getting large designed objects moved into their final working situation. When he “looks around”, he often asks questions associated with how other experts have managed to get people to do jobs in difficult situations.

No matter, wherever I walk as soon as I see a little bit of steel I'm always looking around it. ... You just look at things ... all the time ... how did they get up there to do that (Peter, ET, 5).

The informal experiences, described by James and Peter, that is, looking at design in their everyday world, has been identified as a “developed engineer’s gaze” and “practical intuition” (Sorensen & Levold, 1992, p. 20). An engineer’s gaze concerns a compulsive drive that engineers have that engages them with objects in their environment as they try to find out how and why the objects are designed and made that way.

4.5 Experiences develop knowledge and understanding of materials

Experience that develops knowledge and understanding of materials was an overarching theme identified in these technologists’ data. It appears that this knowledge and understanding of materials helps these experts to select the most suitable material to use in their own designing and problem solving. In this section, the experiences with materials identified by the five experts as developing their knowledge and understanding have been further categorised under six sub-themes; laboratory testing of materials (Section 4.5.1), working experiences using materials in-situ (Section 4.5.2), learning about materials through “hands-on” experiences (Section 4.5.4), developing a “feel” through practical experiences of how to use material in design (Section 4.5.4), seeing materials fail (Section 4.5.5), awareness of materials in specific environments (Section 4.5.6) and choosing and using materials with suitable mechanical properties (Section 4.5.7).

The following quotations from the experts’ data provide a general view of the importance of knowing and understanding about materials in engineering design.

James described the overall critical importance of material selection and understanding about materials in engineering design. He emphasised the importance of knowing the physical and mechanical properties of materials so the most suitable materials are selected to do the job required of them. The wrong material choice can impact significantly on a design outcome.

Material selection is critically important to engineering. You've got to understand what you're dealing with, what the machine or structure is doing, the environment it's doing it in. You've got to understand the physical and mechanical properties of materials... select the wrong materials and the design won't work ... every day and everything I do that comes into play (James, ET, 2).

George also identified how knowledge about hard materials is an important part of designing with these hard materials.

To make [a design] practical you have to know about what you're using [materials] or the materials you intend to use (George, ET, 1).

Therefore, the following Sections 4.5–4.8 present experiences described by the expert technologists that helped them develop their knowledge and understanding of materials that enables them to design with hard materials.

4.5.1 Laboratory testing of materials

In this section, George explained how visual sensory experiences through laboratory exploration of materials contributed to his knowledge and understanding of materials including how materials behave under certain conditions.

George recalled when he was a cadet engineer seeing a steel rod put into a machine in a mechanics laboratory to test it for tensile strength. Tensile strength is the force required to pull a length of steel rod apart and break it. This experience provided George with a visual experience of what can happen to a steel rod when a pulling force is applied to it. The steel rod stretches (deforms), reduces in diameter and eventually snaps apart. George identified how a visual sensory experience was more informative about the limitations of steel in tension than just checking the “numbers” (calculations for tensile strength from a textbook).

When you put [a steel rod] in a testing machine ... break a piece of steel and pull it apart ... see how it stretches and the rest of it, it all starts there because a visual

thing is far better than numbers. ... The greatest thing for an engineer is being able to smash something (George, ET, 1).

George also recalled how he learnt about steel and what happens when it is heated. In a metrology laboratory, he viewed test pieces of welded metal through a microscope that allowed him to observe the molecular changes after steel had been heated during welding procedures. George was able to view through the microscope how heating steel to high temperatures changes its internal molecular structure resulting in a change to its properties, such as strength and hardness. Although the properties of steel after such heat treatment change significantly, the physical appearance of a material such as steel may indicate very little change.

You couldn't design anything without the knowledge of how steel is made and how steel behaves when it's heated up and how to weld it. ... I spent probably five years writing weld procedures in a construction shop I worked in. Because we were building pressure vessels ... I not only wrote the weld procedures, supervised the welding [but] then had test pieces made, cut them and took them up to the lab because we had a metrology lab ... polished them myself and then peered at them with microscopes and ... said we're on the right track (George, ET, 1).

In this section, George explained how sensory experiences testing hard materials in laboratories contributed to his deepening knowledge and understanding of materials.

4.5.2 Working experiences using/seeing materials in-situ

Experiencing the effective use of materials, in-situ, contributed to these expert technologists learning about the effective use of materials. This included seeing how materials were used effectively in different design applications.

James reiterated how the selection of the most suitable material in engineering is a key factor of an effective design.

If you create the geometry for the design and then select the wrong materials ... the design won't work (James, ET, 2).

James described how past design experiences enabled him to transfer his knowledge and understanding and effectively use materials in various other contexts and applications.

Everything you do and everything you learn, it's available for you to use as experience so you get better at it [design] because your experience base is broader. ... You've seen good and bad things and you have a better idea of what works and what doesn't work. I get better at this [designing] as time goes by... If you're

designing a conveyor you would understand ... that there are certain ways of building a roller and you use certain types of bearings and certain types of belt materials and certain folded shapes for the structure of the thing ... those are things you learn along the way (James, ET, 2).

Brian identified that over a working lifetime, he had developed his knowledge of materials through many different experiences.

The greater the knowledge across a wide range of materials the better for design and problem solving.... My knowledge of hard materials has been collected over a working lifetime and over this time one gets to know what will work and what won't. I don't believe I could have learned it all from a book. There really is no substitute for experience and experiencing the real thing (Brian, ET, 4).

George suggested it was a culmination of past experiences with materials that had influenced the rules about how materials today are used in marine design.

In marine work as the ocean is a different shape everyday ... it's very hard to determine the loads for something that's got to last thirty years at sea. ... The rules basically reflect two hundred years of sinkings (George, ET, 1).

While James identified picking up knowledge about the use of materials from books, he also acknowledged picking it up from seeing what others had done—a kind of “osmosis”, as he described below:

Well you see what other people do, you pick some [knowledge of how to use materials] up from osmosis. You pick some of it up from books (James, ET, 2).

The implication from this is that a designer picks up some knowledge about how other designers have used materials effectively. In doing so, they utilise that knowledge in other related applications.

In this section, the technologists identified how experiences using materials, and seeing how others effectively used materials in situated design applications, built their knowledge and understanding of materials and how they are used in design.

4.5.3 Learning about materials through “hands-on” experiences

These expert technologists acknowledged how working “hands-on” with the material develops a deeper understanding of it, and builds knowledge about the material. They believe that working with the material, then seeing how the material performs to do a specific job, are critically important.

It's working with the material, hands-on is a vast thing and seeing the end results, seeing how it performs on the job, hugely important I think ... I don't think from a tradesman point of view that there's a replacement for that [practical experience] (John, ET, 3).

John provided an example where understanding of a material developed from directly working with it.

You know rolling a plate or bending a beam or a pipe ... or heating something. ... You start understanding [the material] by working with it (John, ET, 3).

A practical “hands-on” experience, combined with theoretical descriptive knowledge, provided an effective combination and opportunity to support the expert technologists’ learning to understand materials. They noted how theory can reinforce and explain the behaviour of materials observed from direct experiences. Therefore a combination of theory and practical experiences is important in developing knowledge and understanding of materials.

For example, Brian described how an apprentice’s experience with high carbon steel provided an opportunity to reinforce some theoretical descriptive knowledge about that same material. He noted that theory explained what the apprentices had discovered through a “hands-on” experience.

You see the [apprentices] go and do something with [high carbon steel] when they don't understand and the thing then breaks and they don't know why. I'm able to go and say yeah okay but you went and quenched it in the trough [of water] after you finished doing the welding and you've made it [go] hard and brittle (Brian, ET, 4).

This experience provided the apprentices with an example of how particular types of steel have a tendency to harden and go brittle if quenched in water after being heated to high temperatures (during a welding process). A “hands-on” experience with a material, followed up by theory about why the material (steel) changed, helped to develop knowledge, understanding and learning about this material. This also reinforced what George said he had experienced when viewing steel through a microscope after it had been welded at high temperatures (see Section 4.5.1).

Reflecting on his time as an apprentice, John described first learning theory about materials (metallurgy), such as white cast iron that was later reinforced through a practical experience welding the material.

You've got to understand the composition of materials really ... down at the micro structure of things, and that used to be taught to us as apprentices. ... How brittle white cast iron might be, don't even attempt to put a [welding] arc on it. ... that came through from the metallurgy stuff [theory] and then proven and experienced (John, ET, 3).

Reflecting on his school years, Brian also recalled first learning the theory about heat treating steels and what it does to the steel, then putting the theory into practice by making a tool that required heat treating it to make it function effectively.

As far as heat treating steels go, I learnt it at school. We learnt it in theory and then we had to go and make a cold chisel (Brian, ET, 4).

Brian was referring to cold chisels made of steel that have to be heat treated (hardened) after they have been made to function effectively. If this is not done, the cold chisel steel blade will mushroom and flatten out with the impact and force of a hammer blow. Hardening it makes the steel much harder and resistant to any applied force. The combination of theoretical learning about materials and then seeing how materials could be changed in practice provided a powerful way to learn for John and Brian.

In this section, the technologists identified how hands-on experiences with materials helped to develop their knowledge and understanding of materials. This included working with materials on various jobs, and reinforcing theoretical knowledge about materials through practical hands-on experiences with materials. Likewise, a practical experience with material sometimes triggered the learning of the theoretical explanation behind the experience. That is, a change in a material could sometimes be explained using theoretical knowledge.

4.5.4 Developing a “feel” through practical experiences of how to use materials in design

The expert technologists identified developing a “feel” for the dimensions of materials (for example, thickness of materials), the types of material, and how they could be used in various design situations. Their “feel” for materials developed as a result of their own accumulated experiences of making things with materials and seeing how materials had been used in various practical applications. This “feel”, knowledge and understanding of materials results in designers sometimes just “knowing” which materials, and the dimensions of materials, that should be used in certain design situations.

John and Peter described how this knowledge and understanding developed from practical hands-on experience with materials.

It's a feel thing really I think, just an experience thing ... that experience starts when you do an apprenticeship with the [material]. ... [knowledge about materials] is intuitive you would expect to learn that in 10 years. It would take 10 years hands-on (John, ET, 3).

If I was building something for me, just say a trailer or a gate or something like that you'd be able to say yeah I need to put a gusset in there, I need to put a brace in there ... that just comes from practical work (Peter, ET, 5).

Peter also recalled how a lack of experience with materials resulting in limited knowledge of materials can result in something being built from the wrong type or grade of material for a particular job. With experience, the correct type of high strength steel is likely to have been the “intuitive” choice in this following situation where the wrong grade of steel was used and the material failed.

I had a guy who made some [steel] bracing up for me with some just 20 millimetre [steel] rod bar and it bent, I said did you use Grade 8.8 or 4.6 and he said 4.6. He didn't understand that they needed to be of a really high strength [8.8 Grade]. He just thought it was alright ... but that comes from experience. He was only a young fellow (Peter, ET, 5).

It was through many previous welding experiences with steel that Peter developed his understanding about this material. Currently, he can anticipate confidently the likely problems, such as “heat shrink” (steel changing shape and distorting due to high temperatures when welded), when a large structure requires welding.

I'll sit down with [a client] and they'll be concerned about the heat shrink and all that sort of stuff ... so yeah you do get an understanding what the material is going to do most of the time. But once again that comes from being a tradesman and learning [on the job] (Peter, ET, 5).

Peter's experiences of working directly with hard materials helped him to employ effective methods to design with these materials. His past experiences as a welder provides him with information about what happens to different materials such as mild steel, or stainless steel plate, during welding procedures. Through these experiences, he knows how to design to compensate and prevent these things happening to the material and impacting negatively on design outcomes.

Peter described various methods to address the problems of heat shrink that he has learnt through experience working with materials such as mild steel and stainless steel.

Welding is probably a classic example ... I think over the years with experience, if you put a bigger fillet [weld] in ... too heavy it will kink the [steel] plate up more ... or you know you can off-set it or put another plate on the back to take the heat shrink out so it doesn't move ... stainless steel it takes the heat more and distorts it a lot more (Peter, ET, 5).

Brian recalled how an engineer had calculated the thickness (specification) of stainless steel for a job and how it was much thicker than he “felt” was necessary. His knowledge and understanding, from his many years of experience working with a similar material (in various contexts), informed him that 8mm thick stainless steel was unnecessary.

The engineer was going to make this thing out of 8 [millimetre] stainless steel and that was going to be the specification ... he would sit down for hours and calculate it ... you don't need to go that thick. He had no 'feel' for the material (Brian, ET, 4).

This situation indicates how Brian's experience enabled him to recognise how unnecessarily “overdesigned” the object was using a specification of 8mm thick stainless steel. Overdesigning is necessary in some design situations and results in an artefact being made extra strong for its specific safe function. However, in many design situations, overdesigning is undesirable, and can result in an artefact costing more in materials and sometimes labour and processing costs. In Brian's example, he was able to use his intuitive knowledge of materials and design to suggest how materials could be used more cost effectively without compromising the safe function of the design.

James commented how he is able to draw on his past experience as an engineer, and now does fewer calculations for the simple stuff such as which diameter bolt or bearing size to use in a specific application.

As I get older and have more experience I do fewer and fewer calculations. I used to find myself calculating what size bolt I would need ... I'd go through all the load ratings and these days I just look at it and I know ... you end up using your experience (James, ET, 2).

In other words, James is able to use his intuitive knowledge and understanding built from years of experience for some of the detail in his design solutions.

He described how as an experienced designer he also had developed “a feeling for the scale of things”, types of materials to use, the size of materials and some of the mechanical detail to use, such as the most suitable bearing. Again, James commented that drawing on previous experiences that he had seen and had done allowed him to make quick decisions about design details.

You get a feeling for the scale of things. If you're designing something you try to draw on experience, similar things that you've seen before or done before and that really shortens the time it takes because you can make some snap decisions on some of the design details, what materials, what sizes, what fasteners, what bearings (James, ET, 2).

Through experiences with hard materials these expert technologists developed a “feel”, knowledge and understanding of the way materials should be used in new design and problem-solving applications.

As Peter noted, just by looking at something sometimes, he knows it doesn't “look right” so he changes it.

You know what works and what doesn't and sometimes you'll put something in there ... and think to yourself it doesn't quite look big enough, doesn't look right, so you'll go out and put something else in there (Peter, ET, 5).

In this section, the expert technologists discussed developing a “feel”, knowledge and understanding of the type, size and dimensions of materials, and components such as bolts and bearings, to use in a design. This knowledge and understanding developed through their many and varied experiences working and using materials in various design applications.

4.5.5 Seeing materials fail

In this section, these expert technologists identified the significance of experiencing hard materials fail in various applications. Seeing materials fail enabled them to develop their knowledge and understanding of hard materials. In some of the following examples, the material failed because of design faults. However, the experts believed that the experience of seeing materials fail, whether it was the result of either poor design or the wrong choice of material, enabled them to learn more about the materials themselves.

Observing unintentional failure of materials had provided George and James with some of their most influential learning experiences. In some situations, a poor design contributed to

the failure of the material. The interface of poor design and unsuitable material is often apparent when designed outcomes fail. However, it was seeing the materials fail that provided the technologists with lasting knowledge and understanding of the limitations of materials and the destructive consequences that result. Seeing how the materials behaved when objects and structures unintentionally had failed impacted inevitably on their future designing.

George and James recounted experiences where their own designs had failed. George related the day he watched the materials in a barge he had been involved in designing, bend and break up on a sand bar.

One of the most instructive days I ever spent. I managed to swim around it [the barge] and look at all the pieces that were breaking and bending. It taught me more about engineering and about how big structures work than I could ever conceive ... in books you see a few photographs of a disaster and you apply the maths to make the structure strong enough [and] you look at all these little details that we got wrong. [It] passed the rules, got a certificate ... but we changed our design methods in that office from that day on (George, ET, 1).

James also described failed outcomes as “lessons you remember”. He noted the importance of learning about material and design failure through these practical experiences. He observed how these experiences became embedded in long-term memory.

Failures are the ones that teach you the lessons that you remember best. It crystallises your thoughts. ... I think reading about something and learning by doing it are different. You can read about something and forget it fairly quickly. If you've done it, it seems to be better lodged in your memory (James, ET, 2).

He related one failed outcome using aluminium as being a “good lesson” for him as the designer.

I once designed a pre-tensioning anchorage that wasn't strong enough and it was supposed to take 170 tonnes and when they put 150 tonnes on it, it went bang and took a wall out. ... It had to be as light as possible ... was fatigue [stress] driven, damage tolerant design in minimum weight so it had to be as light as possible ... aluminium is quite difficult to design for fatigue [stress]. ... I'd overlooked a detail in the middle of it that was weakening it and nobody caught it (James, ET, 2).

John, Peter and Brian also recalled seeing materials fail in particular design applications. They had not designed these failed outcomes but had experienced them first-hand. After

they reflected on why this occurred and what had caused the failure, they were able to develop their knowledge and understanding of design.

John recalled a sensory experience of a major failure with a pressurised water vessel built of mild steel plate.

I remember we were pressure testing a couple of big vessels ... there was a one ended thing with a domed end on one end filled up with water and because it was a test thing, there wasn't a dome for the other end so the people in the [work]shop decided that a flat plate of a heavier nature would do but it really doesn't, just because of the geometry of the thing, the surface is just hugely different when applied to a dome or a flat ... I remember the surveyor walking around tapping away with his hammer when the thing was full of water and then it split and he just about got washed out the door because it was a catastrophic failure under test. ... Somebody hadn't really addressed the engineering dome against the flat. If the dome is 10mm, you can't use a 20mm [flat steel] plate (John, ET, 3).

This was a design fault that resulted in material failure. For a successful solution, it required an understanding of design principles combined with the use of suitable materials.

Peter recalled an incident where a particular stainless steel was chosen to replace carbon steel with a brick lining and its subsequent failure as a suitable material choice for the particular application. Peter recalled how his previous experiences with materials were telling him, almost intuitively, that something, as he put it, didn't "feel right" when he was using stainless steel on this job.

We used a special type of stainless steel that was designed [overseas] ... the material cost close to half a million dollars ... the old stuff we pulled down was just carbon steel with a brick lining. ... I kept saying to them something doesn't feel right. ... When they heated it up ... it started cracking so it expanded too much ... then we had a really big downpour of rain ... all of a sudden it started to crumple ... They were trying something different and it didn't work (Peter, ET, 5).

Brian's work often involves adapting the design of objects that have broken and failed. These design adaptations are developed to ensure that failure of the object will not recur. Brian remarked how trying to find out why an object broke is important. The design solution sometimes requires changing to a stronger piece of material or changing the design.

When things go wrong you've got to start figuring out why ... you don't necessarily find that out in a classroom. Usually what arrives at our place is broken. You've got to try and understand why it broke and then you've got half a chance of being

able to change the design of it ... it's usually when things don't work out there's a lesson to be learned (Brian, ET, 4).

In this section, the technologists acknowledged the impact of experiencing the failure of materials provided knowledge about the limitations of materials that influenced these experts' future designs and their ability to problem solve. It required them to think about the reason and theoretical background underpinning the failure and how to use and design more effectively with the materials. At other times, it required them to consider whether the material choice had impacted on the failure, the design had caused the material to fail or whether the failure might be a combination of both material choice and poor design.

4.5.6 Awareness of materials in specific environments

Environmental conditions provide a key determinant of material choice. Specific environmental conditions require a designer to make suitable choices of materials. These experts asserted that for successful design, experiencing and seeing materials used in specific environments contributed valuable knowledge and understanding about materials and raised their awareness of this design aspect.

If you've got a situation where a material is going to get hot and it's in an atmosphere [in which] it would oxidise you then have to think about what material choices you can make there to mitigate that ... you end up with an understanding of the detailed properties of quite a lot of different materials as time goes by (James, ET, 2).

In marine design, there are many different grades of aluminium that are designated by numbers. Each grade has different alloying elements, resulting in slightly different mechanical properties suited to a wide range of applications. The 6 000 series (grades) of aluminium use alloys of silicon and magnesium to obtain specific mechanical properties in aluminium that are desirable for marine engineering. George noted that these were the grades most suited for design in a marine environment.

[In marine design] aluminium ... the 6 000 series would be the main series which is where the marine grades sit (George, ET, 1).

Knowledge of finishing processes is likewise an important factor when considering materials in particular environments. James explained how relevant the environment is when choosing materials in design.

If you've put up a mild steel structure down by the beach you'd better put a protective coating on it or it's not going to last very long. However, if it's ... inside a building ... it doesn't really matter. It's doing the same thing holding something up in the air but the environment is so different that you have to take account of that in a design (James, ET, 2).

Peter identified how currently he is using a specific material that takes into account environmental issues when using steel in a bridge structure. The *weathering steel*, a new innovation in New Zealand, has nickel added to it, which enables a protective film to develop on the steel bridge structure.

This is quite new for [name supplied] ... it's called weathering steel so it's got a high nickel content so it rusts but it puts a film on it and they don't need to paint it ... Then there's coastal weathering steel so [this steel] is better than the other close to the coast (Peter, ET, 5).

Brian noted that theoretically stainless steel might seem an ideal material to make a water jacket to heat hot water in a wood burner. For example, stainless steel is a water resistant form of steel. However, he recalled, in practice, seeing stainless steel fail because of other factors in the environment where it was used. Brian commented how a lack of knowledge about the use of materials in particular environments can result in material and subsequent design failure.

In this example, described by Brian, the designer used stainless steel to satisfy the requirement of a water resistant material. However, the designer did not consider other environmental factors that reacted adversely against the material choice of stainless steel.

Someone designed and built this [water heater jacket] from stainless steel. At first one might think yes ideal material. It won't go rusty but it is notoriously bad at transferring heat, work hardens rapidly. It arrived in our workshop to get cracks repaired. The cracks were in the area where the water jacket didn't cover and it had got red hot and absorbed carbon from the soot and the fire. It would allow you to weld it but the weld pull [shrinkage] just opened up an even bigger crack just next to the old one and the more you welded the worse the [cracks] got ... stainless steel shouldn't be used in that position ... when things go wrong you've got to start figuring out why (Brian, ET, 4).

In this particular case, the failure of the material relates to the heat treatment of this type of stainless steel when it comes into direct contact with a flame. This inadvertent heat treatment of the stainless steel impacted on the material by changing its composition and mechanical properties. Some theoretical knowledge of materials enabled Brian to

understand and learn from this experience. He also learnt there is often more than one factor to consider when choosing materials to use in particular environments.

John described the importance of understanding the limited durability of aluminium in certain conditions or environments. He explained how aluminium may have quite a different life expectancy from steel and this needs to be shared with the stakeholder. He learnt this from his many years' designing with and fabricating aluminium in his own engineering company.

There's the durability of aluminium [it] is a different [material] ... because ... in certain conditions ... things that work harden and become contaminated and fail so the customer has also got to understand that [aluminium] is not like steel. The finished product might look the same as a steel job but the expected life isn't anywhere the same (John, ET, 3).

From his experiences, he learnt that although aluminium is water resistant, it can react to certain contaminants within an environment, work harden, become brittle and result in the material failing.

In this section, the expert technologists recounted how their experiences taught them about the impact the environment can have on materials and design. In some situations, the expert technologists had experienced design failure as a result of the impact of an environment on materials. They had also accumulated many practical experiences using materials in different environments that contributed to their current design knowledge. This included an understanding of the detailed properties of materials suitable for specific environments. That is, they learnt to use the right materials in their designs to satisfy different environmental operating conditions.

4.5.7 Choosing and using materials with suitable mechanical properties

Crucial to a successful design is the choice of a suitable material with the appropriate mechanical properties. The mechanical properties of materials determine such things as the types of stresses and loads the material will endure in a particular application or design. Each material reacts differently to physical force and has a particular set of mechanical properties. As a result of their experiences, these expert technologists had seen certain materials used successfully in specific applications and this enabled them to understand the importance of choosing a suitable material with adequate mechanical properties. For example, specific types of steel with certain mechanical properties are used for shafts. To

take high loading, the shaft also may be heat treated. Knowledge of what the machine or structure is going to do and, therefore, the types of forces and stresses applicable are also factors that determine the choice of material with suitable mechanical properties.

James recognised the importance of knowing the specific operating conditions (forces and stresses) that a material would encounter when designing. For example:

One is it going to be repeatedly bent, is fatigue [stress] an issue, do you need strength? (James, ET, 2)

While mechanical properties of materials can be sourced through books, George and James both agreed that the experience of seeing things made over a period of time built a knowledge base that supplemented theoretical information about materials. Their experiences informed them about the use of effective materials with suitable mechanical properties for different applications.

Well you can read a book ... we still look up its [the material's mechanical] properties and we still check its stresses ... but it's much better to have seen the physical thing built (George, ET, 1).

Certain types of materials crop up time and time again and specific alloys within the aluminium family ... certain bronzes and brasses and certain types of steel you use, particular types of steel for shafts and different types of steel for shafts and different types of steel for structures (James, ET, 2).

Using different materials requires an understanding of the mechanical properties of these materials and how material properties can change after exposure to high temperatures during procedures such as welding. Much of this understanding comes through the experience of using different materials. When using aluminium in place of steel, the designer must acknowledge the differences in these materials, as George explained:

The grades of aluminium we use have the same yield strength as steel but are a third the weight... when we've welded them the yield stresses are lower than steel. ... If we were to convert a boat from aluminium we'd wind up with about half the mass in the hull, not a third, because ... you have to... make aluminium thicker ... to get the same equal strength as steel (George, ET, 1).

Brian described how in his work, he uses materials with slightly different compositions and mechanical properties for different applications and why these choices are necessary. He has acquired this knowledge through his experiences seeing these materials used successfully in specific applications.

Cold drawn mild steel shaft, we use for machining mild steel components. It has a higher sulphur content to assist its machinability (Brian, ET, 4).

Brian further illustrated his knowledge of materials' mechanical properties when he identified the requirement for products such as bolts and shafts. Strength is a fundamental requirement in this application and so material with extra strength is the optimum choice.

High tensile shaft is used for making bolts and shafts that require extra strength that is tough and strong, [this is] machinable but with care, weldable but with care on preheating and cooling rates (Brian, ET, 4).

Knowledge of hardening processes and their different effects on the mechanical properties of materials is important knowledge. James explained how heat treatment carried out in a specific way makes steel much "harder" at various depths below its surface, which is desirable, or even essential in certain applications.

Whether [steel] is 'through hardened' or it's just hardened to a certain depth you might choose a different steel ... heat treatments, the process they use and the time they do it for, it makes a big difference... heat treatments are really more for mechanical properties ... you would heat treat shaft material to get a certain strength (James, ET, 2).

As James identified, the hardening of steel has many variations depending on how hard you require the steel to be for its particular function. His knowledge of heat treatments developed through seeing, using and experiencing heat treatments in a range of designed products.

Peter noted that he has "a rough idea", from his hard material experiences, of the grades of steel that are suitable for an ordinary beam construction. He knows that choosing a different grade would provide a slightly "harder" steel for the same application.

Like ordinary carbon steel, Grade 250 you've got a rough idea that will be alright there for an ordinary beam or does it have to be 350 [grade] which is a little bit harder, so you do learn (Peter, ET, 5).

In this section, these expert technologists' experiences of seeing and using various materials with different mechanical properties had developed their knowledge and understanding of the properties of many different materials and how they are used in different design applications. This enabled them to choose suitable materials to address design issues such as stresses, forces and loading of these materials. These experts

acknowledged the importance of choosing the materials with the most suitable mechanical properties to produce an effective design with hard materials.

4.6 Experiencing processes develops practical understanding

In Section 4.6, these five expert technologists identified the importance of knowing about manufacturing processes. Specifically in Section 4.6.1, the experts' data identify why they require this knowledge to design functioning products. In Section 4.6.2, the experts' data identify how knowledge of processes is acquired. In Section 4.6.3, the importance of realising designs is presented.

4.6.1 Why designers need knowledge of processes

These experts described why knowledge and understanding about available processes to build products is necessary for designers and problem solvers. To design a product that functions, it is necessary for a designer to have knowledge and understanding of available manufacturing processes. These experts had to know about, and to address, the practicalities and problems associated with the manufacture or making of a designed object.

George could not conceive how anyone could design something if they did not have knowledge of how it would be built. He noted that this knowledge is not something you just acquire; it develops over a period of time.

How can you design something unless you know about it?... How do you design something if you don't know how it's built? ... I can't see how you could actually just acquire the knowledge without knowing (George, ET, 1).

Brian described what occurs when there is no knowledge of processes when designing.

Without this knowledge [of processes] you will have no idea what size of material is required and what problems are going to occur later in the life of whatever you are designing. You will also have little appreciation for the difficulties likely to be encountered during manufacture. This is why architects and engineers design things which won't work or can't be built (Brian, ET, 4).

Peter described how designing something requires thinking and knowledge about the processes and the practical understanding of the making and building of an object or artefact. It is not just about designing something to look good.

You've got to think I can make that, that will look good but how do I get a bolt in there or how do I weld in there ... how am I going to weld in there if that's already on there, how do we do that? (Peter, ET, 5).

James identified the importance of understanding, at a hands-on level, how something he designs can be built. This includes thinking about the tools used and how components, such as springs, can be fitted into the assembly.

It's got to be built. [If] there's no practical understanding of that then you're going to find you're in trouble. ... You've got to think about how it's going to be put together. How do you get your spanner on that screw? How do you fit that spring? (James, ET, 2).

Effective design requires knowledge of a range of different specific manufacturing processes that convert a design concept into a realised outcome. In the real design world, not all processes that exist are available necessarily to every designer or in every workshop.

Brian explained how often he has to adapt a design to those processes that are available in a particular workshop, and that he has to constrain his design to what is available.

In part of your design process you need to take into consideration what processes you have available. It's all very well to say you can form a car door out of a piece of panel steel. Well you can in a car factory but we don't have a car factory with the right moulds and stuff like that so you have to make it the best way you can with what you've got (Brian, ET, 4).

In this section, the technologists argued the importance of knowing about manufacturing processes when designing with hard materials. The practical understanding of available processes is a component of being able to design successfully with hard materials. The experts recognised that design also required knowledge and understanding of the practical aspects of how objects are built and constructed using available processes.

4.6.2 Learning experiences develop knowledge of processes

These experts discussed their experiences with hard materials that developed their knowledge of the practicalities of manufacturing and the available processes that are used to manufacture their designs into realised outcomes. These experiences accrued over time. During their initial 4 or 5 year training as apprentices, and later, during their time as qualified tradespeople, Peter and John had direct experiences of manufactured outcomes and processes. George also had access and exposure to production and manufacturing

processes during his pathway to becoming expert. As a result of their experiences, these experts developed a knowledge and understanding of available processes and the practicalities that must be taken into consideration to manufacture a designed outcome.

Peter learnt about manufacturing and production processes, particularly welding processes, from his practical experiences during his apprenticeship and as a tradesperson engineer. This continued as he learnt about the technical heavy processes required to get the things he built (the structures), into place when he went out on-site. Experiencing the technical heavy processes included learning how to utilise cranes to get big structures into their final functioning position on-site.

I did focus on ... the welding and the speciality welding, stainless steel, chrome all that sort of stuff ... once I'd spent a lot of time in the workshop, we ... got a lot of time out on-site and that's where I think you get your practical grounding from. ... It's a bit like number eight wire sort of thing where you can't get a crane in there so how are we going to do this and thinking outside the square (Peter, ET, 5).

Today, in his role as general manager of his company, he employs these skills to oversee what he refers to as the “buildability” of designed projects. This includes working out the manufacturing processes and the practicalities of transporting and installing very large and, often, very heavy structures. Buildability requires the knowledge and understanding of a range of specific processes that enable a design to be built, transported and put in-situ.

One example of some of the problems Peter has to consider relate to the practicalities of building and getting a heavy bridge structure to its final functioning position. He described some of the practical aspects of this project, the buildability, where each aspect requires a specific process to get the bridge in-situ.

When they [engineers] are designing we're helping them with the buildability. ... if you can fabricate [build] it really nice and neatly and don't have to move it, [there is] less chance of doing any damage to it because it's so heavy ... then how are we going to transport it ... then once we get it there how do we get it in position. ... without too much disruption (Peter, ET, 5).

Consequently, Peter is able to draw on a working lifetime's experiences with hard materials when considering the design and the practicalities of this bridge project's buildability.

John explained how he started off working with and welding mild steel as a boilermaker, but later in his own business most of the fabrication work was “geared towards working

with aluminium”. Mild steel and aluminium require quite different welding processes. Modern welding technologies have solved the problems, the “nightmare” that used to be associated with the process of welding aluminium.

I guess as a boilermaker we started out working with mild steel. That’s ... the basic nuts and bolts of everything ... my own business which was geared towards aluminium fabrication; the rules change a bit just because of the different type of material. ... when I did my apprenticeship, aluminium was a very different material to weld. ... Once upon a time it was just a nightmare. ... Now it’s not ... the solid technology in welding equipment has really solved that (John, ET, 3).

John’s knowledge of welding mild steel and aluminium welding procedures resulted from his practical experiences as a boilermaker tradesperson and later in his own business where he focused on aluminium fabrication.

Peter summarised the role of experiencing practical processing and manufacturing during an apprenticeship.

And it just comes to experience, it really does. I can take a first year apprentice out there and say make something and he’d have no idea. But if I said the same thing to him in three years’ time, I’d expect him to know that (Peter, ET, 5).

He believed that after experiencing processing hard materials, an apprentice should have the knowledge and understanding to be able to make something from hard materials. He stated that the practicality of making designed objects is developed from experiencing and building up knowledge of available processes.

George did his early training with an engineering company that exposed him to different processes associated with the manufacture of designed products. He spent short periods of time in various engineering workshop.

Of course [I had practical experiences] there were two city blocks of workshops, foundries, construction shop and pattern shops and the rest of it that I spent time in ... along the way I learnt to weld and play with lathes and play with machine tools (George, ET, 1).

This practical experience enabled him to design in a drawing office using hard materials. He described, for example, designing a gear in the drawing office.

You had to know all of the processes to actually be able to work in the drawing office ... In the kind of training I did you made a drawing and then you ... wrote the

materials sheet ... you saw the project right from beginning to end so that you soon found out what was practical and what wasn't (George, ET, 1).

George described how seeing the design project from the beginning to the end helped him to understand how practical his designs were in terms of manufacturing.

For example, he described the complexity of the drawings to make the gear, and also the necessity of having knowledge of the various production techniques, which in this case included foundry casting, machining, heat treatment and gear cutting.

This gear here for instance would have two drawings ... there would be a casting drawing which was done for the foundry and then there'd be the preliminary machine drawing. ... the heat treatment and then the final gear cutting ... It's impossible to draw [a design] ... unless you know the capacity and the production techniques of the machine that cuts the gears (George, ET, 1).

This selection illustrates that knowledge of the various practical processes, including the type of heat treatment required for the steel, was necessary so that these could be included in the design drawings to enable a design to be manufactured successfully.

In this section, the experts identified the importance for designers of knowing about processes. Without this knowledge, they considered that designers cannot produce realised outcomes of their designs. The experts described how they had experienced various manufacturing processes over many years and how they utilised this knowledge when designing.

4.6.3 Effective designs need to be realised

Currently, James designs on a computer programme. Consequently, he can dream up and draw just about anything in three dimensions on his *solid modelers* computer programme. However as a designer, James is aware of the practicalities of whether or not something he designs actually can be made with the processes and tool capabilities available.

As you get into your design you've learnt from past experience that tools have got certain capabilities and you can't just make anything you can dream up and make with solid modelers [computer programme]. You've got to be able to make it and then if it's an assembly you've got to be able to put it together (James, ET, 2).

As George summed up, in the world of designing with hard materials, the designed object is limited by the practicalities of making it.

Well you can live in Pandora but at the end of the day if you want to be able to sell something out of this office it has to be practical (George, ET, 1).

In Sections 4.6.1–4.6.3, the expert technologists identified experiencing different material production and manufacturing processes. As a result of their experiences, they had knowledge and understanding about suitable and available processes that they could use to ensure their designs could become realised products.

4.7 Experiences provide feedback on effectiveness of design

The following Section 4.7.1 presents the way in which the expert technologists identified the value of feedback on their designs after their designs have been produced into realised outcomes. In particular, the feedback is rich when they are able to see the designed outcome and to see how effectively it solves a problem and/or how well it functions. Through reflection and analysis, they are able to use this feedback to inform their future designing and problem solving. In Section 4.7.2, the experts acknowledged receiving valuable feedback about their design ideas through accessing others' experiences with hard materials. In Section 4.7.3, George described using rules and precedents set up by a community of practice from the collective experiences of its members. These rules and precedents enable marine designers to submit vessels to marine classes.

4.7.1 Seeing design outcomes provides feedback on design

James and George explained how designing something, getting it made and seeing it implemented and functioning in its final situation provides feedback that is important to them as designers. Graduate engineers straight from a university often find themselves designing solely on computers in a design office. They do not necessarily get the opportunity of this valuable direct feedback through seeing the production process or the actual designed outcome realised and functioning in-situ. Engineering design offices are quite likely to be remote from where the designs are manufactured. For New Zealand designers, the manufacturing country is quite likely to be China.

We've said we don't want manufacturing in New Zealand, we'll make China the workshop so basically we're saying to engineers you'd better go overseas and see something. We've got so few workshops left [in New Zealand] (George, ET, 1).

George described this as a problem for the young graduate engineers joining his company. It is quite unlike how he learnt to design as a young engineering cadet or when he worked in a shipyard.

They [graduate engineers] have to just go and see things being constructed and stand and watch other people work. It's not as easy for them as it was for me because that was just outside my door. ... A shipyard exposes you to all those things ... I never left the [ship]yard at night unless it was very late without walking around to see what had happened (George, ET, 1).

Now this activity was more difficult for George as he did most of his designing on computers. His designing occurred in remote locations from where his designs were manufactured or produced.

You need feedback in our business...being consultants you don't get it [feedback] instantly whereas if you're on the [work]shop floor or you've just done a plan and dragged it out there and somebody can't build it you soon know straight away, or you stand there watching and say: 'God that was a struggle; we'll never do that again' (George, ET, 1).

Like George, James also had designed in remote situations where his designs were made elsewhere then tested in another country.

I didn't like that ... [you] only got to find out what happened when things went wrong really. Hey that broke you did a bad job is all you heard. If everything went well you never even saw the things (James, ET, 2).

James described how important he considered it was to see his designed products made and working.

I think it's critical, absolutely critical because that closes the loop for you, that validates your ideas. If you don't know how well it worked, you don't really know whether it was a great idea or not ... I think it's critically relevant. If you don't see how well something you designed worked you really don't know how good a job you did (James, ET, 2).

James recalled working in a research and design laboratory where he had been involved directly in generating new technologies associated with laser designs. When the designing, building and testing of the resulting prototypes were "right", then they were handed onto an engineering department. There, the lasers were developed into a realised product that was used to make computer chips. These products would sometimes require further modification and could be returned quickly to the designers. Later on in the process, James saw his product put into a production line. He commented that to work successfully it had to be reliable as the cost of bringing a production line down was very high. If it happened to be his machine, he was provided with instant feedback!

James found being directly involved in this whole design “loop” extremely valuable for himself as a designer although he was not involved in the hands-on making of the final realised product.

Absolutely you have to have the whole loop to understand whether or not your ideas are good. Building it, testing it, being involved in it, breaking it, fixing it, making it better is all part of the process (James, ET, 2).

This feedback from the design “loop” enabled him, as a designer, to understand the success, or not, of a design idea.

Experiencing and, in some cases, seeing realised outcomes of newly designed or modified objects provided important feedback for the experts. When the outcome was successful, it validated their design ideas.

Brian described how he uses a design idea and then that object is taken away and used elsewhere. It is useful if he can find out whether or not the design idea has been a success. Again, it is about feeding back that “design loop” (acknowledged earlier by James), the success of an outcome validating a design idea. Often Brian gets this feedback by asking a customer directly. If this is not possible, he tends to receive feedback only on failed design outcomes which is also valuable for a designer.

You do something you're not sure really whether that was going to be the correct way to do it so the next time you see [the customer and ask], hey it worked? And he says yeah, no problem so then you know you can use that idea again. ... In our business they bring something into our shop and we fix it and it goes away ... you hear about the bad ones that don't work (Brian, ET, 4).

Going out on-site enables a designer to experience and solve the problems associated with installing a realised outcome. Peter developed the skills that he uses today through making something from the beginning, then going out installing it and getting it to work in its final destination. Being able to experience a successful job from start to finish provided him with positive feedback.

I liked making things from scratch. I didn't like to just make that part there and it goes off to somebody else. I like to make the whole thing. ... It's not easy sometimes ... you've got to get a crane in there and how are we going to do this and thinking outside the square ... I've always liked that challenge ... Once it's all finished and you see it going, I get a lot of pride out of that (Peter, ET, 5).

John also identified the value of seeing a realised outcome installed on-site and reflecting on the designed product's effectiveness, and how this feedback informed him and enabled him to improve future designs.

It's absolutely valuable [to see an outcome at the site] and this is why guys that work at our trade should go out to the sites as well ... it's important that you go and put it in because yeah maybe I got that completely right or maybe I could have [designed] that better and next time you will do it better (John, ET, 3).

In this section, the expert technologists considered the importance of receiving feedback on their realised designs. This included seeing them in-situ for themselves, or finding out directly from other stakeholders how a designed product's realised outcome functioned effectively and/or solved a problem. This feedback informs their future designing and problem solving as it validates successful and good design ideas that they can apply in future design problems. Feedback from unsuccessful design ideas also informs their future designing and problem solving.

4.7.2 Obtaining feedback by tapping into others' experiences of hard materials

The expert technologists acknowledged how they use others' experiences with hard materials to expand and support their learning to design and problem solve. This includes tapping into the various communities of practice associated with engineering expertise and obtaining the community's feedback on their designs and components of their designs.

James described how much he learnt from talking to machinists and communicating with people who make his designs. He recognised that these machinists understand the constraints of processes in a very real hands-on way. James is informed through this feedback tapping into the machinists' experiences of what can be made, and indirectly how to reduce the manufacturing costs.

Going on the [work]shop floor you ask what was it like to make that part and the guy said you know if you give me an extra ten thou [sandths of an inch] I wouldn't break my tools so often. So I can do that ... If you'd had a five minute conversation with a machinist you could have cut the price of the thing in half (James, ET, 2).

James also recalled, in the following extract, how much he had learned through feedback from a particular machinist who had many years of practical experience making parts. James paid this machinist regular visits to discuss his design concepts and find out ideas of how his design could be modified to allow them to be manufactured more effectively.

The owner of the company ... knew everything about making parts and so I used to go up with my [design] concepts ... and show him what I was trying to do and he would say to me well you can't make it quite like that but if you did this it would be better, so yeah talking to old men ... who've spent their lives ... making things was really good feedback and it taught me a lot (James, ET, 2).

Another way James recalled of tapping into the expertise of tradespeople with years of experience working in a specific environment is to share a screen dump of a design model and to ask for their feedback. Indirectly, he is learning about design and problem solving through experiences with hard materials.

Tradesmen who've been there twenty to thirty years... I take my models, do a screen dump, show them the picture and ask them questions about it as a matter of course because very often they'll say no don't do that. We did that twenty years ago and it seems alright on paper but it isn't going to work, for whatever reason (James, ET, 2).

George explained how he shares his years of experience designing and problem solving with hard materials. George has over 40 years of engineering and design experience in mechanical engineering industries to draw on when he shares his knowledge and feeds back information to his young graduate engineers.

First of all they've [graduate engineers] got to know where to start and which direction to go in. University teaches them the maths and the physics and how to operate the [computer] programmes ... I try and explain what's happened in the past and why. ... I try to say before we did this and it broke or whatever and this is the right way, this is the best way (George, ET, 1).

In this section, James shared examples of how he taps into others' experiences with hard materials through communication and social interaction. This enables him to share others' knowledge obtained through their various experiences with hard materials and to utilise this learning in his own designing and problem solving. In a similar way, George described how he shares his previous engineering experiences to provide feedback to young engineers who have limited practical experience of designing and problem solving so they are able to utilise his experiences in their work as designers and problem solvers.

4.7.3 New design develops out of previous experiences

George uses rules and precedents when he designs vessels to be submitted to a specified marine class for classification by marine classification societies such as Lloyds. Specific compliance constraints exist for each marine class and by using this already prescribed

information from this CoP, George is provided with a set of constraints, within which it is safe and practical to design.

In this way, George accesses others' prior design and problem-solving knowledge, expertise and feedback in order to develop and support his own designs. He is using the knowledge and understanding of previous marine designers to help to ensure he designs a safe boat for the duration of its service.

We would normally design something that had been done before, in effect and ... would be relatively easy for classification societies like Lloyds ... to actually say yes we'll accept this vessel into a class and which then would automatically mean it would be able to be registered by a flag state ... so we would have a massive amount of rules and precedents set before we start off [designing] (George, ET, 1).

The use of rules and precedents provides him with information that largely eliminates the role of trial and error design. George explained why this route is not a viable option for marine designers.

We're going to do it right so we're conservative and sometimes we've overdesigned because we're only allowed to do it once ... we don't get a second chance. ... Everything has to happen independently and has to be driven away from the wharf. We can't have trial and error (George, ET, 1).

George's years of experiences at a shipyard and his later years designing vessels and their components have also contributed to his ability to comply with these constraints in his designs (see Section 4.2.1).

James described how engineering design often builds on the feedback of what others have already done. In other words, seeing then building and synthesising others' ideas and designs with your own are ways in which new design develops.

Plagiarism is a really great tool in engineering design. If somebody has already done it why re-invent the wheel if you see a better design than yours then use it. That's how the human race develops designs to a degree. You build on what other people have done before (James, ET, 2).

In this section, George and James described building on others' experience, knowledge and feedback about design. They acknowledged how they utilise previous design ideas, including prescribed rules and constraints, as a kind of scaffold on which to build their new designs. This eliminated the problem for them of having to start from scratch with each

new design. That is, they used the feedback of others' successful designs to develop and input into their own new designs.

4.8 Learning through direct sharing of others' experiences

Section 4.8 describes how the experts learnt from working alongside and directly accessing others' knowledge and understanding from their past experiences with hard materials. In Section 4.8.1, learning through the apprenticeship model is examined where a tradesperson's knowledge is passed onto apprentices by working alongside them in an actual situated workplace environment. This apprenticeship model links to learning through hands-on and situated experiences with materials.

4.8.1 Apprenticeship model of learning: sharing others' experiences builds own experience

Brian, John and Peter experienced the apprenticeship model on their pathway to become tradespeople and expert technologists. All three had learnt by physically working alongside qualified and expert technologists. Throughout their apprenticeships, they tapped into others' knowledge, past experiences and learning, including the tradespeople they worked alongside.

Brian described the early learning stages of apprenticeship. He commented on the learning through the sharing of another's expertise (knowledge and previous experiences), as the tradesperson works alongside an apprentice.

You've got to either work alongside someone who knows because most things you don't figure out yourself. You learn them from someone else. ... That's what apprenticeship is about. ... working alongside and for a start you've got the apprentice here and you're doing the job and he's thinking ahead of you passing you the correct tools to do the job ... then it gets to the point where, well I'm too busy but you saw me do it last week so you have a go, see if you can do it and he gets halfway through it and then runs aground so you go and help him out and so that's how he learns. ... A lot of these guys ... have to learn it from actually seeing it happen (Brian, ET, 4).

John described the apprenticeship model as follows:

It's about people learning stuff as they go and being able to pass it on (John, ET, 3).

Peter remembered starting as an apprentice when he was shown the basic skill of how to correctly and effectively sharpen a drill.

You learnt how to sharpen a drill right through to sand blasting and painting. You learnt the whole nine yards (Peter, ET, 5).

Brian described how his early learning experiences were supported by tradespeople and those working around him. It was also supported by theoretical knowledge provided by tutors through various channels. These people shared their experiences with Brian, enabling him to gain confidence and learn through his own experiences.

When you start you really don't have much idea but as you learn from theory and from other trades [people] and test in practice, you slowly gain in confidence. When I started work, I gained knowledge from those working around me and from the tutors on block courses and the theory [that] was learned by correspondence. You get to a certain level and then you are to some extent able to teach yourself as you learn from experience (Brian, ET, 4).

An apprentice's practical work enabled learning and knowledge to develop. Brian also noted that confidence through practical experiences was an important attribute developed in apprenticeship that enabled apprentices to continue learning through experiences.

If [apprentices] don't have the practical expertise they will never be confident at what they do and the sooner they acquire the knowledge the more work they can do. ... Eventually [apprentices] will pick the practical up because they do practical work but the sooner they acquire the knowledge ... the more work they can do. ... There's no substitute for experience and the more knowledge you have the better the job you can do (Brian, ET, 4).

In this section, learning through the apprenticeship model acknowledged the role of practical experience in situated workplaces guided by expert tradespeople developing confidence and enabling independence in apprentices. Practical experiences through apprenticeship also develops the knowledge and understanding that contributed to three of the expert technologists initial learning to design and problem solve with hard materials.

4.9 Summary

In this chapter, the analysis of the expert technologists' data has identified the ways in which these experts consider experiences with hard materials helped build their current expertise as designers and problem solvers. The analysis provides information on the experiences they consider contributed to building their knowledge and understanding.

The analysis of the data first acknowledges the experts' informal childhood experiential learning with hard materials. The expert technologists all considered this was a contributing factor in their initial learning. Also, they recognised informal learning as observing how others' design in their everyday experiences of the designed world. As engineers, they acknowledged looking constantly at and questioning how and why objects are designed in specific ways. This contributes to their ongoing and informal learning as designers and problem solvers.

The second key point that this analysis chapter has presented is the importance that these technologists placed on their experiences with materials that developed their knowledge and understanding of materials. The experts stated the everyday importance of choosing the most suitable materials when designing with hard materials. They described how crucial to successful design it is to know about the many different aspects of hard materials relevant in engineering design. The experts discussed the many sensory experiences they had that they believe were pertinent in building their knowledge and understanding of materials. These experiences included laboratory testing materials, using materials to design, hands-on use of materials, repeatedly seeing materials used in-situ in various design applications, seeing materials fail, using materials in different environmental conditions, and experiencing the use of materials with specific mechanical properties used for specific components of a design.

The third group of experiences from the analysis of the experts' data presented in this chapter are those experiences associated with processing materials. The technologists believe that knowledge and understanding of processes is essential in their current role as designers and problem solvers as designs cannot be realised if a designer does not have this knowledge. They identified obtaining this knowledge and understanding from their experiences of seeing the available processes and, in some cases, processing materials themselves. One key aspect of this knowledge and understanding is that it enables designers to know how things are made. The technologists believe it is impossible to design if there is no understanding or knowledge of how things are made. Part of their design role is to ensure the feasibility that their designs can be made into realised functioning products.

The fourth group of experiences that the analysis of the experts' data identified as pertinent to their learning to design and problem solve are experiences that provide feedback on both their realised designs and their design concepts. For example, the feedback from a realised

design completes the “design loop” and validates what is effective design that they can use confidently in further design applications. In other words, the expert technologists considered the experience of seeing their own designs as functioning outcomes in-situ an essential component of their ongoing learning as designers. The expert technologists acknowledged obtaining feedback on design concepts sometimes requires tapping into other experts’ previous direct experiences with hard materials. In some situations, the expertise of others provides critical feedback regarding the expert technologists’ own design concepts before these concepts are made into realised outcomes. This feedback requires experts to discuss and share their ideas with others and is linked to the apprenticeship model described below.

The fifth group of experiences identified in this analysis of the experts’ data is experiencing designers’ and problem solvers’ ideas and building one’s own design ideas from these experiences and ideas. This includes, for example, utilising and building on various CoPs, such as marine classification societies, that have developed knowledge and understanding of design and problem solving through others’ previous design experiences with hard materials.

The final experience identified in the analysis of the experts’ data is that associated with experiences on-the-job where learning to design and problem solving begins with directly working alongside another expert and sharing in their previous experiences that have built their expertise. This apprenticeship model of learning, discussed by the expert technologists who had done apprenticeships, recognises the value of on-the-job situated learning enabling experiences with materials, processes, design outcomes and obtaining good and bad feedback about designs. The expert technologists acknowledged the apprenticeship model of learning as also recognising the role of a tradesperson’s experiences with hard materials. A tradesperson’s knowledge and understanding of design and problem solving, learnt mainly through experience, is passed onto the apprentice mostly through practical experiences with materials in specific situations. For John, Brian and Peter, this was their initial pathway to becoming expert technologists.

In this chapter, the analysis of the experts’ data presents the experiences that supported these five expert technologists’ learning to be designers and problem solvers and supports their current expertise.

Chapter 5: Expert Technologists: Complexity of Design and Problem Solving

5.1 Introduction

This chapter is an analysis of data collected from the expert technologists providing detail of how they design and problem solve and their understanding and ideas about design and the role of problem solving in the context of hard materials. This chapter highlights the complexities involved when designing and problem solving and how previous experiences with hard materials enable the experts to address many of these complexities. The second part of this chapter provides an analysis of the experts' conceptions of design and the role of problem solving in the context of hard materials.

As design and problem solving are key features of this research, the first part of this chapter provides insights into how experts in hard material technological contexts approach design and problem solving. The experts' data analysis highlights areas of their design and problem-solving expertise that links back to their learning through experiences with hard materials described in Sections 4.4–4.8. Therefore the sub-research question also guiding Sections 5.2–5.4 of this chapter is:

In what ways do expert technologists consider experiences with hard materials developed their expertise (knowledge and understanding) to design and problem solve with hard materials?

In Sections 5.2–5.4, three key strategic skills associated with design and problem solving are identified in which experts draw on their knowledge and understanding acquired from their various experiences with hard materials. These strategic skills enable effective deployment of knowledge and understanding when designing and problem solving and highlight the complexities of designing and problem solving. The data were obtained from responses to questions asking the technologists to discuss how they design and problem solve as expert technologists. The three strategic skills associated with design and problem solving identified from the analysis of the expert technologists' data are dealing with design constraints (Section 5.2), making decisions (Section 5.3), and using functional modelling, computer modelling and calculation to explore and evaluate design concepts and address problems (Section 5.4).

In Sections 5.5–5.7, the analysis of the expert technologists’ data is presented in response to the expert technologists sharing their understanding and ideas about design and the role of problem solving in the domain in which they work. The sub-research question guiding Sections 5.5–5.7 is:

In what ways do expert technologists conceptualise the relationship between design and problem solving in the context of hard materials?

The analysis identifies the experts’ understanding and ideas of design and the role they consider problem solving plays in mechanical engineering designing. In Section 5.7.8, the analysis summarises the expert technologists’ overall conceptions of design and the role of problem solving. Section 5.8 presents an overall summary of Chapter 5.

5.2 Dealing with design constraints

Constraints are an inherent area of concern associated with designing with hard materials. In this section, the analysis of the five expert technologists’ data identified constraints imposed by stakeholders, compliance regulators associated with health and safety, manufacturing and “buildability”, practicalities and economics. The number of constraints and importance of various constraints depend upon the type of design task. Not all constraints identified by the expert technologists in this section occur in every design project, but often there are more than one that must be overcome. Likewise, these data do not identify or discuss all constraints associated with designing with hard materials.

The expert technologists’ background experiences with hard materials helped them to deal with and work within some of the constraints when designing. Constraints are informed by and depend on an individual’s range of previous experiences. For example, if designers have limited knowledge of processes, this will impact inevitably on how they design a solution to a problem. In this section, the expert technologists provide examples where they draw on their experiences with hard materials to deal with some of the constraints when designing with hard materials.

The following comment by Brian shows how these constraints can be overlapping in any design solution.

There is a need to take into consideration what materials are available, what properties these materials have, the methods available to you to work with the material and the skill of the people who are going to do the job. Economics also

has an effect so a knowledge of how much the finished job is likely to cost is necessary as well (Brian, ET, 4).

5.2.1 Stakeholder's constraints

The expert technologists acknowledged how they often assess information from the stakeholders about the constraints associated with a design project. This occurs usually during the initial planning stage.

Peter noted that working early on with the stakeholders enables all parties to acknowledge the constraints associated with a particular project (problem) before the designing begins.

We've been working with [name supplied] because they know the constraints that they have and we know the constraints that we have (Peter, ET, 5).

He provided an example of a constraint identified (by the stakeholder) affecting the implementation phase of a bridge fabrication and installation project.

We've got twelve hours to put that [bridge] into position and pull the old one [bridge] out of the way (Peter, ET, 5).

In this example, the short timeframe during the implementation phase of the design project is a key constraint impacting on how Peter will design a process so the bridge can be installed in the designated timeframe of 12 hours.

To deal with this type of constraint, Peter uses his knowledge of cranes and gantries.

We'll take this [bridge] to site and those big beams separately, bolt everything up on the side and then get two big cranes and lift them up onto a carriage. The carriage will drive over the existing bridge ... then we've got a special lifting frame we're going to make (Peter, ET, 5).

Peter's practical experience ensures this time constraint can be satisfied through the designed procedure he describes.

5.2.2 Compliance constraints

In many design situations, the context may dictate a set of specific compliance regulations and constraints which must be known for the design task and specifications to be identified. The context includes the domain, that is, the specialist technological area in which the problem exists. Context can also take into account the physical environment where the problem is situated. Rules and precedents provide a form of constraint that the

expert technologists have to consider while investigating the initial problem and must be addressed and incorporated as the design concept develops.

For example, as George stated, if a problem is situated in the context of marine design, there is already a specific set of rules and precedents that exist so that a designed vessel can be accepted into a marine class, can be registered by a flag state and have a set insurance.

We do not design vessels that can't meet [a marine] class readily so we don't invent vessels as such ... by class that means you meet the specification that the ship was built to over its life ... so we would have a massive amount of rules and precedents set before we start off [designing] (George, ET, 1).

This means that over a vessel's lifetime, a marine classification will ensure that a vessel is built and maintained according to a set of specified safety, reliability and environmental standards. The standards are set by a classification organisation, such as Lloyds Register Group, and will involve inspections during the design concept phase, the construction and operation of the marine vessel. There are many different marine classes, each with its own specifications. George's years of experience working in a shipyard and with hard materials (see Section 4.2) enable him to deal with these compliance constraints when designing marine vessels.

All relevant safety standards act as a constraint and therefore must be known "upfront" and considered when looking at the design of a product. John described how sometimes a customer is ignorant of relevant safety standards that apply to a design. As a result, the customer can have unrealistic expectations when discussing a design idea.

A customer that has an impractical expectation, I think, because s/he doesn't perhaps know about the standard that's got to apply to, particularly safety these days. S/he just wants the thing to work but when it kills one of her/his employees because it wasn't safe, they come screaming back to [us] (John, ET, 3).

As a designer with many practical experiences, John is aware of the relevant safety standards associated with specific problems. His designs are constrained by these relevant safety standards.

5.2.3 "Buildability" and manufacturability

In the context of mechanical engineering, the design concept has to be built or manufactured. The need to manufacture and build a design (manufacturability) acts as a

design constraint in mechanical engineering design. The manufacturing processes that are available to the designer restrict what can be designed and made. Experts must know about how items are built, the skills and equipment required to build items, and the availability of plant, equipment and personnel. To deal with this constraint, the expert technologists draw on their knowledge and understanding learnt through their experiences of different manufacturing processes (see Section 4.6), their knowledge gained through experiences of materials (see Section 4.5) and feedback from their many previous experiences of designing and building products (see Section 4.7).

Peter acknowledged that as early as possible it is desirable on large design projects to deal with the constraint of manufacturing and building a project. In principle, this should ensure there are fewer problems further along the way, when the detail of the design is addressed and eventually the product is realised. This attention to manufacturing and building details reduces the time and ultimately the cost involved. Knowing that it has to be built raises awareness of the need to design products that can be fabricated or manufactured.

The manufacturability or the “buildability”, as Peter described it, is a constraint that must be addressed in the design of an object. Peter described how in his company they try to ensure this happens with architects and engineers as early as possible.

We like to get in early with [engineers’] designs so when they’re designing it we’re helping them with the buildability ... we get the architects and engineers on board with that so they come here [to Peter’s company], which they do a lot now, and say this is what we want to build and let’s get on and do it (Peter, ET, 5).

Peter’s key role in designing is to work out the processing of a design concept into a realised product and to design processes to enable very large structures to be implemented in-situ. Peter is able to draw on knowledge developed through his many practical experiences with hard materials and very large structures, described previously (see Section 4.6), to provide this input.

Consideration of the practical aspect of manufacturing and building a designed product requires the technologists to think about, and to problem solve around, associated constraints. These constraints include the materials available to the designer, the personnel available so that the design can be built or manufactured and the cost to produce an outcome. Although the conceptual design begins as an abstract idea, it is strongly situated, not only in the constraints of manufacturing processes, but also in the constraints of

available materials, available personnel, allocation of time and the cost, if it is to become a realised manufactured product.

5.2.4 Practical and cost effective

For George, ensuring that a design can be made into a realised product is a matter of addressing the practicality of a design concept. He describes practicality as a design constraint that incorporates the manufacturability of a design. When developing a design concept to solve a problem, George discussed how he endeavours to be “imaginative and innovative”, thus indicating the creative nature of design. However, he notes, the design also has to be “practical”, that is, it must be able to be realised or be made using hard materials. George’s considerable experiences with materials and processes have developed his knowledge and understanding (see Section 4.5) to enable him to design something that can be made.

George did not believe, in the type of work he did, that you could just have a (design) concept that stands alone. In fact, he identified dealing with the constraints of practically building the design at a realistic cost as the more challenging part of designing with hard materials.

Well if a customer has a problem you would have to be innovative and imaginative but it has to be practical, at the same time that you’re saying innovative and imaginative they’re the easiest bits. It has to be practical and able to be built at a realistic cost ... I have no idea how you would sort of say oh well I’m going to have this concept (George, ET, 1).

By contrast, George indicated if you had no time constraint when developing a design concept, it is possible (almost) to dream up just about anything you like but the practical reality is it would cost too much ever to sell such a design.

You can dream up anything you like, if you’ve got enough time, just about anything, but of course you can’t sell it ... or it just costs too much (George, ET, 1).

James commented that one way to improve a design includes being able to reduce the cost of making something and increase profits.

I think a big part of engineering and product engineering anyway is cost ... if you can halve the cost of making something then your profits are higher ... these things improve your design (James, ET, 2).

Peter described how he has also to take the cost constraint into account when he is pricing all aspects of a job. He cannot *just* take into consideration how a large structure will be fabricated (constructed) but must also consider how it will be moved and put in-situ. He has to design smart ways to do the entire job to keep the cost down and remain competitive in today's market. The reality of this often means reducing the labour costs involved in all of the above. To do this, Peter draws on his extensive range of knowledge and understanding from experiences to think up methods that are cost-effective to do the job he describes below.

If I'm pricing a job it's not just about fabricating, it's about how do I move it. How am I going to make this? ... the reality of it is to be in a competitive market you might have to get [the job] down to 45 man hours a tonne (Peter, ET, 5).

Peter's comment recognises that designing with hard materials, while solving problems with design solutions that have to be built, transported and implemented in-situ, are constrained always by cost.

John also recognised that design is driven by commercial considerations which act as a constraint. In the case below, he highlights trying to think up cheaper alternatives than using a mobile crane to access a job, or to lift something into position.

Another thing that drives design of course is the commercial aspects of it. If you had a situation where you might have to have a crane, a mobile crane is expensive. How would you get around getting access or lifting or whatever alternative to a crane? (John, ET, 3).

James recognises the trade-off between time and money. That is, how well something is designed generally depends on the job it has to do, and the time and money available to spend on the design.

We like to say at work you can gold plate everything but you can't do as much with the dollar so there is a trade-off between how well you design something or how well you design something for its job and how much you spend doing that (James, ET, 2).

Peter believed that his knowledge of the practical side put him in a strong position to have input into a design. Throughout the development of designs, he provides this practical input, drawing on previous experiences that have developed his knowledge and understanding to enable him to think of "smart" ways to build things.

For me it's always about ... how can we build it and then looking at smart ways of doing it ... I believe you've got to have that practical side (Peter, ET, 5).

He recalled how this worked on a recent project where the working drawings developed to make the actual product did not require any changes. In other words, when the detailed design drawings arrived in the workshop ready for the product to be made, no changes had to be made to them.

We had enough time to help work with the designers and all that to get those designs so that when the drawings came out there were no changes. It was, yeah, we know that will work (Peter, ET, 5).

The fabrication problems had been sorted out with all the designers. Peter's input into the practical building of the design had occurred during the pre-realisation phase of the outcome and thereby had reduced time and cost associated with the design. Peter's practical background and many experiences with hard materials enable him to provide this type of input into designing with hard materials in these contexts.

George recalled when working as a young engineer the comments of a very experienced engineer identified the relevance of acknowledging cost and practicality as two constraints in engineering design.

Like old [name supplied] ... that taught me the little I know about engineering, he used to say to me, ... anybody can build a Rolls Royce but Henry Ford was a better engineer because [he] built to a price and it was practical (James, ET, 2).

5.3 Making decisions

Being able to make decisions that reflect good judgements is a second skill associated with design and problem solving that relies to a large degree on the expert technologists having and utilising their experiences, understanding and knowledge of hard materials to deploy effectively their knowledge. This ability involves making initial decisions as to whether or not the designer will be able to design a solution to the problem presented. It also requires a series of ongoing design decisions and problem solving to ensure the design can proceed through to the manufacturing and realisation stage. This can involve thinking "on the job" and utilising considerable previous practical experiences with hard materials. Making decisions based on a designer's informed judgements also indicates the considerable responsibility attached to the role of a designer or a design team.

5.3.1 Project feasibility, making decisions based on previous experience

James stated that finding out about the initial problem required him to make an initial judgement to decide whether or not it was possible and feasible (allowing for all constraints) to come up with a suitable design concept to solve the problem. He noted that he did not know always exactly how to solve the problem in the early stages or where a design might take him. He commented that, although initially there maybe elements of uncertainty, there is often an intuitive belief that it is possible.

Do I think I can do that or not? Yeah I think I can do that. I don't necessarily know how right now but I think that's possible. You don't always know where you're going to end up but if you believe it's possible ... usually there's a way (James, ET, 2).

James' belief that he can do a job is likewise informed by his previous design experiences, as described in Section 4.7.

Brian described how usually when something arrives in his jobbing workshop to be modified, he finds out background information about how it broke before making a judgement and decision about whether it is possible to fix it. This includes finding out whether it broke by fair means or foul.

Usually what arrives at our place is broken. ... if they ran into the fence post then [the machine] wasn't really designed for that well then you can't blame the machine ... either make it bigger or put in a brace or something to put, or it might just simply be increasing the radius in a corner to change the thing. You might change it to a stronger piece of material and keep the same dimensions but you're trying to solve the thing so it won't happen again (Brian, ET, 4).

Brian utilises his extensive practical experiences with hard materials to inform his judgements and decision making regarding these types of problems and to prevent a reoccurrence of the problem.

As information is gathered about the problem or project, already the conceptualisation of a possible design concept may be developing, but a review and a decision as to whether or not it is practical to proceed with the project, to solve the initial problem, has to be made as early as possible. The timeframe for gathering information is inevitably constrained by economic and time factors, and the size and complexity of the initial problem (see Section 5.2).

George described a “design spiral” where a designer starts at the outside and gradually, as information is collected, moves towards the centre of the spiral. He believes a good engineer does not go right to the centre of the spiral, where there is no more information to collect. A good engineer makes a decision as early as possible (before reaching the centre of the spiral) as to whether or not it is practical to proceed with the project.

This is what’s called a design spiral. So you start out here ... You’ve got to collect all the information and you’re collecting and ... collecting the information here but the good engineer knows where to stop and step back and say is this project practical ... we have to say review it and review it you don’t spend three more weeks collecting and collecting oh I can’t do the job now because it’s not practical ... that cost is just too high ... (George, ET, 1).

As George commented, in a commercial design environment, an engineer cannot afford to spend weeks collecting information and then decide a project is impractical. This is far too costly and not how a good engineer works. A review and decision as to the practicality of the project must occur as early as possible in the design spiral. It is clear that a decision about the practicality of a project relies on the learning through experiences with hard materials described in Sections 4.4-4.8.

Peter feels that while it is important to listen to others, if he is controlling the job, his responsibility is to judge others’ ideas and then to make a final decision.

Basically it’s to be open and listen to what other people have to say and if you’re controlling the job ... you can make the decision (Peter, ET, 5).

Likewise, James noted that while it is always good to listen to feedback from others, it is necessary to recognise that not all feedback is “good feedback”.

You have to be careful ... because layman’s understanding of things may not always be good feedback. ... You’ve got to be a little careful ... feedback, it’s always good to listen to it but it’s up to you to decide how much significance it has (James, ET, 2).

As a designer, ultimately it is the responsibility of James to judge and decide its significance.

5.3.2 Using others' ideas, previous designs and own prior knowledge and experiences to make design decisions

When developing and devising a design concept to solve a problem, technologists often adapt and develop others' design experiences, and/or their own previous ideas and experiences. James stated how he has to decide what is a good idea based on all this information, and utilises his own knowledge. In other words, James recognises that decisions are based on his own knowledge and understanding as well as an awareness of others' knowledge and ideas.

When it comes to a design of your own you've really got to take all that database of [others'] experience and add to it your ideas and come up with something that you think is a good idea to solve that problem. ... Sometimes people will say that's never going to work, so you need the courage of your convictions and you also need to be able to sort good feedback from less good feedback (James, ET, 2).

This database includes the expert technologists' accumulated knowledge of available materials, products and processes with hard materials that they can apply to ensure their design concept can be made with hard materials and, where applicable, how the various components that make up the design solution can be assembled. As well, the database includes all the previous design experiences of the expert technologists (see Sections 4.4–4.8).

Peter recalled modifying a design to keep a plant running after a designed product failed that his company was responsible for constructing. A solution required Peter's knowledge and understanding of materials and material processes. Peter and his team had to make some quick decisions to fix the failed design. They used "big beams" to support the rotating kiln structure to keep it running temporarily for 6 months while another modified design was built using different material.

The practical side of it ... was how are we going to fix it because they still need to run it and it was going to take us another six months to build a new one out of ordinary steel and get it re-bricked so how do we fix that ... we had to stiffen up the side with big beams up there and all that, start making a new one and we were fortunate enough we had our big crane so we could lift it in in two big pieces to minimise the down time for [name supplied] because a million dollars a day while it's sitting there doing nothing (Peter, ET, 5).

This example indicates how decisions can be made to modify a failed design to keep a machine working, and reduce the impact for a company when a design of this magnitude

fails. Peter's considerable experience enabled him to provide a temporary solution to this problem. Later, during the implementation of the modified design, he used his knowledge of big cranes to reduce the down time for the stakeholder.

5.4 Functional and computer modelling, and calculation used to explore and evaluate design concepts and address problems

A third area associated with design and problem solving that utilises the expert technologists' experiences, knowledge and understanding of hard materials is the skill to use technological modelling when designing.

Computer models of design ideas and concepts help with the development of designs. However, as James' comment below recognises neither the computer software nor machine tools "do" engineering design. The computer software is a modelling tool that *helps* an engineer to develop design concepts. To be able to design as an engineer requires experiences, knowledge and understanding of hard materials.

[The computer] doesn't do engineering for you. Machine tools don't do engineering, only parts. This software doesn't do engineering it's a tool for developing designs (James, ET, 2).

In some situations, the expert technologists use functional modelling to see if their design idea or concept works before developing a suitable design that can be put into a final product. As James notes, these models provide a rough check on whether or not an idea is likely to work. They are not developed or refined enough to be identified as prototypes. Nonetheless, the function is roughly the same as a prototype. It is important to recognise that considerable engineering knowledge is required to do even a quick test of ideas.

If you're just building one to see if it works ... I would put something together very quickly and very roughly for a quick test to see if my idea works, but that wouldn't be what ends up in engineering going into a product ... you put the thing together and try and break it (James, ET, 2).

Peter described how, when he is working with a team of designers, he is able to use a dummy mock-up of a design component to test and to point out a flaw he feels is likely to occur when it comes to the fabricating or making of the design. In the following situation, the "dummy mock-up" included making a test piece of a component of the design and testing it to demonstrate design flaws to other members in the design team. His years of experience enabled him to build this type of mock-up and to argue his point about the design flaw.

If we feel strongly about something we'll make a dummy mock-up of it and test that and that's what we did with [name supplied] ... we argued at the meeting ... I said next meeting ... we'll make you a test piece and we'll try it (Peter, ET, 5).

When it comes to large structures, such as a bridge beam, computer programmes enable virtual technological models to be drawn to inform the designer of the strengths and weaknesses (stresses and strains) under a particular loading (force). This process is recognised as a Finite Element Analysis (FEA) and is possible using computer software which uses colour. For example, a particular colour may indicate where something may need reinforcing by using a thicker plate of steel. Any adaptation or modification to the design can be trialled further using the computer programme to check if it will make the design safer and more effective. Peter described how his company uses this type of model when designing large structures to detect potential weaknesses in the construction.

We use Solid Works ... You can do a finite analysis on things ... it's all in colour so when it's one colour it's good and then it will show where its weaknesses are ... We can do our own little checks more so now than what we used to be able to do saying just make it out of 20mm plate. We actually say whether we need a 20mm plate or it might be a 25mm plate. It's those sorts of things (Peter, ET, 5).

This type of computer modelling is an effective tool for testing large structures when generally the development of a realised prototype of these designs is not feasible. To be able to interpret an FEA requires an understanding of the materials proposed in the design. For example, if there is a weakness that shows up in the FEA, knowledge of materials may enable this weakness to be addressed by changing the thickness of the steel plate used in the design. The FEA tool is used by engineers alongside calculation to inform and anticipate whether or not a design of this magnitude is safe before it is fabricated into a realised product.

Engineers use mathematics as a predictive analysis tool to ensure that structures and mechanisms are strong enough, rather than using trial and error methods of design which are not economically feasible in most design situations.

You apply the maths to make the structure strong enough (George, ET, 1).

Two of the expert technologists noted that they use 3-dimensional computer programmes to enable them to develop functional models and, in some cases, produce virtual computer prototypes of their design ideas.

With the [computer] software I can actually make this thing go round and round and I can figure out if it works. ... I can see ... whether it works for the space and so you do a lot of prototyping digitally ... There's this whole prototyping process goes on in the computer these days and you develop your ideas and refine them (James, ET, 2).

As James explained, this enables him to refine his design ideas, and in some situations, replace the physical prototyping with real materials of a design concept.

Some initial design sketches and drawings may be very informal. George talked about a vessel he had designed and how he had sketched an initial drawing of the ship on the back of a cigarette packet.

This is a ship that was designed on the back of a fag packet and it was a \$7m vessel just sketched up (George, ET, 1).

George was able to “sketch” in this way because of his extensive background knowledge, understanding and experiences of materials used in ship design and his previous marine design experiences (see Sections 4.5–4.8).

5.5 Design and the role of problem solving

The purpose of Sections 5.5–5.7 is to present the analysis of the experts’ conceptions of the role of problem solving in design with hard materials. To find out about their conceptions of design, it is necessary to find out how experts conceptualise the role of problem solving in design in the broad context of mechanical engineering and hard materials. The research sub-question guiding this section is:

In what ways do expert technologists conceptualise the relationship between design and problem solving in the context of hard materials?

In the literature review (see Section 2.3, p. 25), the two terms design and problem solving are discussed extensively, particularly in their relationship to technology education. The literature review examines the relationship of these terms, together with some of the dilemmas surrounding this relationship in technology education. In Sections 5.5–5.8, the analysis of data enables design, and the role of problem solving associated with it, to be explored from five expert technologists’ perspectives.

As the literature review has already identified, these terms are often used interchangeably in technology education. In Sections 5.6–5.7 the analysis of the data provided by the five

expert technologists unwraps how they conceptualise design and problem solving, in their respective technologically specific working environments.

5.6 Questions regarding design and the role of problem solving

The five expert technologists were asked to consider the following questions in relation to the work they do (Appendix A).

- How do you consider designing with hard materials and how is design related to your current work?
- Can you explain your ideas about problem solving relating to hard materials and the work you do?
- Do you consider designing and problem solving with hard materials are linked, and if so, in what way are they linked in your technologically specific work as an expert technologist?

5.7 Problem solving interrelates with design

The following analysis of data reveals how these five expert technologists consider and conceive of design and the role of problem solving with hard materials. The overarching theme identified from the experts' data showed that problem solving is strongly interrelated with design in the context of mechanical engineering. The expert technologists provided several examples of how problem solving interrelates in their respective work as designers.

As a result of analysis of the technologists' data, seven sub-themes were identified. These sub-themes are examined in detail in Sections 5.7.1–5.7.7. In Section 5.7.1, the first considers how an initial problem defines a need for design; therefore design and problem solving are related. In Section 5.7.2, the second sub-theme considers how design solving a big problem generates subsidiary problems requiring further design solutions. In Section 5.7.3, the third sub-theme acknowledges that design concepts must incorporate technical detail and subsidiary problem solving. In Section 5.7.4, the fourth sub-theme identifies that design is innovative but must also be practical. In Section 5.7.5, the fifth sub-theme examines a problem within a problem that requires a design solution. In Section 5.7.6, the sixth sub-theme acknowledges that there are problems that do not require design solutions. In Section 5.7.7, the seventh sub-theme presents design as a problem-solving process, optimising many factors to find the best possible solution. Finally, in Section 5.7.8, the

themes resulting from analysis of the experts' data are summarised to show the interrelationship of problem solving and design.

5.7.1 An initial problem often defines a need for design indicating their relationship

Brian recognised that, in his engineering work, problem solving and design are difficult to separate and are “closely related”.

In the engineering field [problem solving and design] are very closely related. Sometimes I don't think I could separate them in the line of work we do (Brian ET, 4).

John described a common relationship between problem solving and design as finding out about or defining the problem and then designing around it. He stated that in order to design, in his work, there is usually an initial known problem in the design brief.

You should look at the problems before as a design brief I think ... The problem has to be known up front before you could design around it (John, ET, 3).

Brian stated that in his “jobbing workshop”, each job or problem that needs solving is different. He described a common relationship between design and problem solving also as design solving a problem and summarised designing as either making something new or changing something to solve a problem.

Our workshop is a jobbing workshop so very few jobs are exactly the same, almost every job presents some kind of a problem needing to be solved. ... To me designing is about creating something or changing something to solve a problem (Brian, ET, 4).

5.7.2 Design defines a big problem to solve that generates many subsidiary problems requiring further design solutions

James described how in a complex machine design, the initial big problem is identified and, as the overall design concept develops, often there are many further subsidiary problems that require further design solutions. For example, when developing a complex machine design, there is the necessity to have a concept of the overall machine design with some initial understanding of what overarching (big) problem the machine's function is solving.

James described putting a plastic ball on the end of a fibreglass rod to make a specialised spring as the “big” problem. In fact, he presents the overall function or purpose of the

machine as the “big” problem to solve. In this example, James is trying to solve this big problem by designing a machine to perform this function.

You have to have a concept of the overall machine. ... I'm trying to make a machine that puts a ball on the end of a rod, that's a big problem (James, ET, 2).

After the initial concept, James must consider many details in order to solve the subsidiary problems concerning what the machine has to do physically to perform this overall function. Because of the complexity of the machine design concept, there are many subsidiary problems that require further design solutions for the overall design concept, the machine, to function. These problems are conceptual-type problems that must be addressed during the design phase with design solutions.

5.7.3 Design concepts do not stand alone: they must incorporate technical detail and subsidiary problems

James clarified the relationship of design and problem solving by describing some of the further subsidiary problems nested within the overall problem. He “drills down through the overall problem” to design the details of the machine to solve these subsidiary problems.

... Then you go well how do I get 200 degree plastic plus or minus 5% of 25grams into that mould over there before it cools? And how do I do that at a rate of one per second, which is what this machine does? So there's a problem within a problem and yeah so it's just you drill down through the overall problem into all the details (James, ET 2).

In James' example, he describes a relationship as an initial big problem (the function of the machine) solved with an overall design concept and solution. The overall design concept then generates further subsidiary problems that require design solutions to provide the detail for the overall design solution to function.

Another example of this view of design generating subsidiary problems is presented by Peter. Peter recalled the painting of big and awkward structures after they had been fabricated (built). The handling of these large structures, and providing an area suitable to paint them, was a problem that required a design solution. This subsidiary practical problem occurred in addition to the initial problem and design solution, that is, the fabrication or making of the very large structure.

Painting you've got to handle [big and awkward fabricated structures] out of the workshop where you've got your big heavy gantries [overhead cranes] into a paint

bay. [name supplied] for example they were not heavy but they were really big and awkward so we had to build a special temporary paint bay. They're problems that come up (Peter, ET, 5).

This problem, although subsidiary to the overall problem and design solution, must be solved for the overall design to be realised fully. Therefore, it is a component of design.

The following also provides a rich account of the myriad of subsidiary problems that need solving after the initial problem of floating a vessel has been sorted. While designing a new ship is not solving an overarching problem necessarily, George presents the stages in the design of the ship as problems solved through design. For example, George described, when building a ship, the initial problem is to design a solution so the ship floats upright and keeps out water. However, this only constitutes about 10% of the overall cost of the ship. The other costs arise from the mechanical and electrical engineering design that solves all the problems associated with people living on a ship at sea. Designing solutions to these problems contributes to the major cost of a ship design. The following example of designing a ship identifies an initial overarching problem requiring a design solution, and subsidiary problems that generate further design solutions.

The first thing we have to do is make the ship float upright and keep the water out. ... of the total cost of the design and the rest of it is probably less than 10%. The other 90% is mechanical and electrical engineering. ... it's the plumbing, the sewerage, the water reticulation and the heating, ventilating the whole thing (George, ET, 1).

George acknowledged that to get a design concept to work, you have to provide all the technical details. To provide the technical details, it is necessary to solve a “myriad of little problems” associated with and generated by the overall design. A design concept in engineering design requires many “little” problems to be solved to ensure the technical detail is provided for in the design, so the design functions as intended by the designer. These types of problems are addressed and solved during the design phase.

In real estate they say location, location, location. Well in engineering it's detail, detail, detail ... [design and problem solving] are not separated at all so in other words you can have a concept and then you have to make it work and be practical [with] a myriad of little [problems] (George, ET, 1).

George notes a strong interrelationship between design and problem solving. His perspective states that you cannot separate design from problem solving because to get an

innovative design to the practical (realised outcome) stage requires the designer to address and to solve a myriad of subsidiary problems along the way.

5.7.4 Design must be innovative and practical

George emphasised the important role for a designer of solving the subsidiary problems in a design. He explained how a designer tries to be innovative, but at the same time must solve all the problems to enable a design to become a practical realised outcome. Once again, the interrelationship of design and problem solving are acknowledged in George's remarks.

[Design and problem solving] aren't separated at all, if you're going to provide an innovative design to get to the practical stage you've got to solve all the problems (George, ET, 1).

In many projects, these subsidiary problems are solved with further design solutions during the design phase. They are not concerned solely with the practical manufacturing-type problems to realise a design.

5.7.5 Problems within a problem often require a design solution

Brian described an initial problem (straightening harvester bars) requiring a relatively straightforward procedure that was not a problem needing a specific design solution. Under normal circumstances, it would be solved just by using a procedure involving a hydraulic press. However, in this situation, the process presented a subsidiary problem (hazard of the unsecured pieces flying out of the press) that required a design solution. Consequently, this problem was solved by designing and making a fixture or jig to secure the bar in the hydraulic press so the procedure could be carried out.

We have a job straightening harvester bars after things have gone wrong in felling a tree with the harvester. We use a hydraulic press to produce enough force to straighten it. The problem is that the bar or the packing fly away creating a hazard. The solution is design and make a fixture which retains the packing and prevents the bar slipping off (Brian, ET, 3).

The relationship between design and problem solving in this situation is an initial problem that presents a subsidiary problem, which then requires a design solution to enable the initial problem to be solved.

Often it's not something that you're designing there but something to do the job with (Brian, ET, 3).

This incident provides an example of a relationship between design and problem solving as an initial problem generating a subsidiary problem that requires a design solution in order to solve the initial problem.

5.7.6 Some problems are solved without design solutions

Some problems associated with the realisation of a design do not require a design solution to solve them. As Brian described, some problem solving often occurs in the processing of someone else's design at the realised outcome stage.

Someone who has already created the design and the problem is how do we perform the process to create the designed article (Brian, ET, 4).

A relationship between design and problem solving remains, because the problems addressed during the processing of the design have to be solved. Otherwise, the realised design outcome of the initial problem cannot be realised.

Some of the problems described by George require practical solutions but do not require a design solution.

Some of the work we do is modifying, or parts of ships and systems. ... right now, ... we're going back to putting helicopters on the boat again, we've got to put petrol on the boat and there's all the problems that go with that and putting in new compressors and things like that so we get to solve all those problems right down to doing diagrams for lifting them to make it safe (George, ET, 1).

Peter described sometimes problem solving “on the run”, addressing practical problems and solving them to keep the job going.

I know how to problem solve on the run sort of thing so the job keeps flowing (Peter, ET, 5).

This type of problem solving must be dealt with to realise the overall design but does not require a conceptual design solution. These are different types of problems to the problems that crop up as a conceptual design is developing (see Section 5.7.2). The conceptual problems described in Section 5.7.2 occur at the conceptual phase of the design. They must be anticipated, satisfied and the solution incorporated into the design, as opposed to the

problems solved “on the run” during the realisation of a design described by Peter in the quotation above.

5.7.7 Design is a problem-solving process that optimises finding the best possible solution

James acknowledged that almost all design with hard materials requires problems to be solved. Therefore, problem solving is an important component of designing in the context of mechanical engineering. Consequently, he described design as a problem-solving process. That is, design always has to address and solve problems as the design emerges; design does not just provide an overall solution to the initial or overarching problem (see Section 5.7.1).

I see almost all design is problem solving one way or another. I think problem solving is the right term for optimising something ... if you make it better you've got a better solution to that problem you're trying to solve. ... Not all problem solving is design, almost all design is problem solving as I see it so I have a hard time separating design and problem solving. ... Design is a process but it's a problem solving process (James, ET, 2).

Optimisation is when the designer tries to address all the constraints associated with an initial problem and comes up with the best design possible to solve the initial problem. Merrill et al. (2008) describe optimisation in engineering design as the intention to find the best solution to a problem after all trade-offs have been considered. These trade-offs may include material availability, available processes, expertise of personnel, cost and time, all of which require ongoing problem solving utilising the designer's knowledge, ability and background experience.

Therefore, the designer/s must balance all the pros and cons and ultimately decide what compromises they are required to make to provide the best possible design, as Peter described in the example below.

For example [name supplied] which is the classic thing they had a splice joint there, that was semi-designed but it didn't quite work so we just worked with the engineer to improve the design that did work (Peter, ET, 5).

5.7.8 Summary of expert technologists' conceptions of the ways in which problem solving interrelates with design

The data presented in Section 5.7 were analysed to show five expert technologists' understanding and ideas of design and problem solving. The overarching theme identified from these data is that design and problem solving with hard materials are interrelated strongly in the context of mechanical engineering. The seven sub-themes identified from these data are presented below as the expert technologists' overall conceptions of how problem solving interrelates with design in the context of mechanical engineering and hard materials.

Conceptions of expert technologists: problem solving is interrelated strongly with design in the context of mechanical engineering.

1. An initial problem often defines a need for design, therefore they are related closely
2. Design solves a big problem (big problem may be the overall function of an object or artefact), that may generate subsidiary conceptual problems, requiring further design solutions
3. Design concepts do not stand alone; they must incorporate technical detail and subsidiary problem solving to be realised into an outcome, including the practical subsidiary problems associated with manufacture
4. Design should be innovative but at the same time must be practical (able to be realised)
5. Problems within a problem often require a design solution
6. Some problems can be solved without design solutions
7. Design is a problem-solving process that optimises constraints and trade-offs to find the best possible solution.

5.8 Summary

In Chapter 5, the analysis of the data presents aspects of how the expert technologists engage in design with hard materials in the context of mechanical engineering. The experts identified areas associated with design work where they utilise strategic skills to deploy their knowledge and understanding acquired through the many experiences they have encountered with hard materials. Design in the industrial world of these technologists is not just about conceptual design ideas, it is about being able to realise these concepts in the

material world of hard materials technology. As the analysis of the technologists' data identifies, taking a design concept through to a realised outcome requires the solving of many and various problems that require strategic skills, knowledge and understanding, many of which they acquired through experiences with hard materials that are described and analysed in detail in Chapter 4 (see Sections 4.4–4.7). This chapter has also analysed and summarised (see Section 5.7.8) how these five expert technologists, who work in mechanical engineering related industries, conceptualise the ways in which problem solving interrelates with design.

Chapter 6: Technology Teachers' Conceptions

6.1 Introduction

The following is an analysis of the interview data provided by five technology teachers who are involved currently in the teaching of secondary technology and related subjects associated with hard materials. Four of the five teachers interviewed had careers as technologists prior to entering the teaching profession. The profiles of the five technology teachers are presented in Section 6.2.

The overall aim of this chapter is to elicit data from the five technology teachers relating to the following two research sub-questions.

What are technology teachers' conceptions of design and the role of problem solving in hard materials technology?

What are technology teachers' conceptions of the key traits of successful novice student designers and problem solvers working with hard materials?

In Section 6.3, data is analysed relating to how these technology teachers conceptualise design and the role of problem solving in hard materials technology. This aspect is given prominence because learning of technological design and problem solving with hard materials are core concepts that this research endeavours to investigate. In Section 6.4, teachers' data relating to the second question is analysed to find out what these teachers understand to be the key traits of successful novice student designers and problem solvers.

6.2 Profile of five technology teachers

The five technology teachers interviewed in this research met the purposive sampling criteria (see Section 3.4.2, p. 75) that required these research participants to be involved currently in the teaching of hard materials technology to Year 10 to Year 13 students (14–18 year olds). The technology teacher research participants were from five New Zealand secondary schools with technology departments.

In Sections 6.2.1–6.2.5, the background and current teaching roles of the five technology teachers, Andrew, Kevin, Matthew, Henry and Patrick, are presented. While all five teachers are secondary technology teachers, Andrew, Kevin, Matthew and Patrick also had careers as technologists before entering the teaching profession. The profiles of the five

teachers are presented to establish the influences and experiences that have shaped their individual perspectives as technologists and/or technology teachers.

6.2.1 Andrew, Technology Teacher 1 (TT, 1)

Andrew (TT, 1) had a background working initially as a technologist in the building industry. His original building qualification was a Building Technician's Certificate. After achieving this technical qualification, he worked for a couple of years in an apprentice-type role where he had practical experiences in the building industry that included working alongside an electrician. Andrew then continued his studies and completed a New Zealand Certificate of Drafting (Architectural). After completing this qualification, Andrew worked in a range of related building and design industries both in New Zealand and overseas.

His overseas experience included having his own business working in auto-CAD (a software application used in computer-aided design for designing and drafting plans in two and three dimensions), making props for a nightclub in the United Kingdom, experience in civil structural engineering projects in the oil and gas industry and working for landscape designers in France. His landscape designing experiences included welding, and working with metals. Back in New Zealand, he programmed lasers to cut a wide range of hard materials before completing a 1-year secondary teaching diploma to qualify as a secondary technology teacher. Later, as an in-service teacher, he completed a Masters of Education including a thesis related to technology education.

As a child he recalled pulling things apart. He remembered growing up in the days when there was "unlimited access to rubbish dumps" where he could source things to pull apart, modify and rebuild.

As a kid we used to blow things up and pull things apart and there was unlimited access to [rubbish] dumps (Andrew, TT, 1).

He felt these childhood experiences contributed to his developing a sense of how objects are designed, and how things are made, as well as learning about materials through direct experiences with them. His various background experiences as a technologist, before entering the teaching profession, have also contributed to his knowledge, skills and understanding of processes and designing with a range of different materials. In his current teaching role, he works with a broad range of hard materials in an all-girls city secondary school where he is Head of Department in technology.

6.2.2 Kevin, Technology Teacher 2 (TT, 2)

Kevin (TT, 2) has a technology background in boatbuilding. Prior to entering the teaching profession, he had done some cabinet making and built houses.

I did lots of materials based technological jobs from cabinet making to my trade, when I started off was boatbuilding. Built some houses ... that was the materials knowledge that I brought into teaching (Kevin, TT, 2).

As a boat-builder, he was required to do graphical drawing and design as well as the practical constructional aspects of boatbuilding. Practical boatbuilding mostly involved working with fibreglass and laminated timbers. Kevin described the graphical drawing associated with boats as “quite complex” because of the curves of a boat. He considers he has brought this background as a technologist into his teaching career of graphics and technology and the learning experiences he provides for his students.

Kevin entered teaching after the completion of a 1-year secondary teaching diploma. His technology teaching is centred on wood-based hard materials. During his teaching, he has been involved in the assessment of both design technology and technology, the writing of unit standards for the subject materials technology, and is involved in the writing and trialling of technology Achievement Standards for the New Zealand National Certificate of Educational Achievement (NCEA). He has also been involved in research projects associated with the development of both the 1995 and 2007 New Zealand technology curricula (MoE, 1995; 2007).

I've ... been involved with four or five different research projects, from early technology and looking at technology and technological practice, through to looking at the new strands in technology (Kevin, TT, 2).

Also, he has lectured part-time in technology education at two New Zealand universities. This blend of theoretical and practical experiences in teacher education has broadened Kevin's perspectives on curriculum and pedagogy. Since entering teaching, Kevin has taught mostly a wood-based technology programme and graphics and design. Kevin teaches in an area school (Years 1–13) where he is Teacher-in-Charge of technology.

6.2.3 Matthew, Technology Teacher 3 (TT, 3)

Matthew (TT, 3) has a 20-year technology background in the New Zealand Air Force as an avionics technician, where he worked on aircraft navigation and electrical systems. He was

a pilot for 12 of his 20 Air Force years. He flew helicopters and Orion aircraft in the New Zealand Air Force. During this time, Matthew had experiences with different types of aircraft where he learnt about electronic systems, engines, mechanisms and airframe structures of various aircraft. The Air Force experiences developed his engineering knowledge through seeing, fixing, theoretical learning and flying aircraft.

Matthew's interest in aircraft and flying began as a 12-year-old when he made model aircraft (aero modelling), including building models of his own designs. As a teenager, it continued when Matthew learnt to glide. Matthew considers that these childhood hobbies developed his initial understanding of physics, structures and mechanisms. As a result of his Air Force experiences and his childhood hobbies, Matthew acknowledges that he has had plenty of exposure to mechanical design which all contributes to the knowledge that he uses in his teaching of technology subjects.

I've had a huge exposure to a wide range of mechanical design, real things and there's no substitute for just playing with real things (Matthew, TT, 3).

Matthew has an ongoing interest in all things engineering and is always curious to find out more about anything he sees going on in the world around him.

No matter where I am if I see something interesting going on ... I'll ask people about it, I'll ask questions ... because I'm interested in basically anything to do with engineering (Matthew, TT, 3).

Before entering teaching and while still working for the Air Force, he designed and built his own house. He acknowledges that this project taught him a lot about a broader range of materials outside the world of engineering.

I designed and built my own house ... over a period of maybe ten years ... so I obviously learnt a lot from that (Matthew, TT, 3).

Matthew has a New Zealand Certificate in Telecommunications. His teaching qualification is a 1-year Graduate Diploma of Primary Teaching. Matthew chose the primary qualification option as it provided him with more flexibility in terms of choosing where he can teach. Currently, he teaches in the Year 7–13 level in an independent co-educational city school. His technology teaching involves working with hard materials and includes both wood and metals.

Matthew also teaches a robotics design course as part of an extra-curricular options programme for Year 6 to Year 13 students. He uses his technology background in these courses where students design and build robots to perform certain functions. The students compete in competitions against other schools. Matthew's robotics design students also compete in national and international robotics competitions, and in some classes, his robotics students have won world titles in their respective age groups.

6.2.4 Henry, Technology Teacher 4 (TT, 4)

Henry (TT 4) is the only teacher in this group without a background working as a technologist prior to becoming a teacher. After completing an undergraduate science degree in physics and mathematics, he obtained a postgraduate qualification as a primary school teacher. He taught in primary schools for 6 years. Henry then taught physics for 20 years before becoming involved in the internally assessed School Certificate subject, physical science. While teaching physical science, he discovered the use of LEGO control systems to help struggling students understand aspects of physical science through practical activities.

He came into technology education through teaching control systems and electronics. He has also participated in welding and machining and turning courses at a polytechnic, and in 3-D CAD programming and computer programming courses.

I've never been a specialist woodwork or metalwork teacher although I have taken courses in welding and machining and turning at [poly-technical institutes] over the years and courses in 3-D CAD, courses in computer programming (Henry, TT, 4).

Henry won a 1-year Royal Society Teacher Fellowship, which enabled him to research and study. During this time he worked in the two universities' respective Stage 3 electrical and electronic engineering laboratories. Here he learnt how to work with embedded systems and micro-controllers.

Currently, he is the Head of Technology in a private city secondary college and teaches with a range of hard materials, including wood and metals. Henry considers his primary teaching years influenced how he has set up his technology department, that is, it is "poised ready for action" and that students can see where everything goes back into place.

This organisation encourages students to be self-managing and to be able to work between areas associated with both metals and wood.

[It] enables kids to become self-managing and so that's what we're trying to do with this building here so that we're poised for action using any type of material at any time (Henry, TT, 4).

Henry still has a particular interest in electronics and control technology, which he also promotes at his school.

6.2.5 Patrick, Technology Teacher 5 (TT, 5)

Patrick (TT 5) has a technology trade background as a diesel mechanic and has worked extensively with heavy industrial machinery. As a child he remembers always wanting to make things, and to pull things apart, to find out how they worked. He described his father's reaction to this as follows:

[My pulling things apart and making things] was the bane of my father's life for a long time (Patrick, TT, 5).

Later in life, his responsibilities as a diesel mechanic required him to have a very broad understanding of mechanical processes as well as knowledge of skills that enabled him to weld, cut and repair equipment. During Patrick's apprenticeship, he was expected to learn about general electrical theory and automotive electrical theory associated with heavy industrial machinery.

When I did my apprenticeship we were expected to know a fair amount of electrical theory ... we were expected to be able to weld and cut and repair things as part of our trade. We were expected to have a very, very broad understanding of mechanical processes. We weren't just parts' replacers in those days (Patrick, TT, 5).

This apprenticeship enabled him to learn how these components functioned and about the materials from which they are made. As a result of his apprenticeship training, and his subsequent trade experience working as a diesel mechanic, Patrick considers he obtained a broad skill base that provides him with "versatility" in his technological field.

The versatility of today's tradesperson is not as it was 40 years ago when I started [my apprenticeship] (Patrick, TT, 5).

This versatility means he has understanding and knowledge of both electrical and mechanical componentry associated with heavy industrial machinery that he has been able to bring to his role as a secondary technology teacher.

Patrick has a New Zealand Advanced Trade Certificate in Diesel Mechanics and completed a 1-year secondary teaching diploma that enabled him to enter the teaching profession. Later on in his teaching career he up-skilled to Level 6 on the New Zealand Qualifications framework by completing the specialist teacher secondary certificate qualification. This enables a teacher who has come into secondary teaching with a trade qualification to access a salary equivalent to a degree-qualified teacher.

The subject teacher qualification at Level 6 was probably some of the best professional development that I've done in my life purely because it forced me to think from a totally different perspective (Patrick, TT, 5).

Patrick considers that this subject-specific teacher professional development broadened his understanding of the value of design and theory associated with hard materials that can be supported through practical workshop activities in technology education. Patrick is currently the Head of Technology at a state-secondary city boys' college which focuses on using wood and metal in its technology programmes.

Table 6.1 summarises the five technology teachers' current educational roles and qualifications and, where applicable, their technology backgrounds and qualifications.

Table 6.1: Profile of five technology teachers

Teachers' Pseudonyms	Gender	Position in School	Main Area Technology Background	Pre-Teaching Qualification	Technology Teaching	Teaching Qualification
Andrew, TT, 1	Male	HoD Technology	Building industry	NZ Certificate of Drafting (Architectural)	Technology with range of hard materials Year 9–13	Diploma of Teaching (Secondary) Masters of Education
Kevin, TT, 2	Male	Teacher-in- Charge Technology	Boatbuilding and cabinet making	Advanced NZ Trade Certificate	Technology and Graphics wood based programme Year 10–13	Diploma of Teaching (Secondary)
Matthew, TT, 3	Male	HoD Technology	Avionics technician Air Force pilot	NZ Certificate in Tele-Communications	Technology and Graphics Year 6–13 Some wood, mostly metal, engineering secondary Robotics Year 6–13	Graduate Diploma of Teaching (Primary)
Henry, TT, 4	Male	HoD Technology		BSc in Physics and Mathematics	Year 9–13 Wood, electronics, metal based programme Robotics Year 9–13	Graduate Diploma of Teaching (Primary)
Patrick, TT, 5	Male	HoD Technology	Heavy diesel mechanic	Advanced NZ Trade Certificate	Year 9–13 Graphics, metal based technology engineering programme	Diploma of Teaching (Secondary) Specialist Teacher Certificate

Note. *HoD = Head of Department.

6.3 Technology teachers' conceptions of design and problem solving

Section 6.3 provides an analysis of data to identify these five technology teachers' conceptions of design and problem solving with hard materials and answer the research sub-question:

What are technology teachers' conceptions of design and the role of problem solving in hard materials technology?

The guide questions (Appendix B) were developed to find out these five teachers' views and understanding of design and problem solving. These teachers were asked to share their ideas about design and problem solving and whether or not they consider there is some link between these two aspects. The teachers' views and understanding are analysed to identify their conceptions of design and problem solving with hard materials in Sections 6.3.1–6.3.5. In this part of the analysis, the teachers' technological and teaching backgrounds (see Section 6.2) are acknowledged where they are thought to be significant. A short summary is provided at the end of each teacher's quotations summarising each of these teachers' conceptions of design and problem solving. Because the learning of, and understanding about, these aspects in technology education is a key focus in this research, it is important to establish these teachers' conceptions before finding out the pedagogy they use to develop these concepts with their students. A summary that includes a comparison of the teachers' conceptions with those of the expert technologists is presented in Section 6.3.6.

6.3.1 Andrew (TT, 1)

Andrew's understanding and conceptions of design and problem solving are influenced by his background as a technologist, where he worked mostly with wood-based products, and from his current role as a hard materials technology teacher working with a wide range of hard materials (see Section 6.2.1).

Andrew considered that design with hard materials is where the designer has an opportunity to input their own ideas.

The important part with the design is that it's really your input (Andrew, TT, 1).

He believed that when people are developing their own design concepts, they often are synthesising, comparing and refining others' design ideas that have been used previously.

However, although drawing on others' design ideas, Andrew acknowledged that a design requires one's own unique "input".

What can I copy, what can we not copy? ... In that sort of realisation [stage of design], well I can improve, I can compare, I can synthesise but the design is where you ... are looking at realising your own design (Andrew, TT, 1).

His view of problem solving with hard materials includes recognising an initial overarching problem that must first be understood fully prior to any design.

You look at it and say what's the context of this problem ... So recognition of a problem, understand the context of it and you go through that what if, do I understand what I'm looking at? (Andrew, TT, 1).

Andrew stated that finding out about the overarching problem includes identifying the "context" of the problem, and knowing the "parameters and boundaries". This information gathering may involve having conversations with other people to enable better understanding of the problem.

You pick up sources from having conversations ... So problems for me [are] really just looking at [the problem] and knowing your parameters and boundaries (Andrew, TT, 1).

After gaining "a good grasp" of the initial problem, Andrew believed it becomes a "starting point" from which one can draw on one's own ideas to start designing in an attempt to solve the initial problem. He linked problem solving to design in this way.

You get to a particular stage in your problem solving where you're confident that you've actually got a good grasp of where you think the problem is ... this problem that we've identified gets me to a start point ... along the road with my design [problem solving] is taken over, it's not the design, it's just part of the design (Andrew, TT, 1).

Andrew recognised that problem solving is also involved in the development of designed objects and in this way subsidiary problem solving is an integrated part of design.

Everything that's been designed has had some sort of problem solving prior to it (Andrew, TT, 1).

Finally, Andrew acknowledged the processing of a designed object generates what he referred to as "design decisions", so that the overall design can be made successfully into a realised artefact. He stated that problem solving enables this decision making.

The reality is when you start doing the processing ... that material ... you may make some design decisions saying we need it a bit thicker ... It's a decision, [Problem solving] allows you to make those decisions, informed decisions (Andrew, TT, 1).

Andrew provided an example from his teaching that demonstrated how he considered practical subsidiary problem solving can be interrelated with design. One of his students had designed some seating for a primary school. After the product was designed and made, the student then had to solve further practical problems during the installation of the designed product. This provides an example of further subsidiary practical problem solving when a product is implemented in-situ, *after* it has been designed and made.

That's where your problem solving comes in ...[the outside seat] was all great design but the practical realities of where we were going to locate it ... we went and looked at the site we saw these tree roots and so we had to make an adaptation [to] the actual construction (Andrew, TT, 1).

This later subsidiary problem was solved by an adaptation or modification (further designing) of the original designed product that solved the inherent subsidiary problem of the tree root.

Summary of Andrew's conceptions of design and problem solving with hard materials

The analysis of Andrew's comments reflects his conceptions of design and problem solving as:

1. Design requires some original input usually based on the process of synthesising existing design ideas.
2. Design solves an overarching problem situated in a specific context.
3. Subsidiary problem solving is sometimes an integrated part of developing a designed outcome.
4. When the design is manufactured, there are design decisions that require further practical subsidiary problem solving.
5. Designed products in-situ sometimes throw up new subsidiary problems that require further design modifications.

Andrew's conceptions of design and problem solving acknowledge design solving an overarching problem. He also recognises ongoing subsidiary problem solving that is

integrated with a design outcome. Andrew's background as a technologist is mostly in building and design associated with wood-based materials.

6.3.2 Kevin (TT, 2)

Kevin's understanding and conceptions of design and problem solving relate to his experience as a technologist who worked mostly in wood and laminated timbers, and in his current role as a technology teacher. These are the contexts in which his views are located. For Kevin, wood enables a more creative approach with form and structure than metal.

He stated that when design is mentioned in technology education, it seems to be associated automatically with the commonly used design process that often has prevailed in technology classrooms (see Section 2.3.2, p. 29).

When I talk to people about design I find almost overwhelmingly they're talking about the design process. So when they say design they don't actually mean design. They actually mean a set process that they have prescribed to it. ... For me that isn't what design is about (Kevin, TT, 2).

Kevin's understanding of design incorporated more than just the functional and technical aspects associated with technological design.

I think design means lots of things. ... when you look at a chair what do you see? ... [you should] think beyond just the functional aspects or the technical aspects. ... design can be about lifestyle and it can change people's lives and it can help people (Kevin, TT, 2).

Kevin's ideas about design with hard materials centre around three factors coming together. The first is being familiar with the context where the design is focused. He expressed his ideas in relation to how he would design.

To ... undertake design ... the first thing I think is recognising me in the context (Kevin, TT, 2).

Then, once the specific context is understood, Kevin felt he must recognise whether or not he has the specific technical skills to address the context of the design.

The second thing is having a set of recognisable technical skills that I think could underpin what I'm going to do (Kevin, TT, 2).

The third factor that Kevin felt had to be part of designing with hard materials is inspiration and creativity. Kevin referred to this as the need for "inspiration" to design.

The other [factor] is a certain amount of inspiration ... and perhaps bringing creativity. Certainly it was inspiration ... think beyond just the functional aspects or the technical aspects (Kevin, TT, 2).

Kevin also noted that, in his opinion, “good” and “confident” technical people did not necessarily become designers. In Kevin’s opinion, technical knowledge and experience alone did not automatically enable people to become designers.

I think you can be a good technical person and be a confident technical person for a long time without ever making the step to become a designer (Kevin, TT, 2).

In other words, he considered design required inspiration and creativity alongside knowledge of the design context and technical skills associated with this context.

Kevin acknowledged that design is undertaken in order to solve a problem. He did not express an understanding of subsidiary problem solving being integrated with design. Neither did he identify practical subsidiary problem solving in the realisation phase of the design. Kevin’s concept of problem solving is much “broader” than problem solving linked solely to design.

[You] solve a problem and undertake design ... When someone says problem solving to me I think I have a much broader understanding of what that is. It’s not necessarily tied up with design (Kevin, TT, 2).

He recognised that when addressing a problem in a context using timber or composite materials, it is necessary to have practical knowledge and skills associated with that context. Kevin summarised this as follows:

Do I recognise the context? ... That relies on a certain background of technical knowledge. So if it’s to do with constructing out of timber or composite materials, I’ll recognise myself within that context ... Even if I’m not familiar with the problem, I can still apply [that technical knowledge] to it. ... I would think yes I can bring certain skills to this (Kevin, TT, 2).

Summary of Kevin’s conceptions of design and problem solving with hard materials

1. Designing occurs when the designer can identify the context, can draw on an appropriate technological field of expertise and uses inspiration and creativity.
2. Problem solving applies to learning areas beyond designing with hard materials.
3. Although design problems require technical knowledge and familiarity with the context, these alone do not equate with being able to design.

4. Design solves an overarching problem in a specific context.

Kevin's conception of design is that it should not just be considered as a linear process that takes students through a process of thinking up concepts, designing, making and evaluating a product. His view emphasises the importance of creativity and inspiration as an essential component in design. Kevin holds a more generalist view of technology and does not believe in focusing his teaching on skills or processes because he believes these skills do not enhance students' ability to design. His focus is on broadening his students' understanding of creative design, rather than the practicalities of designing outcomes and the associated subsidiary problem solving in the design detail and the manufacturing of a design.

6.3.3 Matthew (TT, 3)

Matthew's understanding and conceptions of design and problem solving relate to his technology background in engineering and his current role as a teacher who works with a range of hard materials, including electronics.

Matthew described design as a superior form of problem solving.

Probably design is the ultimate problem solving (Matthew, TT, 3).

He commented that designing requires thinking about a series of compromises that includes time and cost.

You certainly need to ... [think] about all the different aspects that you have to compromise with any design, time and cost and inevitably any design is a whole series of compromises (Matthew, TT, 3).

Compromises identified by Matthew, such as time and cost, are referred to as constraints in design by the expert technologists (see Section 5.2, p. 132) and, as Matthew states, when designing, they must be thought about and dealt with. In other words, they are factors that influence how a design develops.

Matthew's ideas about problem solving acknowledge that subsidiary practical problem solving occurs throughout the process of making (designed) artefacts. Anything that is made requires some form of ongoing practical subsidiary problem solving during the realisation of the product. These problems may or may not require design solutions to solve them.

I think [problem solving] is with you inevitably throughout, any time you're ever making anything you're problem solving (Matthew, TT, 3).

This includes redressing any mistakes. He believes that solving subsidiary practical problems of this nature (generated from mistakes) requires thinking and decision making about alternative ways to proceed.

Problem solving goes right down to the small details of correcting mistakes and thinking about how else you can do this (Matthew, TT, 3).

This type of subsidiary problem solving can occur during the realisation of a design but, as stated previously, may or may not require a design solution to solve the problem.

Matthew recognised this similar subsidiary problem solving occurring when someone's design is made into a realised product by another person in a hard materials workshop. Although the initial overall design is developed by someone else, the person making the design may need to solve further practical problems as the design is realised into a product. He asserts that the person making the design is not necessarily designing solutions but is problem solving so that the designed product can be realised. In this way, practical subsidiary problem solving has a tentative association with a designed product. This practical subsidiary problem solving associated with the manufacture of a designed object may be carried out by a different person.

Even if you're making something to [others'] plans, you're not designing something [but] there will invariably be problems you'll have to solve along the way ... You may not have the exact right material available, how are you going to solve that? (Matthew, TT, 3).

Matthew acknowledged that subsidiary practical problem solving occurs often when someone is making things in a hard materials workshop.

So really the whole time you're in the workshop you're pretty much problem solving (Matthew, TT, 3).

Matthew recognised design and problem solving as integrated, describing them as "one".

I see design and problem solving as one and the same thing really... I don't see any differentiation between design and problem solving ... design is the ultimate problem solving that we do ... when you're designing something you're problem solving but at a higher level ... in more detail (Matthew, TT, 3).

Matthew stated that design may also solve an initial problem and that design and problem solving are related in this way.

[If] *you're designing something for somebody, you're solving a problem* (Matthew, TT, 3).

Summary of Matthew's conceptions of design and problem solving with hard materials

1. Optimisation is a factor in design, that is, it is necessary to consider constraints of time, cost, materials, processes and skills.
2. Practical subsidiary problem solving is a component of design, however not all practical problem solving with hard materials requires a design solution.
3. Design solves an overarching problem.
4. Subsidiary problem solving is an integral part of designing.
5. Design is problem solving at a higher level; the ultimate problem solving.

Matthew's conception of design recognises three aspects. First is the role of design in terms of design solving an overarching problem. Second, he recognises subsidiary problem solving as a component within design. Third, Matthew identifies the practical subsidiary problem solving that occurs during the manufacture and processing of a realised design. His views of design and problem solving are centred mostly in the context of engineering. Practical subsidiary problem solving in a workshop does not always require a design solution however Matthew considers it to be a contributing factor in the realisation of a design. Matthew's conception of design is that it is an "ultimate" or higher level of problem solving that is constrained by several factors such as time and cost.

6.3.4 Henry (TT, 4)

Henry felt that designing with hard materials is not something that anyone can do without background experiences with hard materials. As a result, Henry's understanding of and ideas about design and problem solving focused, initially, on the necessity of learning to solve the practical problems associated with the realisation of a design. He believed that learning to design begins with students learning about materials, the processes to manipulate materials and addressing the subsidiary practical problem solving when working with materials.

Henry's ideas about design reflected his belief that learning to design is situated initially in learning about materials, processes and practical problem solving associated with working with materials. He explained this as follows:

You learn to be a designer by problem solving ... you're not a designer already ... a familiarity with processes through problem solving and eventually that will evolve into possibly a full blown design ... awareness (Henry, TT, 4).

To develop knowledge of design, Henry believed that the focus has to be on learning to solve the myriad of minor problems as a design is realised and produced. He considered this practical subsidiary problem solving a key component of designing with hard materials.

He provided an example of how basic, or "prosaic", some of the practical problem solving can be. The very basic level of problem solving he described relates to working out how to use a ruler to measure an object that is longer than the ruler. However basic, it requires a student to think in order to solve this problem.

Totally prosaic things such as ... the Year 13 boy who was wanting to make a boat that was 800mm long and I gave him a ruler that was 600mm long and he said, 'Don't be silly Sir, this ruler is shorter than my boat' (Henry, TT, 4).

Henry considered that a student develops knowledge and understanding of materials as a result of working with the materials. He believed this understanding and knowledge of materials is an important initial component of learning to design, that learning is situated in real materials and their processes.

The knowledge of the materials that you're going to be designing with and an intelligent understanding of the processes that are going to be useful are absolutely critical to good design (Henry, TT, 4).

Henry's ideas emphasised the importance of learning to solve the subsidiary practical problems that occur when a design is made and realised. To be able to solve these subsidiary practical problems, students require experiences processing materials. As a result of learning to process and practically solve problems with materials, students build their knowledge and understanding of the materials used in a design.

Henry also acknowledged the optimising of constraints (parameters) to consider whether or not a design can be realised. The constraints considered include the available processes,

time available and skill level. He related this to the situation in his school when students “come up” with a design idea.

If [students] come up with an idea we look at it whether or not we've got the facilities to actually manufacture that solution to that problem, whether it's going to cost too much, take too much time, take too much expertise, they're the parameters (Henry, TT, 4).

Summary of Henry's conceptions of design and problem solving with hard materials

1. Design requires an understanding of practical subsidiary problem solving that begins with using tools and learning to process materials.
2. Optimisation is a factor in design, that is, it is necessary to consider constraints of time, cost, materials, processes and skills.
3. Learning to solve practical and subsidiary problems builds knowledge of materials and contributes to learning to design.

Henry's conception of design and problem solving focuses on practical subsidiary problem solving being an important component of design. He believes the thinking that occurs when students are confronted with practical subsidiary-type problems helps them to develop their ability to design. He also considers it important to provide his students with opportunities to process and work with actual materials as it enables them to develop experiential knowledge that will feed back into their ability to design with hard materials. As a result of these experiences, Henry believes students are then able to anticipate and solve potential subsidiary practical problems in their own designs.

6.3.5 Patrick (TT, 5)

Patrick's understanding of design emphasises the importance of developing design concepts that can become realised outcomes. With a background as a tradesperson engineer, he recognises the practicalities involved in the realisation of design concepts.

Patrick considered design is based in reality, that is, design concepts should produce something that can be made and not just remain an idea or concept.

You've got to have [design] concepts but what's crucially important I think is to have concepts that are tied to something that's real, and here we go back to that whole thing of that need or opportunity ... the nature of design has got to be coupled with reality (Patrick, TT, 5).

He emphasised design as something that produces a realised outcome. He felt the practical outcome of a design is important as a “proof” that the design has solved the initial problem, need or opportunity. In Patrick’s opinion, it is important to couple a design concept in technology education to a realised practical outcome.

I don’t have a problem with understanding the nature of design but it must be coupled with the practical outcome because without proof positive, where does it lead to? ... design solutions that the boys ... come up with ... are nothing more than paper or card and hot glue and string. They may look pretty but where is the actual learning? (Patrick, TT, 5).

Patrick noted the necessity of knowing about processes to ensure a design can become a realised outcome. Otherwise, he believes, designs are in danger of remaining “simply theoretical”.

What process is it going to use to get those [materials] to work together? And until [you’ve] actually attempted to do something like that [the design] is simply a theoretical outcome or theoretical piece of learning (Patrick, TT, 5).

Consequently, Patrick stated that design concepts using hard materials must be realisable, processed and functioning.

Like concepts of design, but in terms of hard materials it has to work and it has to be processed and it has to be functioning (Patrick, TT, 5).

When working with materials, Patrick considered practical subsidiary problem solving sometimes rectifies the things that go wrong. He noted that this type of practical subsidiary problem solving is distinctive from design.

Problem solving ... you’d be able to pick up a piece of material and you do something wrong and [muck] it up, your job then is to see how that can be redeemed ... that object you’re working on it can be made usable (Patrick, TT, 5).

Patrick recognised that not all problem solving requires a design solution, although these problems still require some thinking and decision making in order to solve them.

Summary of Patrick’s conceptions of design and problem solving with hard materials:

1. Design with hard materials should result in a functioning realised outcome.
2. Practical subsidiary problem solving with hard materials is distinctive from design.

3. Developing a design concept into a realised functioning outcome using hard materials requires knowledge of materials and processing materials.

Patrick's conception of design and problem solving is that effective teaching of design requires a functioning practical outcome, not just a design concept made from glue and string. To enable a design to become a functioning outcome, students are required to have knowledge of materials and processes, and be able to solve practical subsidiary problems associated with manufacture and design. Patrick acknowledges that problem solving occurs in engineering that is distinctive and not associated necessarily with design. Patrick recalled many occasions in his work as a heavy diesel mechanic technologist when he was required to problem solve as in troubleshooting (looking for the problem and trying to find out why it occurred before solving it). This type of problem solving was not associated necessarily with design.

6.3.6 Summary

In Sections 6.3, the analysis of the technology teachers' data identifies their conceptions of design and the role of problem solving in design. These analysed data are important as they build a picture of how these technology teachers' conceptualise key learning concepts that this research is investigating; that is, learning to design and problem solve with hard materials.

In Table 6.2, the common conceptions of design and problem solving identified from the analysis of the teachers' ideas and understanding of design and problem solving with hard materials are summarised. The italicised statements link the expert technologists' conceptions of design and the role of problem solving developed from analysis of the experts' data (see Section 5.7.8) to those of the teachers.

Table 6.2: Five technology teachers’ common conceptions regarding design and problem solving with hard materials displayed with *expert technologists’ conceptions of design and problem solving*

Technology teachers’ conceptions of design and problem solving <i>Expert technologists’ conceptions of design and problem solving (see Section 5.7, p. 145)</i>	Andrew TT, 1	Kevin TT, 2	Matthew TT, 3	Henry TT, 4	Patrick TT, 5
Design solves an overarching problem in a specific technological context <i>1. An initial problem defines a need for design therefore they are closely related</i>	✓	✓	✓		
Subsidiary problem solving is an integral part of design <i>2. Design solves a big problem that may generate subsidiary conceptual problems requiring further design solutions</i>	✓		✓	✓	✓
Design requires practical problem solving as a design is realised <i>3. Design concepts do not stand alone: they must incorporate technical detail and subsidiary practical problem solving to be realised into an outcome</i>	✓		✓	✓	✓
Practical problem solving with hard materials does not always require a design solution <i>6. Some problems can be solved without design solutions</i>			✓		✓
Optimisation is a factor in design, that is, it is necessary to consider constraints of time, cost, materials, processes and skills. <i>7. Design optimises several factors to find the best possible solution</i>			✓	✓	

In Table 6.2, the similarities of the conceptions of design and problem solving between the experts and teachers are displayed. This comparison of analysed data indicates that concepts developed from the technologists’ analysis of design and problem solving are represented in two or more of the teachers’ conceptualisations.

In Table 6.3, a key point that signifies each technology teacher’s individual conception of design is presented. These key points are the result of analysis of the teachers’ responses relating to their understanding and ideas about design and the role of problem solving with hard materials.

Table 6.3: Technology teachers' individual key conception of design and problem solving

Technology teacher	Key point from analysed data of technology teachers' conceptions of design and problem solving with hard materials technology
Andrew, TT, 1	Design requires some original input usually based on synthesising existing design ideas
Kevin, TT, 2	Design occurs when the designer can identify the context, can draw on an appropriate technological field of expertise and requires inspiration and creativity
Matthew, TT, 3	Design is problem solving at a higher level, the ultimate problem solving
Henry, TT, 4	Learning to solve practical and subsidiary problems leads to the ability to design with hard materials
Patrick, TT, 5	Design with hard materials should result in a functioning realised outcome

The analysed data presented in Table 6.3 illustrate the key defining element of these five teachers' conceptions of design and problem solving with hard materials. Andrew's view indicates his understanding that design requires a designer to utilise their own and others' ideas. Kevin emphasises creativity and inspiration as an essential component of design, while Matthew recognises design as a high level form of problem solving. Matthew's view places significance on the problem solving aspect, while Kevin's view stresses the aesthetic creative aspect of design. Henry's view, like Matthew's, acknowledges that learning to problem solve by using materials and processing materials provides a pathway to learn to design with hard materials. Henry's view is situated strongly in design requiring an understanding of, and familiarity with, problem solving associated with processes and working with tools and materials. Finally, Patrick's view considers design with hard materials must have a practical outcome, therefore requiring an understanding of processes and materials. He does not believe design is just about coming up with theoretical concepts. He believes the goal of design should be to produce a functioning outcome using hard materials.

These teachers' conceptions of design and problem solving are reflected in the learning activities and experiences they provide for their students which are presented in Chapter 7.

6.4 Traits of successful novice student designers and problem solvers

Section 6.4 provides an analysis of data to ascertain what these five technology teachers believe to be the key traits of successful novice student designers and problem solvers and to answer the research sub-question:

What are technology teachers' conceptions of the key traits of successful novice student designers and problem solvers working with hard materials?

Analysis of the teachers’ data revealed seven major themes. In the following data, these seven themes have been presented as seven traits of successful novice student designers and problem solvers.

- Awareness and curiosity
- Risk-taking/creativity
- Confidence
- Anticipation of problems
- Evaluation
- Conceptualisation and communication of ideas in three dimensions
- Intuition

Sections 6.4.1–6.4.7 provide analysed data from teachers’ responses to the above question. Words recorded in each of the following tables (Tables 6.4-6.10) are underlined in the following quotations discussing each of these seven traits. In this analysis, students who are novices will be referred to as student designers and problem solvers.

6.4.1 Trait one: awareness and curiosity

Awareness of and curiosity about the world in which students live is the first trait identified from analysis of the teachers’ data. The key words and phrases from this analysis are recorded in Table 6.4.

Table 6.4: Key words and phrases identifying trait: awareness and curiosity

Key words and phrases: awareness and curiosity	look at, studying, questioned, pick things apart, why, attuned, observant, take-in, notice, real world, interested, technological/intellectual curiosity, wondering how, thinking, how it works
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These teachers acknowledged students who manifest traits of awareness and curiosity are students who are interested and look at how and why things are made in the world. They question what materials objects are made from and how things work. Teachers indicated that these students are aware of the world around them and question the “made” things in it. In many cases, they try to find answers to their questions.

Matthew described successful students as those who are aware and curious about the world around them and are interested in and look and study things in detail. They ask how and

why questions. They question how things work, what materials they are made from, and why they are made in a particular way. They are not happy to accept that things are just “there”. Matthew believes that these students have the potential to become good designers.

It's the [students] that then go that step further and actually look at the materials they've used in it ... It's that sort of interest that develops your knowledge ... those [students] that pick things apart, those ones that are interested and they're studying it, they want to know how it works, they're not just happy to accept the fact that it's there. How does that work? ... Why they've made it that shape? ... they're the ones that will go on to be good designers (Matthew, TT, 3).

In the following extract, “attuned” is an adjective Henry uses. He uses the word attuned when he is referring to engagement with one’s environment in a meaningful way. Henry described successful student designers and problem solvers who are aware as being “attuned” to the real technological world around them. These attuned students, who engage with their environment, take in information from their experiences with tools and materials and find out the way things work. They notice and are interested in made objects in the real world.

[Successful students] are attuned to the environment. They're attuned to the way a tool works. They're attuned to the properties of materials. ... They're observant and they take it all in and they just notice. They're certainly in the real world of materials and how things work and they[re] interested (Henry, TT, 4).

Many of these students are curious because they wonder and think about things they look at in their everyday world and question how these things work, and are made to function. Henry summarised these qualities in students as an intellectual and technological curiosity.

They've got an intellectual curiosity in that field and so when they look at a bicycle they'll be wondering how the chain is making it work or how do the brakes work or when they look at anything, they're always thinking about how is that made to work and they've been doing it all their lives. It's a technological curiosity that's there (Henry, TT, 4).

These students’ curiosity enables them to observe technological things in their everyday world and to inquire and think about how and what makes them work. In their everyday lives, the expert technologists also commented that they instinctively look at the world around them always wondering why and how things are made and what they are made from and how this in an informal way builds their design knowledge (see Section 4.4.7, p. 99).

These teachers assert that being aware and curious requires students to be interested in, and questioning of, the world around them. They also indicate that these are likely qualities of students who may be creative (see Section 6.4.2). Students who are absorbing others' designed ideas are developing a database of information that is likely to inspire their own future design and problem solving ideas. The teachers believe inspiration is a component of creativity.

6.4.2 Trait two: risk-taking/creativity

Risk-taking/creativity is the second trait of successful student designers and problem solvers identified from the analysis of the teachers' data. The key words and phrases from this analysis are recorded in Table 6.5.

Table 6.5: Key words and phrases identifying the trait: risk-taking/creativity

Key words and phrases: risk-taking and creativity	risk-taking, creative, confidence, resilient, thinking, ability to do things, figured out a better way, focused
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These teachers are of the opinion that students who are willing to take risks are confident, creative and wanting to find ways to improve their design ideas. Kevin identified successful novice student designers and problem solvers as creative students. This description reflected the strong emphasis Kevin placed on creativity in his own technology programme and belief that inspiration and creativity are essential components of designing. He described very creative students as having a combination of several other qualities. These include students being confident and resilient and, when confronted with a problem, they are able to work through it in a quiet confident manner.

Most kids that are really, really creative are generally ... confident, resilient ... with a problem they'll bring their thinking to bear and quietly work their way through it (Kevin, TT, 2).

Patrick noted that generally students who take risks are unafraid to try something different. He associates risk-taking with being confident, another key trait that was identified from the analysis of the teachers' data (see Section 6.4.3). Patrick also associates confidence with being able to do things.

It is risk-taking ... it's definitely a confidence and their ability to do things (Patrick, TT, 5).

He believes that confidence enables students to take risks which also develops an ability to do things that enables them to take further risks. In other words, one characteristic feeds off, and promotes, the other.

Matthew described some of his successful robotics students as enthusiastic, and focused, constantly thinking up better ways to improve their robotic designs. They are not afraid to try new ideas in their quest to make a better robot.

Each year you'll have three or four [robotics] students who will be completely focused on it. They will think about it day and night. They'll come rushing up to you ... I've figured out a better way of doing it and you know they live it and breathe it (Matthew, TT, 3).

This requires them also to be able to anticipate problems, another key trait identified from the analysis of the teachers' data identifying the traits of successful student designers and problem solvers (see Section 6.4.4).

6.4.3 Trait three: confidence

Confidence is the third trait relating to successful student designers and problem solvers identified from the analysis of the teachers' data. The key words and phrases from this analysis are recorded in Table 6.6.

Table 6.6: Key words and phrases identifying trait: confidence

Key words and phrases: confidence	effectively design, very keen, high quality, be right, can-do this attitude, they know, personal belief, success, validation, good perceptions, good feelings, confidence
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Confidence develops from knowing that you can do things. Patrick identified confidence as a key trait possessed by his successful student designers and problem solvers. He believes that confidence allows students to take risks, which also enables creativity to develop.

Patrick noted that students who have developed their practical skills are able effectively to produce viable designs. He believes that the skills students develop build confidence that impacts directly on students' ability to design.

I think you need to look at practical skills as a bank account and the amount of skills that they acquire is directly proportional to their ability to effectively design and turn out viable designs of their own (Patrick, TT, 5).

Once students have a certain amount of skills they have the confidence to acquire new skills.

They know they can acquire the skill set that they don't have reasonably quickly (Patrick, TT, 5).

As a result, these successful students are able to produce high quality outcomes, have a keen determination to do a good job, and have a “can-do” attitude. Students’ confidence and personal belief are located in their ability to produce high quality outcomes as a result of their practical skills. Patrick identified students having confidence as a key component of this success. The combination of confidence and ability enables them to aim high and achieve.

They're very keen to get on with the job and actually produce things of high quality, that's an absolute fundamental. ... They want it to be right. They have that I know I can do this, attitude. ... there's a huge amount of personal belief. ... this whole confidence thing is absolutely crucial to success (Patrick, TT, 5).

These students’ internal confidence enables them to produce high quality outcomes. Their external confidence, gained from producing a high quality outcome and the acknowledgement of this, further develops their internal confidence.

Andrew and Kevin felt that good students develop their confidence through seeing success using materials and also by having successful outcomes that validate their ideas and give them positive feedback.

When [the students] see success with whatever material they've used ... the element of validation is definitely there and I would say all those good perceptions, good feelings about using materials confidence... getting more confidence the more and more we do things [with materials] (Andrew, TT, 1).

They ... gain confidence of themselves through executing something that they are proud of (Kevin, TT, 2).

The validation and positive feelings as a result of a successful design outcome help to build students’ confidence. The successful outcomes build students’ internal confidence. This confidence motivates students to do more and more things with materials.

6.4.4 Trait four: anticipation of problems

Anticipation of problems is the fourth trait of successful student designers and problem solvers developed from analysis of the teachers' data. This includes being able to integrate different pieces of information about a problem and its design solution. The key words and phrases from this analysis are recorded in Table 6.7.

Table 6.7: Key words and phrases identifying trait: anticipation of problems

Key words and phrases: anticipation of problems	integrated, thinking like engineers, understand multiple levels, do this/affect that, thinking ahead, consequences, implications, planning, decision making, bear in mind, good managers of time
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This trait, anticipation of problems, requires students to think ahead, to be able to anticipate then respond to the many subsidiary or nested problems that are part of design and problem solving with hard materials. To respond to these subsidiary problems, students have to think through any change or adaptation they make and how this can affect and alter an initial design. Matthew described this type of thinking as “thinking like engineers” and he considered his robotics programme develops this ability in his students. The programme not only provides students with a microcosm of various integrated types of engineering but it develops an ability to understand cause and effect and requires students’ thinking to occur at “multiple levels”.

This reflects what the expert technologists identified—that design requires an engineer to anticipate and solve the many subsidiary problems that are an integral part of designing with hard materials (see Sections 5.7.2 & 5.7.3).

These teachers believe that students who can anticipate potential problems and work on possible solutions have success in technology. Matthew’s robotics programme provides opportunities for students to anticipate problems as it integrates a range of technologies with hard materials that require students to problem solve in this manner.

Robotics incorporates ... all the key aspects of hard material technology disciplines and mechanical engineering materials, electronics, software ... all those things are integrated together so it's a real microcosm of what's going on out there in the world. The boys who really get into it and take it seriously they leave here ... thinking like engineers. (Matthew, TT, 3).

Students understand that anything they change in their design affects other aspects of the robot’s design. It therefore requires an ability to anticipate and predict how changes can

affect other aspects of a design and how these subsidiary problems can be addressed, and if necessary, the design modified. Matthew described this as understanding at “multiple levels”.

They understand okay if I do this, ... then it's going to affect that and then it's going to affect that and the software is going to have to be different. They understand on those multiple levels (Matthew, TT, 3).

Henry identified students who can “anticipate” as students who are able to think ahead when planning and make suitable changes to their designs. They are able to consider the consequences and implications of design changes in terms of materials and the making of a design (cause and effect). This enables these students to anticipate the constraints such as time and cost when designing.

[Students] start thinking ahead and they can see the consequences of what they're planning to do before they've actually done it and you can see them changing their decision making even when it's only pencil and paper. ... it's just this whole ability to think ahead and see what the implications of what you're currently thinking of doing are going to be in terms of the materials or ease of making or the cost of it or the time it's going to take and they bear all of that stuff in mind while they're in the act of designing (Henry, TT, 4).

Anticipating the effect of changing various elements in a design and how this impacts on other aspects of a design is an important component of these students' thinking skills.

Patrick recognised that students who are able to anticipate problems are students who are good time managers.

They're generally very good managers of time as well because they're prepared to put in quite a bit of time to get the outcomes (Patrick, TT, 5).

The implication of this is that students are able to anticipate the effort required to produce a satisfying outcome.

6.4.5 Trait five: evaluation

Evaluation is the fifth trait of successful student designers and problem solvers developed from the analysis of the teachers' data. The key words and phrases from this analysis are recorded in Table 6.8.

Table 6.8: Key words and phrases identifying trait: evaluation

Key words and phrases: evaluation	evaluation, able to evaluate, critical thinking, reflective practice, modifying design, refining, improving, scrapping, thinking about
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These students are able to evaluate their own outcomes in a critical way, which enables them to inform and improve the next things they make, providing them with the “full loop” of design.

If they do an evaluation of what they attempted to do they invariably come up with the ideas of I didn't do that right, ... so there is, the full loop of it is finding out or being able to evaluate the project or the processes that you've used to achieve an outcome ... this is crucial to their repertoire of skills that they're going to use for the next thing [they design and make] ... Critical thinking absolutely crucial and then to be able to ... say or come to the conclusion how could this be improved upon (Patrick, TT, 5).

Henry identified this characteristic as “reflective practice” and the hallmark of his top technology students.

Reflective practice, that's the hallmark of the top [students] (Henry, TT, 4).

Matthew described how his robotics team can identify others' good design ideas at their regular monthly competitions. Seeing others' designs motivates his students to think critically about, and reflect on, their own designs. On a monthly basis, this often results in them pulling their designs apart, adding things, beginning again, modifying to improve and refine their own designs. In some cases, this knowledgeable reflection enables them to graduate all the way to the national finals robotics competition. Matthew described his students' ongoing evaluation.

We have our monthly schools [robot] competition, our kids are all competing and then they see someone else's robot and oh that's a really good idea, why didn't I think of that so they tear back and pull theirs apart and add things on and they're constantly modifying their design all the way through right up to the nationals. ... They design a product they're constantly refining it all the time and improving it and scrapping it and starting from square one again (Matthew, TT, 3).

Matthew's example of his students' forward thinking about robot design manifests itself in the modification and refinement of their own robots. Also, they are able to be self-reflective as Matthew identified, asking, “Why didn't I think of that?” when seeing another student's good idea.

Matthew described how particularly good it is when students reflect on their designs in their own time, outside of class time, and want to share these reflections. In other words, they are beginning to self-evaluate their designs while still requiring teacher feedback and input.

You've got kids coming up to you out of class time ... 'do you think that will work Mr [name supplied], I've been thinking about that', and if they're doing that, that's really good (Matthew, TT, 3).

6.4.6 Trait six: conceptualisation and communication in three dimensions

Conceptualisation and communication in three dimensions is the sixth trait of successful student designers and problem solvers developed from the analysis of the technology teachers' data. The key words and phrases from this analysis are recorded in Table 6.9.

Table 6.9: Key words and phrases identifying trait: conceptualisation and communication in 3-D

<p>Key words and phrases: conceptualisation and communication in three dimensions</p>	<p>think in 3-D, communicate ideas, do design, draw ideas, express in 3-D, work in 3 dimensions, implement ideas, visual literacy</p>
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Conceptualising and thinking in three dimensions and being able to communicate these ideas effectively through drawing in three dimensions are identified as characteristics of a successful student designer by Henry and Matthew.

Some kids can think in 3-D and can draw and can communicate their ideas ... and do design (Henry, TT, 4).

Being able to flip something around in their head, conceptualise in three dimensions and being able to communicate ideas through drawing, including 3-dimensional drawing, are abilities that Matthew identified as being very helpful for students. Clearly, these abilities enable students to work in three dimensions.

I usually find a good yard stick as to whether [students are] able to implement their ideas is whether they can draw [ideas]. ... Their ability to sort of express themselves in 3-D ... their ability to flip something round in their head and draw it generally means they can work in 3 dimensions (Matthew, TT, 3).

Patrick described an overall purpose for what has been known commonly as graphics. He believes it enables students to look at a model (drawing or sketch) and visualise it as a real

object. In this way, students are able to reflect critically on how they can improve the design through using their visualisation skills.

Graphics or now design and visual communication is important because it teaches [students] what we'd like to call visual literacy. One of the foci of graphics in its traditional sense is being able to look at something and say, why was that made that way (Patrick, TT, 5).

Students who are able to sketch in three dimensions practise this ability of visualisation and are developing their visual literacy.

6.4.7 Trait seven: intuition

Intuition is the seventh trait of successful student designers and problem solvers developed from the analysis of the technology teachers' data. The key words and phrases from this analysis are recorded in Table 6.10.

Table 6.10: Key words and phrases identifying trait: intuition

Key words and phrases: intuition	intuitive skill, can see it straight away, understand, talented, instinctively, design, what am I going to make, hands-on, real understandings
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Intuition is a trait identified in students who often find the written aspects associated with technology, such as “folder work”, a major challenge. These male students were identified as having intuitive skill associated with design and making products. They use a workshop environment in a purposeful way that enables them to design and make things. Matthew compared these students to New Zealanders known for their practical engineering achievements, who developed many aspects of their designed products (motorbikes and personal jetpack) through “doing”.

Just by doing it. They're John Britten's and the jet pack guy [Glenn Martin] ... They've got a lot of intuitive skill and quite frankly a lot of them will run rings around the more academic ones, the ones that can produce these lovely folders (Matthew, TT, 3).

Matthew explained how these students with intuition see mechanical problems straight away and, in his opinion, could become good practical engineers. He provided an example of a project designed and made by a talented student who struggled with written work.

If there was some sort of mechanical problem, no that's too heavy or that's not going to be strong enough they can see it straight away. They understand and they're the sort of boys that actually would probably make quite good engineers ...

The first year I did any Level 3 standards ... one [student] that struggled with written work but he built a live bait bin for his project for his father's boat, pumps, levels, did everything, functioned. That's a very talented young man (Matthew, TT, 3).

Henry also identified students who are not academic necessarily, but instinctively know how to work with materials.

The funny thing is that the people who are not all that academic, can end up being the amazing ones ... They instinctively know how to work with things (Henry, TT, 4).

Henry emphasised these students work purposefully and cleverly in a workshop environment designing and making things.

Matthew reiterated how much he valued the talent of a number of his students who are able to design, but struggle with the associated written work.

There'd be a number of boys on my course that would just design [other students] under the table but you know they can't be bothered producing a folder or they struggle with dyslexia or whatever but they're actually very talented ... If I had a design problem to solve ... it would be those students I'd give it to (Matthew, TT, 2).

He acknowledged how at “options evening”, these students yearn to find out what they are going “to make”. Matthew also noted that the design “process” has become so dominant in some curriculum documents that it obscures the actual purpose of design, that is, to produce a realised solution to a problem. The sentiments expressed in these documents lack appeal for some of his male students, who are interested above all in what they design and make.

These boys when it comes to options evening next term their question is, 'What am I going to make?' It's as simple as that. ... One of the reasons we don't get any students for the IB [International Baccalaureate] design technology is fundamentally because the blurb in the handbook is just a rant and rave about the design process. Boys their eyes glaze over and next? (Matthew, TT, 3).

In Matthew's opinion, the best engineers, regardless of their academic or trade background, require some form of hands-on practical experiences to give them what he referred to as the “real understandings”.

... The best engineers will always be the ones that have had their hands-on, I've been in engineering all my life in one form or another. Those are the people that have the real understandings those are the people who are probably more likely to produce solutions (Matthew, TT, 3).

This trait, expressed as intuition in this analysis, recognises those students who have a type of natural aptitude in terms of hard materials and technology education. While trying to “teach” intuition may be an unrealistic goal for educators, the findings do suggest that this type of technological intuition should be nurtured and developed through specific practical learning opportunities that challenge these students’ thinking and understanding. Likewise, the skills that contribute to students’ intuition can be supported through teachers’ pedagogy. These skills include being able to make quick decisions, ability to work practically on problems in a workshop situation, and the opportunity actually to make things and try them out.

6.5 Summary of traits

In Table 6.11, the seven traits of successful student designers and problem solvers, from the findings of the five teachers’ data, are summarised. Included are key words identified from teachers’ data associated with each of the seven traits.

Table 6.11: Summary of key words/phrases identified from teachers’ findings defining traits of successful student designers and problem solvers

Key identifying traits of successful novice student designers and problem solvers	
Awareness/Curiosity	look at, studying, pick things apart, questioned, why, attuned, observant, take-in, notice, real world, interested, technological intellectual curiosity, wondering how, thinking, how it works
Risk-taking/Creativity	risk-taking, creative, confidence, resilient, thinking, ability to do things, figured out a better way, focused
Confidence	effectively design, very keen, high quality, be right, can-do this attitude, they know, personal belief, success, validation, good perceptions, good feelings, confidence
Anticipation of problems	integrated, thinking like engineers, do this/ affect that, understand multiple levels, thinking ahead, consequences, implications, planning, decision making, bear in mind, good managers of time
Evaluation	evaluation, able to evaluate, reflective practice, critical thinking, modifying design, refining, improving scrapping, thinking about
Conceptualise 3 dimensions	think in 3-D, communicate ideas, do design, draw ideas, express 3-D, work in 3-D, implement ideas, visual literacy
Intuition	intuitive skill, can see it straight away, understand, talented, instinctively, design, what am I going to make, hands-on, real understandings

The relevance of identifying traits of successful students is that ideally they are the traits teachers would like all their technology students to develop during their time at school.

The pathway for teachers to develop these traits relevant to design and problem solving is located in their pedagogy. That is, the relevant learning experiences they provide for their students. The analysis of the pathways that these five teachers provide for their students to develop these key traits is presented in Chapter 7.

6.6 Summary of teachers' data

In Chapter 6, the analysis of the teachers' data presents three aspects associated with design and problem solving that are relevant and influential to teachers' pedagogy enabling students to learn to design and problem solve with hard materials. These three aspects are summarised as follows.

First, the background profiles of the five technology teachers, is presented (Section 6.2). The teachers' background information presents the expertise and significant influences that have informed these teachers' learning as technology educators. Of particular significance is four of the five technology educators had been practising technologists prior to becoming technology teachers.

Second, the analysis of the teachers' data records the teachers' conceptions of design and problem solving with hard materials (Section 6.3). Section 6.3.6 provides a summary of the commonality between the teachers' conceptions and compares their individual conceptions of design and problem solving.

Third, the analysis of the teachers' data identifies the traits that successful technology students demonstrate and that teachers would also wish to develop in all student designers and problem solvers (Section 6.4). These traits are summarised in Section 6.5.

Chapter 7, the following chapter, presents the analysis of the teachers' data indicating how these three aspects are linked to the learning experiences and pedagogy the teachers provide for their students in their technology classrooms to support students learning to design and problem solve in the context of hard materials.

Chapter 7: Technology Teachers' Pedagogy

7.1 Introduction

This chapter presents an analysis of the interview data of the five technology teachers who shared aspects of the pedagogy they provide for their students which they believe enables students to learn to design and problem solve with hard materials. The teacher interview guide questions (Appendix B) used to obtain data for this chapter focus on asking teachers in what ways they consider knowledge of hard materials, and experiences with them, contribute to students' learning, and how they provide these learning experiences for their students. The overriding research question guiding the analysis in this chapter is:

In what ways do teachers consider learning experiences with hard materials can influence and support students' knowledge, understanding and learning to design and problem solve with hard materials?

First, in Section 7.2, three issues are examined relating to the teaching of design and problem solving with hard materials. These three issues were identified from the analysis of the teachers' responses to the interview questions and relate to students' experiences of hard materials and the teaching and learning of design and problem solving, using hard materials. The role of experiences with hard materials in learning to design and problem solve is a key focus throughout this analysis.

Second, in Sections 7.3–7.7, the analysis of the teachers' interview data examines and presents these teachers' pedagogy. Section 7.3 provides an introduction to this pedagogy section. Section 7.4 examines the data analysis addressing students' limited experiential learning with hard materials. Section 7.5 presents the data analysis addressing students' limited experiential knowledge of materials. In Sections 7.6 and 7.7, the analysed data indicates in what ways the teachers consider their pedagogy provides experiences with hard materials that enable students to learn to design and solve problems with hard materials. Specifically, in Section 7.7, the analysis provides information about how teachers scaffold learning for their students. Section 7.8 provides a brief summary of key points.

The analysed data in Sections 7.3–7.7 link to three aspects of data findings presented previously in Chapter 6, namely:

- How teachers' pedagogy is influenced by their individual experiences as a technologist and/or teacher (Section 6.2)
- How teachers' own conceptions of design and problem solving (Section 6.3) are acknowledged in their pedagogy
- How teachers foster the key traits of successful novice student designers and problem solvers (Section 6.4) through their pedagogy.

7.2 Experiential issues relating to teaching design and problem solving

The analysis of the teachers' data in response to questions asked about their students' experiences with hard materials and their learning to design and problem solve with hard materials revealed three issues associated with the teaching of design and problem solving with hard materials. While there are many overlapping areas between these three issues, they are presented separately in Sections 7.2.1–7.2.3. The three issues are:

- Students lack experiential learning with hard materials (Section 7.2.1).
- Students lack the experiential knowledge of materials that enables experts to design (theoretical, practical, processing and manufacturing knowledge) (Section 7.2.2).
- Students lack previous experience of designing and problem solving with hard materials and the knowledge, understanding, skills and attitudes this provides (Section 7.2.3).

7.2.1 Students lack experiential learning with hard materials

The first issue arising from the analysis of the teachers' data relating to the teaching of design and problem solving with hard materials is that many technology students lack practical childhood experiences in the real world. Particularly, these students lack experiences of manipulating and making things with hard materials. In other words, these students have limited experiential learning with hard materials when they arrive in their secondary technology education class. (The "real" world is defined in this analysis as the actual physical world as opposed to a simulated or virtual world.)

Henry identified his students' lack of experience as an important constraint associated with learning hard materials technology in a school environment.

Here at school we have cost as a constraint and hugely more important than that we have time as a constraint and even more important than that we have the lack of the kids' experience as a constraint (Henry, TT, 4).

As a consequence of this lack of experience, Kevin commented that he had to “start from scratch”, getting students used to working with real things. Kevin explained this problem:

The kids don't come to us with an enormous reservoir about what technology is or why they do it or anything like that. You are constantly starting from scratch (Kevin, TT, 2).

Andrew explained how his students ask questions about materials that sometimes surprise him with their naivety.

I mean some of the questions students ask me are, 'Can you bend glass?' ... all this hard material ... around them ... but they've never queried [it] (Andrew, TT, 1).

Matthew contrasted students' lack of experiences in the physical real world with his own childhood experiences.

Kids these days have far less understanding than like in my generation where we made little push carts and we were out and about. You'd go up the river and make a dam across it and you were always playing in the physical world ... [students'] understandings of the real world are actually quite limited ... their lives are just filled with all these products they use (Matthew, TT, 3).

Like Matthew, the expert technologists (Section 4.2) all acknowledged having similar experiences when growing up. The experts' experiences included pulling apart things made from hard materials, building things using hard materials, fixing broken things and trying out the things they made in the real world to see how effectively they worked. This gave these experts their initial experiences with hard materials in the real world.

As Henry commented, today, for many students the prevalent type of play growing up does not include making or interacting with physical objects that are real. As a result, Henry believes his students are not building their knowledge about how things work in the real or physical world.

Increasingly it's the stuff that [students] are playing with is not very helpful for design because it's just computer games ... intuitive knowledge of how the world works ... kids build up from playing with real things (Henry, TT, 4).

Patrick noted that the passing on or sharing of knowledge by parents, that may have occurred in the past, is largely absent from many of the lives of the boys at his school.

We don't see dads playing with their sons in the garage making stuff anymore. That is the exception rather than the norm ... [the boys] often lack that 'oh dad can you give me a hand to fix my bike?' (Patrick, TT, 5).

Andrew expressed concern that many of the female students at his school have never been challenged before to think about “how things work” in the real world.

My experience with these girls is that the old 'how do things work'... there's this blank, they don't really question how things work (Andrew, TT, 1).

This is an experiential gap Andrew tries to fill when choosing suitable learning experiences for his students. Initial experiences are designed to raise awareness about the students' everyday world.

Patrick makes the same point when he recognises the significance of students who have had practical experiences in the physical world, and how these experiences support their learning with hard materials and ultimately designing with hard materials. The significant number of students at Patrick's school have grown up in an urban city environment. However, a percentage of his students have farming backgrounds.

I think you'd find that this would be ... quoted everywhere round New Zealand is that the students who take engineering or woodwork who come from a rural or a farming background are yards and yards ahead of boys or students who live in the cities ... they've been out there doing stuff ... whether it's just fixing something, pulling something apart, making something work, trying to adapt it ... they have not necessarily come in and sat down in front of a play station or TV (Patrick, TT, 5).

Henry also commented how farmers' sons have had valuable growing-up experiences that they bring to their learning. They have had more practical opportunities in the real world than some of the other students at his school.

Farmers' sons.... Growing up on the farm, live a practical life versus an accountant's son where if anything goes wrong you just pay someone to fix it (Henry, TT, 4).

In summary, the first issue relating to the teaching of design and problem solving identified from the analysis of these teachers' data is that many students arrive in their hard materials technology classes with limited practical growing-up experiential learning using hard materials in the physical real world. As a consequence, students lack an awareness of what,

where, why and how materials are used in the physical world in which they live. This is a gap in students' experiential learning that teachers' pedagogy must consider and try to address in both the initial and ongoing learning experiences they provide for their students.

7.2.2 Students lack the experiential knowledge of hard materials that enables experts to design and to problem solve

A second issue identified from analysis of the teachers' data is that students learning to design and problem solve have very limited previous knowledge associated with hard materials. This relates also to the first issue discussed in Section 7.2.1. That is, students' limited experiential knowledge of materials is partly the result of their lack of previous practical experiential learning with hard materials. As well, most students have no manufacturing or processing knowledge about hard materials. Because of their lack of experiences with materials, students have limited knowledge of their characteristics or properties. Learning about the properties of materials (descriptive/theoretical knowledge) can develop through practical experiences with materials as well as through some "book" learning. For example, the properties of different materials can be found recorded as quantified grades in relevant textbooks. However, it is very useful to discover and compare the relative hardness and ductility of materials through working directly with the materials. It appears that practically working with materials provides an experiential way to learn about materials and is likely to provide a more comprehensive understanding of the differences.

Students' lack of knowledge about materials contrasts with the body of knowledge that expert technologists utilise when designing. The expert technologists in this research noted how they are able to draw on their practical, theoretical, processing and manufacturing knowledge of hard materials when designing. As detailed in Sections 4.5–4.7, these experts put great value on learning this cluster of experiential knowledge relating to materials through their many experiences with hard materials on their journey to becoming experts. The experts' experiences with materials included activities such as working with materials, hands-on experiences, seeing materials fail and seeing materials used effectively in design.

The five teachers observed that their technology students do not have the cluster of experiential knowledge of materials that technologists draw on when engaging in design and problem solving with hard materials. Consequently, they need to provide learning opportunities for their students to build this understanding and knowledge. Normally, this

occurs through a teaching programme to provide appropriate interactions with materials in support of their learning, as discussed later in this chapter (Section 7.3).

Matthew acknowledged the importance of understanding materials when designing with hard materials:

It's essential I think. I don't think you'd really be much chop designing anything unless you understand the materials you're working with ... where you need supports, where you need to brace it, where the stresses and strains are going to be, how is it going to weather, is it in an environment that's corrosive, will you get galvanic corrosion if you join it with two different types [of material, e.g. aluminium and copper]. All those things (Matthew, TT, 3).

Henry recognised that expert technologists have substantial knowledge at their disposal when designing and problem solving with hard materials. This includes knowledge and understanding of materials and processes.

[An expert] can look ahead and anticipate problems. [S]he already knows the resources and tools [s]he's got at [her]/his disposal and what they're able to do ... [An expert] knows already how the materials are going to respond to the way [s]he treats them ... it's a well-known concept within the design world that you do bring your experience and understanding of materials and processes to bear (Henry, TT, 4).

Henry described his experience of students trying to design with no background of practical experiences with materials or understanding of material processes.

Some courses teach design with not a lot of practical component to it at all ... my experience of kids ... who try and design things from that sort of background is that the things don't work or can't be made because they've got no understanding at all, no genuine understanding of the materials or the processes they use to actually realise the designs (Henry, TT, 4).

As a result, students try to design using concepts or ideas that are impossible to produce with available materials, or are unable to be realised into a functioning real object or product.

[Students] design things that are impossible or impractical or not feasible or too expensive or plain won't work (Henry, TT, 4).

Henry believes that knowledge and understanding of materials and the processes that can be used with materials are “critical” elements in design.

Knowledge of the materials ... and an intelligent understanding of the processes that are going to be useful are absolutely critical to good design (Henry, TT, 4).

In summary, the expert technologists have accumulated knowledge and understanding of a wide range of materials and the processes available to realise and produce a design into a product. Also, they have resources of descriptive theoretical knowledge of materials they can draw on when designing. Experts have developed part of their knowledge about the properties of various materials through their experiences of designing with them. This accumulated knowledge of materials enables experts to develop design concepts and to understand the problem solving associated with concepts before they are realised into an actual product. Teachers assert that students do not have this knowledge base as novices beginning to design with hard materials. As a result, teachers' pedagogy supports students learning to design in a different way to that of experts. They believe that students require particular types of learning experiences with hard materials to help them develop and build their experiential knowledge and understanding of materials if they are to learn to design effectively with these materials.

7.2.3 Students lack experiential design and problem solving knowledge with hard materials

The third issue identified from the teachers' data analysis relates to students' general lack of design and problem-solving experience with hard materials. Again, this contrasts with the expert technologists who have years of experience providing them with a rich and varied range of design and problem solving experiences including design outcomes. The analysis of the experts' data (Sections 4.4–4.8) confirms how they use previous experiences of design and problem solving when they anticipate a new design problem. As a result of many design and problem-solving experiences, these experts have an accumulated database of knowledge and understanding about effective design and problem solving on which to draw. The experts have experienced previous design outcomes being successful and, in some situations, failing. As a result, these experiences provide experts with important feedback that contributes to their current understanding of the complexities and detail required to design effectively with hard materials.

These technology teachers noted that students have to begin their journey as novice designers and problem solvers through a different pathway from expert technologists.

Henry believes that the linear design process (see Section 2.3.2, p. 31) available to experts to use as a model is not how novice students are able to design or to problem solve because, unlike experts, students have no previous design experiences on which to draw.

The design process that we hear touted in technology education is a process that's used by experts and it's fine if you give it to an expert to use it. But the advantage that the expert has over the novice is that he's been through the whole situation many times before (Henry, TT, 4).

Matthew feels that the current New Zealand technology curriculum (MoE, 2007) tends to be unrealistic in terms of the expectations it places on students to design with hard materials with limited or no previous design experiences.

The modern technology curriculum tends to put the cart before the horse in some ways (Matthew, TT, 3).

Of course, as noted above, students as novice technologists do not have a bank of experiences that includes knowledge and understanding of materials, as well as knowledge about the available processes and problems that crop up when designing. Therefore, Henry does not believe it is effective pedagogy to use a design process that requires a level of knowledge and understanding similar to that of experts.

[Students] don't [have the background design experiences of experts] and so they need to have a different approach to learning design. I've come to the conclusion now you don't teach design by taking the [students] through the design process as used by experts (Henry, TT, 4).

As a consequence, Henry believes it is necessary to have a modified plan to teach design and problem solving to novices or students.

You have to produce a modified plan of attack ... when you're working with novices (Henry, TT, 4).

Patrick reiterated what Henry noted about beginning student designers. Students find the complexity of thinking through a series of steps required to design and problem solve extremely difficult with little previous experiences. Anticipating the order or series in which things should be done is problematic for beginning students.

The boys don't have the experience to think their way through a whole series of things. They don't know ... that series of step by step process, I've got to do this, this and this before I do that. If I do that first, then I can't do one of these steps here ... that's something that they don't really have a handle on (Patrick, TT, 5).

In summary, the third issue for teachers relating to teaching design and problem solving is that novice student designers have very limited, or no, previous experiences of design or problem solving with hard materials. Therefore, students cannot create design concepts when confronted with an initial problem without having design and the related problem solving unwrapped through some form of a scaffolded supported pathway. This pathway includes teachers providing a range of experiences with hard materials to introduce and develop experiential knowledge of how to design and problem solve with hard materials.

7.2.4 Summary of experiential issues relating to teaching design and problem solving with hard materials

The three issues identified from the analysis of the teachers' data in Sections 7.2.1–7.2.3 relating to students learning to design and problem solve with hard materials are summarised as:

- Students have limited or no **experiential learning** in the physical real world using hard materials.
- The **experiential knowledge** that experts possess relating to the characteristics of hard materials contrasts with the lack of this knowledge in novice student designers and problem solvers.
- Students have no **experiential design and problem solving knowledge**. That is, students have no previous experience to draw on when designing of either successful or unsuccessful design outcomes. In many situations, students have never designed or problem solved with hard materials.

In Sections 7.3–7.7, the analysis of the teachers' data indicates how the teachers' pedagogy is focused on providing learning experiences that address these three issues.

7.3 Mining the data for technology teachers' pedagogy

Sections 7.3–7.8 focus on presenting the analysed teachers' data that provide information about the sub-research question guiding this chapter:

In what ways do teachers consider learning experiences with hard materials can influence and support students' knowledge, understanding and learning to design and problem solve with hard materials?

To obtain these data, teachers were asked to share their pedagogy that includes experiences when using hard materials as a context that supports students' learning of design and problem solving. Teachers were asked also to explain the value for their students of these experiences with hard materials in terms of their impact on the development of their learning to design and problem solve.

In Chapter 6, the profiles of the five teachers' technological and teaching backgrounds were presented, along with their conceptions of design and problem solving and the key traits teachers considered successful novice technology student designers and problem solvers displayed (Sections 6.2–6.4). These three aspects, together with data presented earlier in this chapter (Section 7.2), provide clues to the teachers' choice of pedagogy to enable students to learn to design and problem solve with hard materials. Consequently, in Sections 7.4–7.7, the analysis of the teachers' data:

- Identifies the learning experiences that acknowledge and try to solve the three issues identified in Section 7.2 relating to teaching design and problem solving in hard materials technology.
- Recognises the influence of teachers' technology-related backgrounds described in Section 6.2 and their conceptions of design and problem solving presented in Section 6.3.
- Indicates how the identified key traits of successful novice student designers and problem solvers in Section 6.4 are fostered and developed in all students.

Specifically, in Section 7.4, the analysis of the teachers' pedagogy considers how to develop students' limited **experiential learning** in the physical real world (Section 7.2.1); Section 7.5 shows how teachers compensate for students' lack of **experiential knowledge of materials** (Section 7.2.2); and Sections 7.6 and 7.7 show how teachers take into account and supplement students' lack of **experiential design and problem solving knowledge** (Section 7.2.3).

7.4 Pedagogy developing students' limited experiential learning of hard materials

In Section 7.4, an examination of the teachers' pedagogy provides information about in what ways the five technology teachers take into account the issue of students having limited experiential learning of hard materials. In response to this issue, the teachers provide learning experiences that include analysing existing designed products. In addition,

the learning experiences described by the teachers encourage students to become more curious, aware and critical of their everyday world, including the creativity located in the objects designed and made from various types of hard materials. Awareness and curiosity, risk-taking/creativity and the capacity to evaluate are three key traits of successful novice student designers and problems solvers, hereafter referred to as key traits, recognised by the teachers and noted in Sections 6.4.1, 6.4.2 and 6.4.5. These teachers aim to foster and develop these traits in all their students by providing the following learning experiences.

7.4.1 A pedagogy to develop awareness of design, creativity, materials and how things are made

These teachers acknowledged the value of getting students to explore designed products to develop their awareness and curiosity. Through discussion, students are encouraged to evaluate these designed products, and acknowledge the innovation and creativity of the design. That is, developing three key traits: awareness and curiosity, risk-taking/creativity and evaluation.

The expert technologists recognised the importance of these types of experiences described in Section 4.4. Indeed, the five experts acknowledged growing up with access to this type of experiential learning with hard materials.

One of Andrew's strategies is to provide opportunities for students to examine and evaluate designed products. A focus of this activity is to get students to consider, reflect on and describe what they think might have contributed to the making of a product. For example, the materials and the processes used. This exercise aims to raise students' awareness and curiosity about their everyday world by getting them to think about what materials make up everyday things and why they are made from particular materials, such as steel. It encourages them to ask the "what and why" questions about how things are made.

We've had some fantastic discussions about what's the road made of, what's that ... Viaduct made out of. ... how they join it, what would they use to join it, and why do they use steel. ... We've actually just walked around and just look at the buildings and the range of materials that we've got here [at school] (Andrew, TT, 1).

Andrew considers it valuable for students to "deconstruct" a designed product or "break it apart" to see how it is made.

The best way I've found to introduce to the students they get it in their hands and they can deconstruct it and break it apart (Andrew, TT, 1).

In essence, Andrew believes that this pedagogical scaffolding with his students develops an understanding of construction through “deconstruction”.

Matthew likes getting students to “touch and handle” others’ designed artefacts to develop students’ awareness of design possibilities before designing a similar project of their own.

If they've got lots of things to look at and sort of touch and handle. It certainly helps in developing their [design] ideas and they can sort of see what can be done and what can't be done ... there's no substitute for just playing with real things (Matthew, TT, 3).

Another pedagogical strategy used by Kevin is to share technologists’ designs with students in order to raise their awareness of design in the world around them. He argues that a part of technological creativity is having an awareness of materials used in successful designed objects and how that relates to the problem and design in hand. Such awareness increases the potential in students to think beyond their normal experiences and provides the capacity and potential for original and new creative solutions to problems. Kevin stated that Hundertwasser architecture provides a particularly creative example of design that utilises an unusual range of materials. Also, through this type of experience, students get to evaluate a designer’s work.

[We] do things like let's have a look at the existing work of [designers] what they recognise as being quality, what is common about their materials? Why do we like these? What are we going to do in our project that's going to make us respond in the same way? ... Tuesday we are going to look at existing architecture and look at the Hundertwasser model [of a proposed alteration to an existing building] and go to a chapel. We go look at timber places and we wander around (Kevin, TT, 2).

This kind of exposure to how different designs are integrated is also provided by Matthew, who takes his Year 11 class to see and appreciate the integration of the many different technologies when a super-yacht is being built, beginning with the design and ending with a realised outcome. The students begin their visit in the design office and then go and see the materials and different processes that are used to make a super-yacht. Seeing an overview from the design phase through to the development of a final functioning product develops the key trait of awareness and curiosity in students about the complexity of processes, and the many and various materials involved in the realisation of a design

concept of this magnitude. As well, students are encouraged to appreciate the creativity of the end product.

I take my Year 11 course out on a whole day trip and we go to [name supplied] so they see these multi-million dollar floating works of art being created. They see all the integration of all the trades that are required to build these things. They start in the design office and ... work their way down onto the [work]shop floor and see the cabinet makers making all the fittings for the boat and they all have to be properly sound proofed and how they make the air conditioning ducting ... so they really get to see what's involved. ... at the end of that day it's really got them thinking ... I think there should be far, far more relationships between industries and schools (Matthew, TT, 3).

During this visit, the students are presented with a “global” picture of super-yacht construction. As well, they experience the deconstruction of the super yacht by seeing the number of different components, trades and expertise required to build it. Seeing design realised in the commercial world develops students’ awareness of the design possibilities with hard materials, and the creative ways materials and design combine to make an aesthetic functioning product.

These pedagogical experiences described by the teachers help to compensate for the deficiencies in students’ past experiential learning and help develop some of the key traits in students identified in Section 6.4.

7.5 Pedagogy and learning experiences to address students’ limited experiential knowledge of materials

The issue of students’ lack of knowledge about materials in contrast to expert technologists’ extensive experience of materials was discussed in Section 7.2.2. The five technology teachers acknowledged the importance of knowing about materials so that students are able to design effectively with hard materials. Consequently, the teachers sought to provide students with meaningful experiences of hard materials to build their understanding and knowledge.

For example, Henry described why he considers that students need to learn about materials and processes very early on in their journey to becoming designers.

[Students] have no knowledge of what they're doing. ... no knowledge of how to make the thing. ... have no knowledge of the processes. So what they design they design in ignorance ... and they're really unable to ever realise any of those designs ... or they just don't work (Henry, TT, 4).

Henry, therefore, believes that students require some knowledge of the materials and the processes by which things are made to support them and enable them to realise their own original designs. He does not consider this just happens with no support.

You don't really want people to be constrained by conventional wisdom, you want them to think of new and original stuff and then just make it happen. I can understand that, but then I think if you did that 90% of the time you'd end up with a pile of rubbish (Henry, TT, 4).

In Section 7.5.1, the purpose of providing sensory experiences with materials for students is analysed. In Section 7.5.2, the purpose of students learning about and experiencing the processing of hard materials is discussed. The way these learning experiences develop key traits, as identified in Section 6.4, is also highlighted throughout Sections 7.5.1 and 7.5.2.

7.5.1 Sensory experiences with materials

All five teachers provide experience of materials for their students at a quite rudimentary level, beginning with an initial sensory type experience of being able to touch, feel and even smell various hard materials. The teachers consider this a necessary stage for those students who have had very limited previous experiences with hard materials.

For example, Andrew described the importance of having a multi-sensory experience of materials as different from just seeing a material.

You can visually look at [the material] but when you start feeling it it's a lot different so when they get it in their hands and they can deconstruct it and break it apart ... tactile, using all their senses (Andrew, TT, 1).

He also acknowledged that from these initial sensory experiences the brain can connect with the material in a more meaningful way.

Once you get it in your hand and you feel it, only then will you [think] oh is this what it actually feels like, I know what it weighed, I know what it looked like, I know the testing of it but when I actually feel it your brain connects with it (Andrew, TT, 1).

Henry believes that students learn about materials in a way they are never going to forget through practically working with and experiencing them. He provided the following example.

A really meaningful way when they [the students] are trying to actually use materials to do something they want ... if they get a little piece of thin acrylic sheet and they're trying to use that to build the base for a robot and they drill holes in it and it cracks all the time, they will learn about that material in a way that they're never going to forget and then when you say okay this material will drill beautifully suddenly they will fall in love with PVC and they will hate acrylic. They've got a real vested interest in the properties of the material because their knowledge and understanding of it has come out of a situation which had emotional cachet with them (Henry, TT, 4).

Matthew believes that people have to learn to appreciate and understand materials through doing things and working with them, applying this belief to build his students' understanding of the characteristics of hard materials.

How people learn and like two-thirds of it is by doing and a little bit is by multi-media and ... a little bit is verbally but people essentially learn by doing, so I think to appreciate and understand materials you've just got to work with them (Matthew, TT, 3).

Kevin also recognised the importance of students actually using materials to find out about them.

You can't describe a material or show them how to work it in the abstract. No matter what you do they have to get in and use the material (Kevin, TT, 2).

This experience is invaluable at a young age and Patrick described the relevance of students having experiences with real materials as 12 and 13 year olds, at Year 9. He considers that this introduction to real materials and ongoing opportunities to work with materials builds students' confidence (Section 6.4.3) and contributes to their ability to design by the time they reach Year 13. Initially, he teaches students to use tools so they can work directly with real materials.

In a way you're supporting their learning at Year 9 with teaching them how to use tools and introducing them to real materials is a sort of contributing factor that a student by the time they're [in] Year 13 is capable of doing 85% of the design (Patrick, TT, 5).

A further sensory experience Matthew described involves students experiencing directly the strength of everyday materials such as newspaper. Matthew described a simple activity he uses to demonstrate to his students the potential strength of newspaper when a braced design is used effectively. The activity he described uses tightly rolled up tubes of newspaper to build a frame. The frame is "braced" to strengthen it. Matthew believes that

students can learn by experiencing and seeing this type of activity. Even though it is a form of demonstration, students get to stand on the design outcome to discover and verify its strength.

Just things like understanding bracing, making a joint and bracing it and just how much more rigid it is when it's braced. ... I make a little square box really accurately just out of thin tubes [of newspaper] braced, put a bit of MDF [medium density fibreboard] on it and just get a kid and stand them on the top. They're just amazed by it. Just a few things of newspaper can support their weight and you only really appreciate that by doing I think (Matthew, TT, 3).

This demonstration enables students to see how effective design can impact on the usefulness of materials. It is an experience that links effective design with the properties of materials and contributes to students' experiential knowledge of materials and design knowledge.

Henry described how he gets students to experience and to learn about materials by first teaching them to use tools safely in a project-type activity.

We would use a project to teach [students] how to use tools, for instance ... safely and skilfully. ... But also they will be learning about materials when they're doing that. They can't help but learn about materials ... definitely [filters into being able to design and problem solve] (Henry, TT, 4).

By learning to use tools, students get direct access to materials and therefore are able to manipulate and work with them in order to learn more about them.

7.5.2 Processing materials helps students to build experiential knowledge of materials

All these teachers provide students with opportunities that enable them to build their experiential knowledge of materials using tools and a wide range of processes. They argue that by experiencing processes and making objects, students are building their understanding and knowledge about the materials, including some theoretical conceptual knowledge about material properties such as machinability and hardness.

Kevin supports his students' learning by getting them to experience various processes with pewter. Particularly, he likes using this metal because of its versatility. The experiences provided for students include melting, casting and making moulds. Through seeing and

sharing each other's design ideas students become aware of the creative potential of the material. He argues the value of this learning for students.

We melt [pewter] and we pour it in and we beat it around and have practise cutting the moulds and all that. It's really focused on I want them to experience the materials. ... Not really until they've made their first one and seen what other kids have made that they can actually go, oh those are the possibilities of that material (Kevin, TT, 2).

Matthew also believes that students need to process materials in order to learn about them. This includes using processes that join materials, such as welding and soldering, and shaping the material through folding (bending) it.

I think you definitely have to work and fold [materials] and weld it and solder. You have to do all those things (Matthew, TT, 3).

Because these processes enable materials to be formed into 3-dimensional products, these experiences equip students with skills that enable them to make their own realised designs with actual materials.

Andrew also stated that students build their knowledge of materials through learning how to process them. Once students have some knowledge of several different processes, they have to learn to select the most appropriate process for the job at hand.

If you're new to a material you need to know the processing ... how you subtract things from it, how you join it, so when you subtract something do you drill it, do you cut it, do you bend it, form it so the processing is, yeah, you just pick up that knowledge (Andrew, TT, 1).

Henry described how students can discover the distinctive properties of materials through learning to process materials. This is pertinent when students know very little about materials. He argues that by getting students to learn to process materials he is enabling them to make comparisons between various hard materials' properties, for example, which material is easiest to machine on a lathe (machinability).

They come in not knowing a lot about materials ... In the end they learn through all their little problem solving efforts what materials will turn on a lathe, what materials will splinter when you try and bang a nail through them, what materials are going to crack when you drill a hole in them, what materials are going to really turn beautifully ... like a bit of butter on a lathe. They pick up that stuff pretty well (Henry, TT, 4).

Students learn about materials in the example above as a consequence of working and processing the materials in different activities. They also build their confidence, a key trait, in how to use different materials.

However, Henry emphasised that teaching properties of materials in a de-contextualised way would not be as effective. Rather, experiences with materials have to be meaningful if students are to learn from them.

I wouldn't run units of work on learning about the properties of materials per se. I think that's dull and boring ... but kids learn about materials in a really meaningful way when they are trying to actually use materials to do something they want (Henry, TT, 4).

Patrick provided a practical example where students can experience the changes made to the properties of a material through the process of heat treatment. This experience of a process develops their understanding and their theoretical conceptual knowledge of steel when it is heat treated. A carburising flame is obtained by using very little acetylene flow in an oxygen-acetylene gas welding torch. Applying a carburising flame to the outside of a piece of steel causes a molecular change to the surface that hardens the outside (known as case hardening), making it much harder and therefore more difficult to file.

It's interesting talking about the whole business of case hardening, for example. Even just getting a piece of steel ... heating it up and then use a carburising flame on it and ... getting the boys to file it is very interesting. It doesn't file so good as what it once did and so that's a whole understanding (Patrick, TT, 5).

A further example Patrick provided was a particular experience with materials that enables students to compare how two different materials react under the same conditions. This includes the fatigue stress point (point with repeated force that a piece of metal will break) of steel and aluminium when it is bent in a vice. Through this experience, students are able to compare the two materials' bendability, which is an indicator of the materials' ductility. Ductility is an important property of hard materials when considering design and construction issues.

They've got to have an understanding of what properties various materials have. ... you get a piece of aluminium and you bend it at a right angle. ... You've got a fatigue point which is prone to break. You try and bend it back and what happens, when you do that to steel ... it's a very different story. You've got a lot more ... forgiveness in a piece of steel than what you've got in aluminium (Patrick, TT, 5).

Aluminium deforms and snaps when bent repeatedly, but a piece of steel has much greater ductility and will stretch or deform before it breaks.

Appreciation of cost as a design constraint can be learnt through processing materials. Andrew believes that working with real materials provides an opportunity for a teacher to get students to appreciate and consider the cost factor involved when using real materials. It introduces them to the optimisation component of design.

I think it allows them to look at optimisation and cost especially at the moment, when you put it in a real sense that you're cutting glass. That amount of glass is \$80 (Andrew, TT, 1).

The cost factor also was highlighted by Henry who recognised the importance of students understanding the cost of different types of hard materials.

None of them consider [cost] until you tell them that they're paying for it. They have pretty big ideas ... if cost isn't an issue they'd build everything out of titanium (Henry, TT, 4).

His comment indicates when students are the ones paying, they get an appreciation fairly quickly of the cost factor as a constraint associated with their choice of hard material.

7.5.3 Summary

In Sections 7.5.1 and 7.5.2, these teachers described students learning through sensory experiences and processing materials to enable them to develop their experiential knowledge of hard materials in order to be able to design and problem solve with these materials.

A further consequence of this learning is that students can develop their creativity and their potential to risk-take as they build their confidence in how to work with materials. These key traits are attributed to successful novice student designers and problem solvers (see Sections 6.4.2 and 6.4.3) and are traits that teachers try to develop in all students.

Through sensory experiences of materials that include learning to process materials, the teachers believe that students are building robust understanding and knowledge of materials. From their comments, these teachers believe students are developing an intuitive knowledge of hard materials by experiencing and learning to use these materials in a purposeful and productive way.

7.6 Pedagogy to develop students' design and problem solving knowledge

The analysis in this section of the learning experiences described by these teachers addresses the issue of students having limited design and problem solving knowledge experiences using hard materials. This situation contrasts with expert technologists' extensive experiences of design and problem solving. The beginning and ongoing learning experiences that the technology teachers provide are described throughout Section 7.6. Developing students' experiential knowledge of design and problem solving encompasses all of the learning experiences that teachers have discussed previously in Sections 7.4 and 7.5 (experiences with designed objects, sensory and processing experiences with materials). The teachers' data analysis in this section provides information about these teachers' pedagogy. That is, detail of learning experiences with hard materials they believe will ensure design and problem solving knowledge is initiated and developed in their students.

Sections 7.6.1-7.6.5 identify how each of the teachers' backgrounds and conceptions of design and problem solving, identified in Sections 6.2 and 6.3, are reflected in the learning opportunities they provide for their students. As well, the teachers discuss the learning opportunities they provide to foster and develop the key traits identified in Section 6.4. Also woven into Sections 7.6.1-7.6.5 are the ways in which the teachers' pedagogy addresses the three issues relating to the teaching of design and problem solving with hard materials. That is, students' lack of experiential learning, lack of knowledge of hard materials and, their lack of design and problem solving experiences with hard materials (Section 7.2).

7.6.1 Andrew (TT, 1) – designing: evaluating and synthesising one's own and others' ideas

A key element in Andrew's understanding of design and problem solving recognises design requires some original input, although designs often utilise and expand existing design ideas (see Table 6.3). Hence, he begins by looking at real, obvious things that his students encounter every day. Because his background includes architectural design (see Section 6.2), Andrew is able to focus on raising students' awareness of architectural design. Awareness is identified as a trait of a successful novice student designer and problem solver in Section 6.4.1.

My [experience in] architectural design ... we've actually just walked around and just look[ed] at the buildings and the range of materials that we've got here [at school] ... most of the students I talk to they all recognise it but they can't understand the language of how to describe it (Andrew, TT, 1).

In the following example, Andrew described providing a learning experience where he encourages his students to analyse and evaluate existing examples of design.

Some of the things we do it comes back to that analysis and evaluation ... everyday products ... we'll just come in with some junk mail and say right we want you to get a whole collection of six to 10 images, ... and we'll start evaluating it ... One of the girls just glued down an aluminium pot and ... the handle was aluminium also so everybody was looking at it and thinking oh there's nothing wrong with it and I said well, just have a look at the property of that material ... you turn that aluminium pot on and it heats up and the heat is going to go up and it's going to go to the handle and only then when it got to the handle did they realise oh that's a big problem (Andrew, TT, 1).

Some of the questions Andrew asks his students are basic but his purpose is focused on building their awareness of design and trying to get them to evaluate design in their everyday world. For example, he asks questions such as:

Who said we have to have the dollar this shape or this size and so real obvious things that come along you make it simplistic for the students (Andrew, TT, 1).

Experiences such as these encourage students to develop key traits, that is, to be aware of and to evaluate design.

7.6.2 Kevin (TT, 2) – designing: inspiring students to be creative with materials

Kevin's conception of design recognises the importance of the designer not only identifying the context of a problem and drawing on a technological field of expertise, but also using inspiration and creativity (see Table 6.3). This pedagogical focus reflects his background working in wood and composites (see Section 6.2), where design lends itself potentially to more flexibility in terms of inspiration and creativity. He noted that creativity/risk-taking is a key trait (see Section 6.4) and therefore is important to develop in all students.

As a result of his belief that design requires inspiration and creativity, Kevin ensures this is prevalent in the learning opportunities he provides for his students. Kevin believes his students should have exposure to a variety of creative examples of designed outcomes to

develop their awareness of realised design and to inspire creativity in their own designs (see Sections 6.4.1 and 6.4.2).

The wider range of exposure that you have to a variety of outcomes of designers, the better. Good, bad or otherwise, something that I try hard to do with my students (Kevin, TT, 2).

He feels that when students produce a creative quality outcome, they become inspired. Kevin's comment reflects his view that design requires inspiration and creativity, not just technological knowledge.

I think you have to have a bit of a focus and say ... what's important to me that is still in line with the curriculum? For me it's producing high quality outcomes that the kids are inspired by, that are creative (Kevin, TT, 2).

Kevin explained some of the creative things that students are doing with materials in his senior technology class.

We have five students [Year 13]: one is making a concrete sculpture for their garden, one's making a laminated sun lounger thing that goes on it; one's making a hinge and pivot; one's making a glass plate, fusing glass and something in glass plate. One of them is making a Maori panel with rope and flax woven around it. For me, I look at that and think wow that's really good, they're actually being creative with materials. They understand the properties of materials; they can really dream and draw from a really wide range of context, and be able to find themselves in there and then apply the materials to it. (Kevin, TT, 2).

Kevin believes that these examples of students designing are an indication of his students understanding of the properties of materials and being able to realise the potential of these materials in several different creative ways. These students are confident to take design risks resulting from their rich and developing knowledge of materials (see Sections 6.4.2 and 6.4.3). It reflects the value that Kevin places on creativity in his technology programme.

7.6.3 Matthew (TT, 3) – designing: problem solving as an evaluation tool and a component of design

Matthew's conception of design and problem solving recognises design as problem solving at a higher level (see Table 6.3). In other words, Matthew recognises the component of problem solving in design. A situation where he is able to use his technology background is in the robotics programme that he teaches and leads in his school. Matthew's robotics

programme, which utilises his background as an avionics technologist (see Section 6.2), provides complex design opportunities for his students, who consequently are learning to problem solve. Matthew particularly likes the way this programme integrates different aspects of technology that enable students to solve practical problems to develop a successful design outcome. Students in this programme constantly are anticipating problems, evaluating their robots through competing in monthly competitions and learning to take risks and be creative with their designs. These three traits, anticipation of problems, evaluation and risk-taking/creativity, were identified in Section 6.4.

Robotics incorporates ... all the key aspects of hard material technology disciplines and mechanical engineering materials ... All those things are integrated together ... [in] that problem solving challenge. ... In aviation you know it's fairly high tech cutting edge type stuff and it's all integrated together in a package. So the robotics is very similar, ... also ... one of the reasons they've developed it, is the sort of thing that captures the new generation tech savvy kids (Matthew, ET, 3).

Another way in which Matthew ensures students learn and develop their understanding of problem solving is encouraging them to reflect and think about how they can solve the practical problems they encounter when working in the workshop. Reflecting and thinking are skills associated with evaluation, which is a key trait (see Section 6.4.5) teachers endeavour to develop in all their students.

Well, for example ... down in the workshop [students] are often making mistakes so I say to them okay you made a mistake, how are you going to recover from it. You've made this too short. What are you going to have to do to compensate for that to get them thinking. That's developing their understandings and skills along the way. It's often good that they make mistakes, it really gets them thinking. I don't just let them start again and make another thing and waste more material. I think well 'how can you recover from this ?' (Matthew, TT, 3).

Enabling students to work in a workshop environment also encourages them to utilise any intuitive practical technological skill, and one way to develop this intuitive skill further is getting students to think about how to solve the ongoing practical problems they encounter. Intuition is another identified key trait (see Section 6.4.7).

7.6.4 Henry (TT, 4) – designing: begins with students “thinking with their fingers”

A key element in Henry's understanding of design and problem solving acknowledges the importance of students learning to solve the practical and subsidiary problems that eventually lead to the ability to design effectively with hard materials (see Table 6.3).

Henry believes that learning problem solving begins with the practical problem solving when a design is realised. He considers that students need to experience and learn to sort out this type of practical problem solving with hard materials as an introduction to designing with them. In Henry's view, these experiences supplement students' initial lack of experiential learning with hard materials and contribute to their experiential knowledge of materials (see Sections 7.2.1 and 7.2.2).

A trait attributed to successful novice student designers by these teachers is the ability to anticipate problems (see Section 6.4.4) that arise in a project. Henry believes learning to solve practical problems enables students to learn through first-hand experiences of working with materials that any decision they make impacts on something else, and therefore any modification must be thought through, and the possible effects and problems anticipated and understood.

Problem solving is the core of technology education. ... it boils down to the prosaic, simple little things and if you're not turning out kids who can sort that ... stuff out you're not really doing the job. ... You learn to be a designer by problem solving (Henry, TT, 4).

Henry's approach to teaching his students to address this type of problem solving includes getting students to develop the skills with tools needed to process materials in ways that enable them to solve any practical problems that occur. This opportunity raises students' awareness of the problem-solving aspects that designers need to consider and address as a design is realised. It also develops students' ability to anticipate these types of practical problems when designing (see Section 6.4.4). The practical activities provide an opportunity to build students' confidence (see Section 6.4.3) with materials, particularly if they are starting from scratch.

I would approach [the teaching of design and problem solving] ... by giving kids a whole lot of little problems and just letting them think with their fingers and work out all the little problems and gradually build up a familiarity with materials,... with tools and ... with processes through problem solving that will evolve into possibly a full blown design process awareness (Henry, TT, 4).

Henry's pedagogy enables students to develop their experiential knowledge and understanding of materials and material processes. He believes that it builds students' understanding that a key part of designing is ensuring the artefact can be made practically. In other words, that experiential knowledge of materials and processes are basic components of knowledge required to design. Henry's approach recognises two of the

issues acknowledged in Sections 7.21 and 7.2.2, that is, students' lack of experiential learning in the physical and real world and their lack of experiential knowledge of hard materials.

7.6.5 Patrick (TT, 5) – designing results in a realised outcome

Patrick's conception of design and problem solving expressed the importance of design producing a functioning realised outcome (see Table 6.3). To provide opportunities for his students to design and produce a functioning realised outcome, Patrick acknowledged the importance of the boys at his school being able to learn experientially in a physical workshop context. He believes that experiences in the workshop build students' confidence and their ability to take risks. They also develop students' ability to anticipate problems in the realisation of a designed outcome and enable them to develop their intuitive practical design ideas. These are four key traits identified earlier (see Sections 6.4.3, 6.4.2, 6.4.4 and 6.4.7). In this situation, workshop experiences go some way to addressing two of the key issues identified by teachers: that students have limited previous experiential learning with hard materials and limited knowledge of hard materials, including manufacturing or processing knowledge, in contrast with expert technologists (see Sections 7.2.1 and 7.2.2). These experiences also provide a productive environment for those students identified as having intuition (see Section 6.4.7), who like to work practically hands-on designing and making objects they can take home.

The boys at [school name supplied] are very, very interested in getting hands on and doing stuff. They want to make things and they want to take them home. They're not interested in a pile of paper which says I did this and nothing else to show for it (Patrick, TT, 5).

To enable the boys to work in a real workshop environment so they are able to produce realised outcomes of their designs, legally, Patrick is required to enforce the same safety requirements as would apply to an industrial engineering workshop. This is because of the many potential safety hazards when using machinery and tools to process and make objects with hard materials. Patrick fosters a culture of safety consciousness and responsibility in his students because he understands this is all part of the learning culture that enables his students to work effectively in a physical environment such as a workshop. His background as a tradesperson technologist supports his understanding of workplace safety (see Section 6.2).

It is crucial in my opinion that the boys are in a physical environment where it is experiential learning. We absolutely unashamedly demand industrial standards of personal safety and behaviour in our work [shop] places. Senior boys, in fact from Year 10 in the engineering side, have their own safety glasses. They are responsible for them. It is the key to the door to the workshop. If they don't have them then they are transferred to another room where they'll do related studies (Patrick, TT, 5).

Students being able to work in an authentic environment, such as a workshop, are able to access real materials to work with and to learn how to process real materials. In this situation, students learn experientially through working with real materials, and develop their experiential knowledge and understanding of materials (see Sections 7.2 and 7.3). Patrick believes that through this practical learning, students develop knowledge that contributes significantly to their learning to design. Ultimately, students are able to make their own designs into a functioning outcome, through experiencing first-hand the many practical problems that have to be solved along the way as a design with hard materials is realised fully.

Patrick also believes in the importance of a workshop environment being an emotionally safe working environment. He considers that an emotionally safe working environment enables both teachers and students to evaluate mistakes and can become a valuable learning opportunity. Patrick acknowledged the problems for both teachers and students when students are “too frightened to make a mistake”. He described the support he tries to provide as “allowing enough freedom”. In this type of environment, students can learn to evaluate their work, can build their confidence and can risk being creative with new ideas. Evaluation, confidence and risk-taking/creativity are three key traits identified in Section 6.4.

I think we've got to allow enough freedom for them to make mistakes but the environment to actually say well what went wrong there. That in itself is a future proofing of where these young people are going to end up. If they're too frightened to make a mistake ... the teacher concerned is going to have to be alongside them every minute of the day (Patrick, TT, 5).

Patrick builds an increasing element of design into his students' programme from Year 9 through to Year 13 as they acquire more skills and confidence, and broaden their range of experiences with materials. His teaching places importance on students having experiences with materials that not only develop the three key traits of confidence, risk-taking and intuition, but that eventually lead students to be able to design and produce functioning realised outcomes of their own. To be able to do design, Patrick stated, students also have

to learn how to think for “themselves”. He believes their acquisition of skills and experiences with hard materials is a key element developing their ability to design.

Spread over a Year 9 through to a Year 13 state we’re looking at design being perhaps 10% of Year 9, which is very few options, through to probably 85–90% at Year 13. And if you join those up, you’ll find that there is an increasing amount of design that’s handed over to the students as they progress through the year levels. And it’s based on their acquisition of skills that allow them to seriously look at the design and what they’re capable of producing within the confines of the school itself ... If you’re still telling them what to do by the time they get to Year 11, and controlling very tightly the outcomes, then they’re not thinking for themselves (Patrick, TT, 5).

Patrick’s background in engineering allows him to provide practical activities in a workshop. However, he expressed concern that, in the future, this may be made more difficult because of the costs involved and the difficulty of finding certificated teachers who have a practical background and can provide activities in a workshop where students can learn to design and produce a functioning outcome of their design.

I do have a fear and that is the price of schools being able to stump up with the equipment needed to have a sound practical based programme. It’s not cheap. The other side of the coin too, is teachers able to teach a good practical based programme which acknowledges the importance of design, and its implications are getting to be as scarce as chicken choppers (Patrick, TT, 5).

Patrick’s comment reflects his belief in the importance he places on his students having the opportunity to both design and produce a realised outcome using hard materials in a workshop environment.

7.7 Scaffolding learning to develop design and problem solving knowledge

Teachers *scaffold* learning through pedagogy that supports students in their learning, at the same time as it tries to extend and provide a degree of challenge to students in terms of their learning. The learning principle behind scaffolding learning was discussed in detail in the literature review (see Section 2.9). The examples of learning expressed throughout Chapter 7 have already described various forms of scaffolded learning that teachers provide through their pedagogy to enable students to learn to design and problem solve with hard materials. However, in this Section 7.7, the technology teachers described more specific examples of scaffolded learning. That is, the strategies teachers use to enable students to engage successfully in learning tasks that would be too demanding for them to tackle unaided.

First, in Section 7.7.1, the analysis of the technology teachers' comments indicate how and why initially they provide structured-type practical *projects* to support their students' learning experiential design and problem-solving knowledge, how they sequence activities carefully, provide advice, guidance, support and encouragement, and guide students towards successful engagement with the various tasks. The technology teachers' descriptions once again reflect both the influences of their technological backgrounds and their conceptions of design and problem solving (see Sections 6.2 and 6.3).

Second, in Section 7.7.2, the analysis of the technology teachers' data considers how technological modelling as a specific form of scaffolding provides a "low stakes" and emotionally safe way for students to evaluate their design ideas, anticipate potential problems and build their confidence as designers.

7.7.1 Scaffolding practical projects

A scaffolded *project* provides learning to satisfy all three issues relating to teaching design and problem solving (see Section 7.2), but it focuses particularly on building students' understanding of design and problem solving for students who have no previous experience of this in the context of hard materials (see Section 7.2.3).

Through these scaffolded practical projects, the teachers aim to foster and develop key traits in all their students including: building students' awareness and curiosity; building confidence; teaching students to anticipate problems; providing students with models of creative and risk-taking design outcomes; encouraging evaluation of a product, including how the outcome might be modified and improved; showing how drawings conceptualise a design idea that relates to a realised outcome; and providing students with opportunities to develop their intuitive practical skills (see Section 6.4).

Kevin provides scaffolding for his Year 9 students (first year of secondary education) by getting all of them to make a sand-board project. He is able to utilise his technological working background in timber and composite materials to support student learning in this project (see Section 6.2.2). The Year 9 students are provided with an opportunity to interact with and evaluate their sand-board's function in the real world. To evaluate their sand-boards' effectiveness in terms of function, they take them and trial them on a sand dune. This experience enables students to realise a product in which they have had some design input. As well, they get to experience using materials and the relevant processes required to make the sand-board. With the support of their teacher, Kevin, students go

through the overall experiences associated with design, making, implementing and evaluating a product. The capacity to evaluate is a key trait (see Section 6.4.5).

Through trialling their sand-boards, students are motivated to evaluate and to think about how they can make their boards function more effectively through modification of their design. As a key part of developing students' capacity for evaluation, Kevin gets his students to discuss and evaluate their sand-boards' impact on the sand dunes and the wider community.

To make the experience real and useful ... when we construct our sand-boards, we actually implement the outcome by taking all the students to the beach for the day ... sliding down the hills and getting them to interact with their product (Kevin, TT, 2).

Patrick described a scaffolded project he uses with his Year 9 boys. Its primary purpose is to introduce students to tools, processes and working with hard materials. By taking students through the overall process of producing a realised outcome of a design, Patrick considers that the project also enables students to familiarise themselves with the processes involved in making a functioning designed outcome and appreciating the order in which these processes must occur when a design is realised. In this way, the project helps to build an awareness of the relevance of being able to anticipate problems (see Section 6.4.4) and introduces students to making a designed product. This project reflects Patrick's view of design that it should produce a realised functioning outcome (see Table 6.3.5).

One of the projects [at Year 9] ... allows the boys to actually do the same thing in a subtly different way two or three times and they're using quite a variety of tools ... a series of processes ... They end up with an almost identical outcome as far as the finished product is concerned, but there's a lot of different processes which sort of give them ideas on what to do and when, and at what stage (Patrick, TT, 5).

Patrick described how to support students' learning in the early stages and how the scaffolded-type projects also allows some "wriggle" room for students to make mistakes without completely "destroying" the whole outcome.

The projects that we really need ... our students to get involved with allows them quite a large amount of wriggle room ... if they get it wrong in one place it's not going to destroy the whole thing ... Having those, I suppose safe places where they can take pride in some aspects of that project, is crucially important to success because you're not going to get perfection ... from our students (Patrick, TT, 5).

This encourages students to take pride in their work and in this way can still contribute to building their confidence (see Section 6.4.3) as they begin working and learning to design with hard materials.

Matthew also acknowledged the importance he places on developing students' design input by scaffolding learning; that is, providing students with projects that enable increasing levels of design input. This also provides students who demonstrate some intuitive skills with an opportunity to have more input and control of their projects. Intuition is a key trait (see Section 6.4.7).

I like to see [students] having their own design input in each of their projects and my ideal is that with each passing year they do a little bit more and a little bit more. But it needs to be scaffolded (Matthew, TT, 5).

Matthew described how and why he considered there was value in supporting students to make an initial individual project. Seeing and taking ownership of an outcome students have designed and produced gives them a sense of pride because they have made it themselves, even with a suitable level of teacher support.

Kids these days are used to having very sophisticated products made for them in their lives and even just a simple unsophisticated sort of thing ... they can look at it even though it's quite basic ... The fact that they made it themselves ... they can still have a lot of pride that they actually made that, even though the sort of solutions they can go and buy down the mall are far more sophisticated and far more engaging in some ways (Matthew, TT, 3).

This sense of pride is likely to develop students' confidence (see Section 6.4.3) and encourage them to engage in ongoing designing and problem-solving activities.

Henry described how he views the purpose of scaffolding learning for students who may have struggled initially with a practical project. With some support, these students not only experience some success, but often a new world of learning to design and problem solve is opened up for them. He believes a student's success builds their confidence (see Section 6.4.3) and can motivate them to continue with their learning.

If [students] have done something one year they've really struggled with and in the end, it's been successful and really well developed, well designed; once those kids get the bug, you've got them hooked ... What you've actually achieved there is you've unlocked a key to just huge strides in their learning capabilities (Henry, TT, 4).

The take-home value of an individual project has been hotly debated in technology education. Henry noted that, for some of the academic students he teaches, the practical learning to work with materials in a supportive environment is important. However, for other students, producing something through processing materials that they can take home is motivating and gives them a sense of pride in what they can achieve.

For some kids it's really important for them that they can have something that they can take home ... and be proud of. That's hugely motivating for some people. For the more academic people they can go through the course and they can get to the end of the year and they go thanks very much, I've learnt heaps and I don't need to take anything away and they're perfectly happy with that. So they've both got their place (Henry TT, 4).

As Henry noted, both approaches have their place and for some students, being able to take something home validates their achievement and therefore supports their learning and builds their confidence. Clearly, Henry believes that both groups of students learn from their practical experiences and develop their confidence (see Section 6.4.3).

7.7.2 Modelling as a form of scaffolding learning

All five teachers noted that modelling provides a “low stakes” way for students to evaluate their design ideas, anticipate potential problems and build their confidence as designers. Evaluation, anticipation of problems and confidence are three key traits that teachers wish to develop in all their students. In this section, modelling is presented as a form of scaffolded learning for students. These modelling techniques include freehand 3-dimensional sketching; drawing using 2-dimensional and 3-dimensional CAD drawing programmes; and instrumental drawing of designs. In the following section, teachers describe learning a modelling technique as a useful scaffolding experience supporting students' learning to design and problem solve with hard materials.

Andrew believes that to support and develop students designing capabilities, they should learn to sketch their ideas, and where possible, use CAD programmes to create digital prototypes. However, he noted that this complements the use of real materials, which he believes remains important for students' learning.

So you've got some sketches and some ideas of a particular shape or something using whatever hard material you want ... The CAD component is always around ... representation I mean that's all great, prototyping and ... that's fine ... but the use of the real material is I think vital (Andrew, TT, 1).

Kevin noted also the importance of technological modelling to support students and enable them to develop their ideas in a relatively safe situation where it isn't an "all or nothing gamble". Technological modelling allows them to experiment with some more risk-taking and creative ideas (see Section 6.4.2).

I think you've got to give them room to experiment and fail. If they're always within an envelope of safety I think that would also take some of their sense of accomplishment out of the end of it. ... Teaching the kids to use modelling and test pieces and mock ups and have a go at things, are really useful tools that give them pathways, so it's not an all or nothing gamble (Kevin, TT, 2).

Kevin considers that by using a graphical form, students can gain confidence to design in a "safe" way that they then can transfer to a practical technology situation.

Giving kids confidence to design something because they've managed to do it in a safe way in graphics, [they have] more confidence to tackle it in technology (Kevin, TT, 2).

Confidence is a key trait identified by the teachers in Section 6.4.3.

Kevin noted that designers who make up drawings of a bridge may not get to build the bridge. However, as the purpose of the drawing is to enable *someone* to build a bridge, their designs are embedded in practicality.

[Designers] don't sit there all day making drawings of bridges and then throw them all away. ... They are constantly tying it back into practical practice, just because you are not part of the job ... bolting it together, doesn't mean that it isn't embedded in practicality (Kevin, TT, 2).

Kevin's remark reminds us that technological modelling, including students learning to sketch or draw a design, are tools that are "embedded in practicality" and support students' creating designs that can become realised outcomes.

Matthew recognised the value of both 3-dimensional isometric-type sketching and then learning to draw using a CAD computer programme. He considers that both these modelling tools support students in learning to design. Some 3-dimensional CAD computer programmes extend the opportunities for students to visualise design ideas in three dimensions. These teachers believe that 3-dimensional sketching (isometrics) and learning to use CAD programmes foster and develop students' visual conceptualisation in three dimensions, a key trait identified in Section 6.4.6.

I think sketching skills and CAD skills ... it's good if students can sketch isometrics, that's a good skill to have whatever. ... My ideal sort of programme in terms of the drawing would be sketching, and then once they can sketch reasonably well, then onto CAD (Matthew, TT, 3).

Henry described the usefulness of a virtual technological modelling tool, such as a 3-dimensional CAD programme in supporting students learning to design and problem solve. Importantly, students can use this type of 3-dimensional programme to pick up design problems before the design is realised using materials. A 3-dimensional CAD programme supports students by enabling them to evaluate their design ideas after creating 3-dimensional drawings that can be viewed from many different angles. It is a more sophisticated computer programme than a 2-dimensional CAD programme.

That's where I think 3-D CAD has got a huge amount going for it because you can just flick the thing round and look at it from the back and you can say when I designed this I was only thinking of the front but now I turn it round I see it's not right and you can do all that virtually (Henry, TT, 4).

Henry considers that this activity fosters the development of students learning to visualise in three dimensions and the capacity to evaluate, two key traits (see Sections 6.4.6 and 6.4.5).

Patrick described an example of scaffolding learning for his Year 13 engineering students in which they are able to produce accurate drawings (as opposed to sketches of ideas) of their designs, to assist them to produce a viable realised outcome of a design. To achieve this, he teaches his students to *loft* out plans that model some of the components that make up the push scooters and chopper bike frames they are designing and making. *Lofting* out is a drawing method that produces a 1:1 full-sized model of a shape. It is a useful modelling tool for some applications and supports successful technological realised outcomes, at the same time minimising wastage of hard materials. Essentially, the lofted plan becomes a paper template of the angles required for accurately bending tubing and pipes into various shapes.

I think for students who are into design ... producing a viable outcome is to be able to draw accurate plans. ... I work very hard ... with my Year 13 students in engineering ... for them to be able to loft out size-for-size plans. A number of them have been making things such as push scooters. A couple of boys were designing a chopper frame ... they're drawing 1:1 drawing ... being able to draw that out accurately and then find the place where they were going to bend a piece of tube ... helped them immensely to have an accurate outcome. And they could actually take

it out of the bender and then offer it up on the plan to see how they were going ... There was an absolute minimising of wastage (Patrick, TT, 5).

This modelling technique supports students in designing a realised outcome and reflects the importance Patrick places on design with hard materials producing a functioning realised outcome (see Table 6.3). At the same time, it enables students to design their own individual chopper frame shapes.

Patrick described how in his programme he tries to develop students' consideration of the many different aspects required when people design an outcome with hard materials. This occurs over the 5 years that students work in technology programmes. The design progression through learning skills and working with hard materials contributed to his Year 13 graphics programme, in which students use their accumulated knowledge of materials, skills, processes and how to make things to support the design of a product. They have learnt also to sketch and draw, which they now utilise in order to design a product (see Section 6.4.6).

Just looking at Year 13 graphics is really one that looks at design; you know primarily that's what its focus is. We're no longer trying to teach skills, they've acquired those, how to draw, how to do things. They're now starting to look at or they're looking very carefully at a product and following through an evolutionary process (Patrick, TT, 5).

In this quotation, Patrick sums up his goal for his students by the time they reach Year 13. The students have had their learning scaffolded through practical projects, learning practical skills and various modelling skills and now, as Year 13s, their key focus is to design with hard materials.

By learning modelling techniques, students are able to explore creative ideas in a safe environment and develop their design concepts choosing a range of different and available modelling techniques. Modelling, as presented in this section, is a tool that helps students to clarify and modify their design ideas before they become fully realised outcomes. In this way, modelling is a tool that enables students to design and provides opportunities to explore design options and problem solve without the emotional trauma that might be associated with design failures using real materials.

7.8 Summary

In this chapter, the analysis of the learning experiences that teachers recounted as important in their pedagogy provide a base on which students develop their own learning to design and problem solve with hard materials. The learning experiences described by the teachers enable the three key issues of students' lack of experiential learning, knowledge of hard materials and lack of experience in design and problem solving with hard materials (Section 7.2) to be addressed. This lack of experiential learning contrasts with that of expert technologists who have a great deal of experiential knowledge on which to draw when designing and problem solving with hard materials. To deal with these experiential learning issues, the teachers' pedagogy reflects an approach to learning from the bottom-up rather than the top-down approach that expert technologists are able to employ when designing with hard materials.

This chapter illustrates, as a result of the analysis of the teachers' data, the importance these five teachers attach to providing students with opportunities to develop their experiential learning with hard materials, their experiential knowledge of hard materials, and their experiential knowledge of designing and problem solving with hard materials. A further goal of the learning experiences provided by these technology teachers is to develop key traits of awareness and curiosity, risk-taking/creativity, confidence, anticipation of problems, evaluation, conceptualisation and communication in three dimensions, and intuition. In this analysis, it is evident that the learning experiences and opportunities developed by these five teachers reflect their own diverse backgrounds and knowledge.

The key role of scaffolding was also evident; that is, the design of learning experiences in ways that enable students to achieve, with appropriate guidance, support and encouragement, a level of performance they could not achieve unaided. Key elements of scaffolding identified by the teachers include scaffolding practical projects and the learning of various modelling techniques to support students learning to design and problem solve with hard materials.

Chapter 8: Using Learning Theories to Analyse Learning and Pedagogy

8.1 Introduction

In this chapter, the analysis considers, first, the data provided by the five expert technologists concerning their learning to design through their experiences with hard materials (see Sections 4.4–4.8) with reference to four established learning theories based on activity and experiences discussed in detail in the literature review (see Section 2.9). Second, data collected from the five technology teachers are analysed with reference to the same four learning theories and uses data relating to experiences these teachers provide to support students learning to design and problem solve with hard materials (see Sections 7.3-7.8). The complex nature of learning to design and problem solve through experiences has been established in the previous four analyses chapters. To analyse this complex learning through experiences, it was considered necessary to use four learning theories.

The key points of four learning theories provide a framework to analyse what expert technologists and teachers discussed. This analysis provides an overview of how expert technologists consider experiences helped them learn to design and problem solve, and what experiences teachers believe support their students learning to design and problem solve with hard materials. Because three of the four learning theories (situated cognition, distributed cognition and activity theory) utilised in this analysis chapter are social cognitive learning theories, this analysis also demonstrates in what ways social interactions enable a full expression of learning through experiences as described by both the technologists and the teachers. Therefore, the analysis in this chapter provides some insight concerning the experiential role in learning to design and problem solve. At the same time, this analysis acknowledges the role of learning as, and within, a social group. Both these elements should be promoted as relevant in future curriculum decisions concerning technology education, where learning to design with hard materials is debated, discussed and/or developed. Likewise, this information enables teachers to justify their pedagogy in terms of learning theories that have been identified in this thesis to explain the nature of situated experiential learning in context.

The four learning theories utilised in this analysis are: ELT (Section 8.2), situated cognition theory (Section 8.3), distributed cognition theory (Section 8.4) and activity

theory (Section 8.5). Each of these four learning theories is used to analyse transcribed interview quotations from the expert technologists and the technology teachers. The research question that emerged from the literature review guiding this chapter of the research is:

In what ways can experiences with hard materials be theorised regarding learning to design and problem solve with hard materials?

8.2 ELT (Experiential Learning Theory)

ELT comprises four stages or elements (see Section 2.9.1, p. 56). According to this theory, knowledge is created through experiences, with the entry point to the cycle being an initial *concrete experience* that involves the senses or whole person in the experience (Moon, 2001). The *concrete experience* initiates and forms a base that enables *reflective observation* to occur. *Abstract conceptualisation* of the experience, and observation and reflection on it, makes use of existing knowledge and understanding to develop new knowledge and understanding of the experience at a conceptual level (D. Kolb, 1984). As Kolb (1984) proposes, the final stage, *active experimentation*, is the testing or applying of new knowledge and understanding to future applications or to new experiences.

The key points of ELT are:

1. ELT regards learning as a four stage learning cycle that creates knowledge through experiences, with the entry point to the cycle being an initial concrete experience that involves the senses.
2. The cyclic learning process identifies two of the four stages as opposing ways of perceiving experiences: (i) concrete experience, likened to doing (doing occurs during the initial experience), and (ii) abstract conceptualisation, likened to thinking. Kolb (1984) sees two ways of transforming or processing these experiences: (i) reflective observation (reflecting observing) and (ii) active experimentation (acting is the reconstruction and applying of learning to new experiences).
3. Experience is the key component that is rationalised and interpreted through thought, reflection and discussion into concepts that can be applied to new and different situations that can be used to re-enter into the experiential learning cycle to build on previous knowledge (A. Kolb & D. Kolb, 2005).

4. ELT theorises how concrete experiences can be developed into more than just “doing” exercises, that is, through thought and reflection, and using learners’ previous knowledge and understandings, experiences become abstracted knowledge and understanding.

In Sections 8.2.1 and 8.2.2, ELT is used to analyse the data presented by two expert technologists (George and John) recounting particular experiences that contributed to developing their expertise. Each of the two technologists’ quotations is presented in full then analysed in detail. In Section 8.2.3, one of the five technology teachers, Patrick, discusses how, by providing an experience with hard materials for his students, they learn about the concept of tolerance associated with designing with hard materials. The learning from this experience is analysed using ELT. The key points of ELT are indicated in brackets (using the notation ELT 1, ELT 2 etc.), where they apply to specific sections of data.

8.2.1 Technological expertise and ELT: George ET, 1

George recalled his experience of observing a boat that he had designed break up, after it attempted to cross a sand bar. The underlined words and phrases are discussed in each of the following analyses.

One of the most instructive days I ever spent was watching a barge break up on the [name supplied] Bar because I designed it. It taught me more about ship building in a few hours than I’d learnt the previous 20 years because it was smashing up and I could watch it smash up in front of me. ... I watched it breaking in half on the beach in the surf ... I managed to swim around it and look at all the pieces that were breaking and bending. It taught me more about engineering and about how big structures work than I could ever conceive ... in books you see a few photographs of a disaster and you apply the maths to make the structure strong enough [and] you look at all these little details that we got wrong, not wrong as far as [it] will pass the rules, got a certificate ... but we changed our design methods in that [design] office from that day on. ... The people said well it broke up on the bar and it shouldn’t have been on the bar, that was why it broke up (George, ET, 1).

In this example, George recalled the initial concrete experience, the beginning or entry stage of the experiential learning cycle. The concrete experience was a ship breaking up and bending that George witnessed first-hand. This concrete experience began as he recalled swimming around “watching” and observing a barge after it had been broken in

half in the surf when crossing a sand bar. As George noted, for the owner it was a “disaster”.

It was a disaster. It was a \$3M disaster for the owner (George, ET, 1).

However, it was a “disaster” that initiated a key learning experience for George. This experience played a central role in which George identified as being one of his most “instructive” learning days. It was a highly sensory experience as he not only “watched it breaking in half” and “smash up” but likely, was able to hear the associated sounds as he swam around the vessel (ELT 1).

As George swam around the vessel, he was able to observe all the parts that were “breaking and bending” despite having worked out mathematically the stresses and strains on the designed vessel— supposedly the mathematics and stress and strain formulae ensuring the barge was designed utilising materials to resist forces that potentially could break it.

Through reflection during his observation, George acknowledged although they applied “the maths to make the structure strong enough” he witnessed all the “little details” that they had “got wrong” in their design that resulted in the design failing under these conditions. George distinguishes between the correct maths and the design details which he is able to observe. He implies that through his observation of the breaking boat and his reflection, he learned that the mathematics (in stress and load formulae) applied to design the vessel had not been adequate in producing an effective design. This is the reflective observation stage of the experiential learning cycle where an activity is not only experienced but also thought about using the concrete experience, existing conceptual knowledge and understanding of those involved in the reflective observation (D. Kolb, 1984) (ELT 2).

Observers of the event, without George’s experience or close connection to the design of the vessel, commented that the vessel “shouldn’t have been on the bar and that was why it broke up”. While this may have been a contributing factor, George, who had previous design knowledge related to this concrete experience, understood the experience at a more complex level than these observers (ELT 3).

In fact, George had brought much prior knowledge and conceptual understanding about ship design to this reflective observation stage. He described what he learnt about

engineering from this observation, reflecting on the “little details” that he and his fellow designers “got wrong” despite the fact that the vessel had passed all the rules and “got a certificate”. Supposedly, it was strong enough according to the mathematical calculations, had passed the regulations and been marine certified (ELT 4).

Through this very central concrete experience, his observation and reflection, George was able to identify flaws in the design method that had contributed to the vessel breaking up. Through this observation and reflection, George was able to transform the concrete experience (observation of the barge breaking) into new knowledge about design (D. Kolb, 1984).

The identification of design flaws implies that he was able to extract information from the experience and to conceptualise this experience into abstract knowledge that he applied subsequently to change and improve his design methods (ELT 4). Kolb (1984) describes this as “reforming” understanding and knowledge through experience: knowledge already exists and concrete experiences contribute to learning as part of a continuous and ongoing process. As George noted, this experience “taught me more about engineering and about how big structures work” that he could otherwise conceive. George’s conceptualisation of the experience relates to the abstract conceptualisation stage of the ELT.

George relates how this experience influenced future designs in that design methods were “changed ... from that day on”. This transformed the experience, creating knowledge (D. Kolb, 1984) that he was able to reapply to a new learning situation, in this case the design of future vessels (ELT 4). This knowledge equates to the abstract experimentation stage of the ELT - being able to apply knowledge to future design methods.

In summary, it was apparent from this analysis that George’s learning began with a real concrete experience which played a central role in the learning. George then had the opportunity to observe and reflect as he swam around this disaster while it was occurring. Using his existing knowledge and because of his direct involvement with this designed vessel, George was able to use this knowledge, understanding and other experiences to further develop his conceptual knowledge and understanding about design details and their impact on materials as he watched the vessel breaking in half in the surf. He acted in response to this experience and changed aspects of his future marine designs. As George noted, from this experience “in a few hours” he learnt more about ship building that he had “learnt the previous 20 years”.

8.2.2 Technological expertise and ELT: John ET, 3

John recalled an experience in which a cylindrical pressure vessel was being built and pressure tested. Usually, a domed or dished end shape is desirable for this type of pressure vessel. That is the identified engineering end shape that enables a vessel to resist the stresses when pressurised that could otherwise cause it to explode and become a safety hazard. Because a pressure vessel is one that will operate under pressure and there is a danger of it bursting, it has to be tested, inspected, and issued with an operating certificate that effectively says it is safe to operate at a specified pressure.

To obtain an operating certificate, a test is conducted that usually includes using a pressure well above the normal or standard operating pressure for the vessel. This is to ensure it has a pressurised safety margin. The dished or domed ends of a cylindrical pressure vessel generally are made separately from the cylinder and welded on afterwards. In this particular case, the vessel was made from mild steel. John recounts this experience.

I remember we were pressure testing a couple of big vessels with domed ends ... there was a one-ended thing with a domed end on one end and filled up with water ... it was a test thing, there wasn't a dome for the other end so the people in the [work]shop decided that a flat plate of a heavier nature would do but it really doesn't ... I remember the surveyor walking around tapping away with his hammer when the thing was full of water and then it split and he just about got washed out the door because it was a catastrophic failure under test ... you've got to go away and think about this thing ... somebody hadn't really addressed the engineering dome against the flat... because of the geometry of the thing, with just the surface is just hugely different when applied to a dome or a flat. ... If the dome is 10mm thick you can't use ... a 20mm plate or a 50mm plate, it's got to be a whole lot different (John, ET, 3).

The analysis of this incident of “pressure testing a couple of big vessels” experienced by John reveals that the activity begins with a concrete experience, the initial stage of the ELT. The concrete experience began with the welded cylindrical “vessel” being pressure tested by a surveyor to obtain an operating certificate (ELT 1).

One of the large cylindrical vessels had been welded up using one dished or “domed end” and one “flat” end because in John’s workshop, they didn’t have two domed ends. Domed ends have to be made separately and are often pressed into shape from a flat piece of material such as steel plate. Sometimes they are brought in separately after being shaped in a specialist workshop.

After the pressure vessel was filled up with water, pressure was applied to the water to test the strength of the vessel, in particular the welded seams used to join the steel plate. Passing the test would enable the vessel to obtain an operating certificate. Using pressurised water is less hazardous during a test situation. A certified marine surveyor conducted the testing and John could “remember the surveyor walking around and tapping away with his hammer”, when the pressurised vessel “split” open, allowing water to rush out under pressure (ELT 1).

After John had experienced and observed this “catastrophic failure”, he said he had to “go away and think about this thing”, to reflect about why this had happened (ELT 3).

Through his observation and reflection, John identified the “engineering” aspect and the importance of the “dome” end design which had been overlooked. Although there was a dome shape already in place at one end, the thinking and reasoning underpinning construction in the workshop “decided that a flat plate of a heavier nature would do” but as John pointed out, “it really doesn’t”. John identified the effect of the “geometry”, how surface pressures are quite different when applied to a flat, as opposed to a domed, geometric shape. In a domed shape, the pressure goes in a variety of different directions. However when a flat piece of steel is welded on the end, the pressure is in one concentrated direction. Consequently, the pressure on the flat end is huge compared to the distributed pressure of a domed-shaped end piece. In this particular incident, as John noted, nobody had “really addressed the engineering dome against the flat” (ELT 3).

John’s experience, his observation of the event and his reflection and thinking about the failure indicated that he understood at a conceptual level the relevance of a domed shape. The reference to the “geometry”, the “engineering” and the surface pressure highlighted this understanding. Utilising his prior knowledge and the concrete experience where he witnessed the failed design of the pressure vessel with one flat end, he was able to conceptualise why this failure happened and how to ensure it did not recur. As a result of this learning, he was aware of the importance of a domed end piece when designing any future pressure vessels. As John noted, “If the dome is 10mm thick you can’t use a ... 20mm plate”. In other words, the dome cannot be replaced with a thicker piece of flat steel plate (ELT 3). The conceptual understanding was reinforced through his experience and his reflection on it. In this way, learning from such an experience could be applied to all new similar design situations (ELT 4), addressing the active experimentation of the experiential learning cycle.

In summary, this experience reflected the four stages of the experiential learning cycle, that is, the initial concrete experience (experiencing the vessel fail when pressure tested) which enabled John to observe and reflect why this failure had occurred (reflective observation). He then recalled going away to “think” about what he had experienced and observed and at this stage identified the theory behind why the failure occurred, using some of his previous theoretical understanding. That is, the formation of abstract conceptions, from the experience. Finally, he identified how to address the design issues behind this failure which he could apply in future designs (ELT 4). This stage related to the active experimentation of the experiential learning cycle.

8.2.3 Pedagogy and ELT: Patrick TT, 5

The analysis of the following extract from the teachers’ data uses ELT to describe student learning through experience provided by descriptions of how teachers support their students’ learning through their pedagogy. The extract is presented in full then analysed.

Patrick described an experience he provides for his students to help them explore and develop an understanding of the concept of “tolerance” when working with hard materials in an engineering context. His students “design” and make a “little novelty hammer” with a handle that is press fitted onto a shaft. To be successful, the diameter of the hammer shaft has to be machined accurately within a specified size range. The specified size range is the tolerance (the amount a measurement can be plus and/or minus the specification) and is provided with the specifications. An “interference fit” requires a shaft and hole to be almost size-for-size so that they can be “pressed” together using a hydraulic press and the two parts will stay joined.

We get the boys to design [and make] a little novelty hammer and one of the set pieces of assessed work is for them to be able to produce an interference fit so they’re given a tolerance [between] 0.05 of a millimetre, to 0.15 of a millimetre. Obviously if they’re less than the .05 [the handle] won’t stay and if it’s too tight or greater than 0.15mm when you press it together the shaft bends so it’s an interesting situation ... when they actually learn to measure properly and then get the pressed result, that’s when a lot of lights go on and it opens up the whole world of what tolerance is about and it puts a very, very tangible understanding on why you have a measurement plus or minus so much. It’s being able to interpret hard data given specifications and then move into something real. Until you actually are forced to come to terms with that in a physical environment you don’t appreciate just how little say 0.1mm is (Patrick, TT, 1).

The initial concrete experience in this example is making the hammer (ELT 1). Regardless of whether the outcome is successful or unsuccessful, the experience brings home the relevance of why precision measurements must be accurate, as defined by the tolerance factor - that is, the variation permitted, how much greater than, or less than, the measurement can be, according to its specification.

Patrick described the consequences of going either over or under the specified tolerances, “if they’re less than the .05” the handle “won’t stay and if it’s too tight or greater than 0.15mm when you press it together the shaft bends”. In other words, the tolerances have significant impact on the outcome in this exercise. The students are able to observe and reflect on both these outcomes.

Students are able to observe a successful outcome when the specified tolerance has been adhered to and the handle presses onto the shaft without bending the shaft or falling off. By reflecting on these observed experiences of measurements between the tolerance level, Patrick believes “a lot of lights go on for students” and they begin to see why “tolerance” is relevant. Through discussion, they can begin to understand why tolerance is so often an essential aspect of designing with hard materials. As Patrick noted, the experience helps to “open up the whole world of what tolerance is about” for students. If the tolerances are not used in the manufacturing process, the parts that make up this product can’t be put together effectively and the product can’t be made. Patrick described how, this exercise, “puts a very, very tangible understanding on why you have a measurement plus or minus so much” (ELT 3).

Through this concrete experience in the workshop, the concept of tolerance is developed in Patrick’s students. Tolerances are a significant aspect that must be considered when designing with hard materials, particularly when metals are involved. As Patrick acknowledges, fine tolerances such as 0.1mm, are hard to conceptualise or “appreciate” without a “tangible, physical” and “real” experience. The hammer-making experience provides this for his students.

As students develop a conceptual understanding of the relevance of tolerance (ELT 4), they are able to apply and actively experiment with this understanding in other situations. Through thought, reflection and discussion, students develop an understanding that tolerances cannot be ignored, either when making or designing parts that must fit together (ELT 3).

This exercise could be dismissed easily as a project prescribed by teachers where students learn to machine steel and use a hydraulic press. However, as Patrick emphasises, this is a carefully thought-out project that enables students to develop an understanding of tolerances as applied to engineering-type design and manufacturing of products. It commences with the concrete experience of making a hammer that enables students to observe and reflect on both successful and unsuccessful outcomes as the handle is pressed onto the shaft of the hammer. It develops a conceptual understanding of tolerance and its relevance in engineering design. As this conceptual understanding of tolerance is acknowledged, students are able to utilise this understanding in their future projects (ELT 4).

8.3 Situated Cognition Theory

Situated cognition theory is described in detail in Section 2.9.2, p. 58 of the literature review. It is a theory of learning that considers context to be a key factor in learning. Inherent in the context are the cultural and social aspects of the learning environment (Brown et al., 1989).

The key points of situated cognition theory are:

1. It recognises that knowledge gained is a consequence of participating in practical activity that takes place within a specific context, where the culture of the context provides substance to the learning experience, resulting in learning that is embedded in both a social and physical world (Brown et al., 1989).
2. An authentic situation or context is considered to provide the resources to co-produce the knowledge and learning.
3. Situated cognition suggests that, initially, activity and perception (beginning level of understanding) occur prior to a conceptual level of knowledge and understanding resulting from the activity.
4. Lave and Wenger (1991) argue that cognition is shared through learners entering a Community of Practice (CoP) through the social experience and by enculturation in the environment where learning occurs (Petrina, 2007).
5. Apprenticeship emphasises the relevance of activity in learning and knowledge and highlights the inherently context-dependent, situated and enculturated nature of

learning (Collins et al., 1991); in essence, apprentices enter a CoP where learning is scaffolded.

6. Learning in apprenticeship is about the increasing participation in a CoP—whole person, mentally, socially and physically acting in the world.

The analysis of the two following quotations, recounted by expert technologists, Brian and George, identify the development of their design expertise through working and learning in engineering environments. Their experiences involved learning from other people, both directly and indirectly. The culture of apprenticeship is described by Brian in Section 8.3.1, as he related the relevance of practical activity in learning and knowledge and the context-dependent, situated and enculturated social nature of learning (Collins et al., 1989). The relevance of learning about processes through active participation in real working environments and how these processes are applied to the design and production of an outcome is described by George in Section 8.3.2. Developing knowledge and understanding of processes was identified by George as a necessary factor in design and problem solving with hard materials.

In Sections 8.3.3 and 8.3.4, two of the technology teachers (Henry and Patrick) provide examples of learning situations that are analysed using this theory. Henry's description of the learning environment he provides for his students is analysed using situated cognition theory of learning in Section 8.3.3. Patrick's description of the learning environment he provides for his students is analysed also using situated cognition theory of learning in Section 8.3.4. Each quotation is presented in full then analysed in detail. The key points of situated cognition theory (SCT) are indicated in brackets (using the notation SCT 1, SCT 2, etc.) where they apply to specific sections of the expert technologists' and technology teachers' data.

8.3.1 Technological expertise and situated cognition theory: Brian ET, 3

Brian recalled how knowledge gained through experiences requires participation in the activity and how learning occurs in apprenticeship in a situated and real context. In other words, apprentices enter a social and cultural working environment that requires their interaction with others, specifically the tradesperson who work with them supporting their increasing participation and learning.

You've got either to work alongside someone who knows because most things you don't figure out yourself. You learn from someone else. And the tradesmen that you're working alongside of have a solution that half-way works and you modify what he did to make it better ... that's what apprenticeship is all about. ... You're working alongside and for a start you've got the apprentice here and you're doing the job and he's thinking ahead of you passing you the correct tools to do the job with because you're in an awkward place and ... then it gets to the point where well I'm too busy but you saw me do it last week so you have a go, see if you can do it and he gets halfway through it and then runs aground so you go and help him out and so that's how he learns ... I don't care how long you spend in the classroom you'll never learn that stuff. ... A lot of these guys ... have to learn it from actually seeing it happen (Brian, ET, 4).

Brian described, in the beginning, apprentices “work alongside” a tradesperson in quite a peripheral capacity (SCT 3). Their participation may be at quite a basic level as they are introduced into the working context and environment. So “for a start” Brian noted “you’ve got the apprentice here and you’re doing the job”.

The work occurs in a real situation (context) that is embedded in a social and physical world (SCT 1). The learning is scaffolded at first by an experienced and qualified tradesperson. This process requires a continuous social exchange between both participants, in this case, the apprentice and tradesperson. There is constant talking, describing, explaining and codifying of the culture of the particular trade by the tradesperson (SCT 4). The apprentice observes and absorbs during this learning time, as described by Brian, “you learn from someone else”.

The learning may be at the very beginning level of understanding, perceiving only the procedure and watching how others solve problems in the context (SCT 3). As Brian notes, in the early stages, the apprentice only may be “passing you the correct tools to do the job”. At a later time the apprentices may be provided with the opportunity to “have a go”, to try a similar type of job on their own and develop more independence with increasing participation (SCT 6).

Lave and Wenger (1991) consider learners in situated cognition as entering a CoP at first on the periphery but with increasing participation both mentally and physically as they move from novice to master. In the case of an apprentice, this may be when an apprentice tries a job on their own, but if there is a problem, the tradesperson will step in and provide the necessary “help”, support and encouragement if the apprentice “runs aground”. In other

words, the apprentice's learning is scaffolded as their participation in the CoP increases (SCT 6).

When learning is analysed from a situated cognition perspective, the context of the learning co-produces the knowledge and learning. Brian identified how learning occurs from “seeing it happen” in context. He sees this occurring with the apprentices he works “alongside”, as well as being aware of it in his own learning. Brian emphasised that this aspect of learning in an apprenticeship cannot occur in a “classroom” just by discussion, the experience in a practical context is a crucial component of the learning situation (SCT 5).

A classroom is not a real working context and does not provide this type of learning from “actually seeing it happen”, whereas being in a real work environment does. The learning includes seeing and being involved in the fixing or making of real things (SCT 5).

Brian also noted how the tradesperson has sometimes only “a solution that half-way works” and apprentices are expected to think for themselves and begin to modify and improve the solution to problems that arise in these real contexts. In this way, the apprentice is learning to think and beginning to conceptualise their level of knowledge and understanding from an activity. The apprentice is required to move beyond the reproduction of learnt activities or using specific tools for specific designated jobs. They must know the right tool for the job and how to solve the problems presented to them. Situated cognition theory requires participation in a real context that enables learning to occur that can be conceptualised and reapplied to other real contexts. It requires learning in a social situation from someone who guides, criticises, encourages and scaffolds the learning (SCT 2). Brian described this in his opening statement, working “alongside someone who knows” because “most things you don't figure out yourself”.

Through working alongside a tradesperson, an apprentice enters a real working context and develops the skills, knowledge and understanding that are key components of learning and situated cognition. Ultimately, the goal is for an apprentice to be able to work independently and effectively as a fully participating member of a CoP.

8.3.2 Technological expertise and situated cognition theory: George ET, 1

George described the practical contextual experiences he had that helped his learning to become an expert designer. His experiences began in the middle of his training as a cadet

engineer. He stayed with this company for 14 years and experienced designing in his later years when in a drawing office. He recounted several of the situated learning experiences that contributed to his learning to design.

George is not a tradesperson, but he had the opportunity when training to spend time in several engineering environments, within the same engineering company. This opportunity contributed substantially to his knowledge and ability to design. He arrived at the large engineering company with some theoretical knowledge and a partly completed NZCE. As part of his learning experiences, he spent several months working full-time in the foundry, the workshop, machine shop and pattern shop, as well as learning to use lathes and to weld. A foundry is where metal is melted and cast into various products, a pattern shop is where parts are machined and made that enable metal to be cast into specific shapes and forms, while the other workshops are where products are made or refined further into products. Welding is generally involved in construction type work, while a machine shop uses lathes and milling machines and is focused on producing products or components with finer tolerances and finishes. George recounts this experience.

... Of course [I had practical experiences] because there were two city blocks of workshops, foundries, construction shop, machine shop and pattern shops ... that I spent time in but in the kind of training I did you made a drawing and then you went and saw it, you wrote the material sheet ... you saw the project right from beginning to end so that you soon found out what was practical and what wasn't ... I learnt to weld and play with lathes and play with machine tools ... because ... you couldn't design anything like this [gear] ... This gear for instance would have two drawings ... there would be a casting drawing which was done for the foundry and then they'd be the preliminary machining drawing and then the heat treatment and then the final gear cutting, so you had to know all of the processes to actually be able to work in the drawing office. ... I spent several months working in the [workshops] full time when I did things like that. ... It's impossible to be able to draw it up unless you know the capacity and the production techniques of the machine that cuts the gears (George, ET, 1).

George's practical experiences included spending "time" in "workshops, foundries, a construction shop, machine and pattern shops". These experiences enabled him to learn in a hands-on way about the processes and production techniques, which included such aspects as casting in the foundry. This knowledge of "all of the processes" or how things were made was essential to design and "to work in the drawing office" (SCT 1). George began as a peripheral member of a drawing office and was provided with lots of contextual learning in a range of engineering workshops (SCT 3).

George's company provided a physical and social engineering environment and culture that enabled him to view the complete journey of a project "from beginning to end" (SCT 4). Working in this large engineering company enabled George to design something and then see the project progress all the way through to the manufacturing phase that produced a realised outcome.

As George states, it enabled him to view a "project from beginning to end". This also allowed him to find out quickly what design was "practical and what wasn't". The feedback from designs created in a drawing office that were then manufactured in environments to which he had direct access, taught him a lot. From this exposure, he learnt about the processes required to make a product such as a gear (SCT 3).

These experiences contributed to George's conceptual knowledge and understanding that he applied when he designed parts in the drawing office. For example, designing and producing a "gear" requires many different processes. When George designed a gear, he had to identify what processes were required to produce it. He was able to do this because he had actually "spent several months working in the [workshops] full time" where each of these processes occurred (SCT 4). As George noted, "it is impossible to be able to draw" a gear without knowing "the capacity and the production techniques of the machine that cuts the gears" (SCT 5).

During his time in each of the practical engineering environments, George worked alongside expert tradespeople learning about the culture of mechanical engineering through social interaction and physically participating in the processes within the various workshops (SCT 4). Part of the culture is the language associated with various processes, the time involved in processing, and the constraints of processes. During this time, George learnt through communication and participation, the language, concepts and values associated with engineering. In other words, he was enculturated into engineering through his active participation in this CoP (SCT 5). George described being able to see "the project right from the beginning to end" which provided him with a learning environment that enabled this enculturation.

In the drawing office, he was surrounded by other designers and, within this engineering environment, the people and the machines that produced and manufactured his designs. Throughout these 14 years, George remained in the heart of a large and diverse engineering environment, covering "two city blocks". His immersion in the CoP

contributed to his learning to become an expert designer (SCT 4). This situated learning began when George “spent time” in each of the various workshops to learn and experience the various processes that produced designed objects (SCT 1). It finished with him using this acquired knowledge and understanding, at a conceptual level, to design products in a drawing office that required him to know and identify which processes were required in specific workshop environments to produce his designed artefacts. As George noted, without such knowledge, “you couldn’t design anything” like a gear. George’s experiences also enabled him to determine the feasibility of his designs, that is, whether or not they could become functioning outcomes with the available production processes (SCT 6).

8.3.3 Pedagogy and situated cognition theory: Henry, TT, 4

In the following extract, Henry described how the technology workshop environment is set up in his current school to enable students to work through solutions to problems. This set up allows them to consider the constraints of cost, time, expertise of students and manufacturing facilities, and are similar to the constraints considered by the expert technologists (Section 5.2).

The design of Henry’s workshop environment is unusual in that it permits both wood-working machine tools and metal-working machine tools to operate (at opposite ends) in the same workshop. This is achieved by use of a specially adapted extraction “airflow” system. The learning environment is set up to model a CoP (Lave & Wenger, 1991) (SCT 4). That is, it is a physical learning environment that makes available a range of tools, materials and teacher expertise to support and enable students to design, problem solve and produce realised outcomes using a range of hard materials (SCT 2).

We don’t put a heck of a lot of limitations on the sort of problems that the kids want to address. If they come up with an idea we look at it, whether or not we’ve got the facilities to actually manufacture that solution to that problem, whether it’s going to cost too much, take too much time, take too much expertise, they’re the parameters we look at and if we can meet those criteria then we just go ahead with it. ... We’ve structured the airflow in the room so that the dust is systematically kept down one end of the room and the most dust sensitive things are kept up the other end of the room. ... [we] enable kids to become self-managing ... so that we’re poised for action using any type of material at any time and we often do team teaching so there will often be several teachers in the room at once, plus a technician and so quite often there’s a range of expertise in the classroom as well and the kids are free to go and talk to anyone they want to (Henry, TT, 4).

The environment enables students to learn through accessing a broad range of facilities that allows them to design and manufacture artefacts (SCT 1). By being “poised for action”, the workshop space allows students to participate practically, working through solutions to problems and producing outcomes using “any type of material at any time” (SCT 2).

As students are able to move around the workshop space, they “are free to go and talk to anyone they want to” that models a CoP (SCT 4). The open plan nature of the room means the students can access freely “the range of expertise” of the several technology teachers and the workshop “technician” (who has an engineering background). Students have the opportunity to discuss their ideas with the teachers and the technician, who help them to decide whether or not their ideas are feasible. Like any CoP, there are constraints or “parameters” such as “whether it’s going to cost too much, take too much time, take too much expertise” and these are discussed with the students (SCT 5). However, Henry stated that if possible, they try not to “put a lot of limitations on the sort of problems that the kids want to address”.

As well, students are encouraged to “become self-managing”, that is, they are able to participate in the learning at the rate or level of engagement that matches their ability (SCT 3). Consequently, students can work independently and tap into the expertise of adults and other students in this workshop CoP.

This situated learning environment provides students with a place to learn where the learning is situated in a unique environment set up to be quite different from a general classroom or laboratory, and where learning can occur through activity and experience with a range of hard materials. The context in situated cognition is a central component of learning. Henry’s workshop set-up provides a CoP where the practical experiences and the social interaction in which students engage help to support their learning (SCT 1). The freely available expertise of the staff further support this situated learning environment.

8.3.4 Pedagogy and situated cognition theory: Patrick TT, 5

The following quotation describes a learning environment provided at Patrick’s school that provides students with a context that intentionally, is similar to a workshop environment in an industrial workplace. Patrick describes how this workshop environment, in quite subtle ways, provides students with learning they cannot obtain anywhere else in a school environment, including in its use of “swarf” (the waste metal material that is machined or turned off a length of metal when reducing its diameter in a lathe).

There's no amount of virtual training that can actually equip you for the harsh reality of getting it wrong. When you're at a lathe ... you get this great black snake coming off a piece of steel you know you're not going to touch it or get anywhere near where it's going to grab hold of you. The best thing you can do is get a burn. How can you actually understand the implications of that in a virtual environment? You can't. Or you're turning a piece of material that doesn't actually turn off as a large piece of swarf but fires bits and pieces all over the place. You've naturally got to think ... well what about my eyes. What about this being done up so you don't get the hot pieces of material running down the shirt so to speak. So it is crucial in my opinion that the boys are in a physical environment where it is experiential learning. We absolutely unashamedly demand industrial standards of personal safety and behaviour in our work places. Senior boys in fact from Year 10 in the engineering side have their own safety glasses. They are responsible for them. It is the key to the door to the workshop. If they don't have them then they are transferred to another room where they'll do related studies. No ifs or buts and again while we're not talking about design we're talking about understanding or adopting of a culture ... design is a part of that as well (Patrick, ET, 5).

Situated cognition theory identifies the context as a component that helps to produce the learning. In the above quotation, Patrick describes the difference between this workshop context and a “virtual environment”. First, he states that working in this environment requires students to sometimes face the “harsh reality” of making mistakes that are much harder to rectify than is the case when working in a “virtual” world (SCT 1).

Second, the learning he describes is sensory, that is, students get an understanding of a process but also learn how “when you're at a lathe” large amounts of heat are generated that can burn them and how the material reacts when it is processed in this way (SCT 2). Different materials produce different types of “swarf”. Some metals when turned on a lathe fire “bits and pieces all over the place” and the reality of why use safety glasses and “what about this being done up” on a pair of overalls begins to hit home when working in this physical and practical environment (SCT 4).

A key element in the learning described by Patrick is students learning about the culture of safety in a workplace such as a workshop (SCT 4). Students from Year 10 are empowered to look out for their own safety by being “responsible” for “their own safety glasses”. They are the “key to the door to the workshop” and the consequence of not having their glasses is not being allowed to enter and do work in the workshop (SCT 6).

This replicates what happens in industry, where workers are fined for non-compliance with safety rules. Because machine tools can cause serious injuries, students are learning “about

understanding or adopting of a culture” that is safe. In other words as result of their physical participation in a workshop environment, students are learning about culture and attitude that results in “industrial standards of personal safety and behaviour” (SCT 6).

Indirectly, this learning environment is associated with the culture of design. If students cannot work safely in this context, they are unable to realise their designs into functioning outcomes as they have no knowledge as to what is involved or the manufacturing options available. As well, they are unable to learn or experience materials and processes first-hand to build the knowledge and understanding that contributes to their learning design.

Situated learning is about learning in an authentic context, where the culture of the context contributes to the learning of the CoP. There are two key learning elements in this CoP that helps students to learn. First, students are learning about the culture of safe behaviour in a workshop environment (SCT 4) and second, students learn in a physical active environment using real machine tools, real materials and are able to make real things, including objects, eventually, they will design themselves (SCT 2).

As Patrick commented:

It is crucial in my opinion that the boys are in a physical environment where it is experiential learning. We absolutely unashamedly demand industrial standards of personal safety and behaviour in our work places (Patrick, TT, 5).

8.4 Distributed Cognition Theory

Distributed cognition theory describes learning as mediated by tools, technologies and other artefacts that are distributed between the mind, the environment and the context. This learning theory acknowledges how the cognitive mind or groups of minds work in co-ordination with external factors, each in turn stimulating the other. The external factors include artefacts, technologies and environments (Hutchins, 2001). Distributed cognition theory is described in detail in Section 2.9.3 of the literature review.

The key points of distributed cognition theory are:

1. Cognition is not confined to the individual; rather, it is distributed and co-ordinated between the mind (mental activity) and the environment/context, which is mediated by a variety of physical objects, including tools and other technologies (Hutchins, 1993).

2. The social context is the use made of other people or systems that involve people to support and/or stimulate and may be essential to the cognitive activity and learning.
3. Physical objects develop and stimulate mental activity and vice versa; mental activity makes use of physical objects, which may include machinery.
4. Cognition involves the whole system (environment, artefacts and other people) within which a person operates using a range of tools not limited just to the “skin and skull” (internal mental processes) (Hutchins, 2001).
5. There is no gulf between the cognitive process and the external world. This is sometimes thought of as a “co-ordination” of the internal (mind and skull) and external (artefacts, technologies, environment). These work in parallel or “with”, as opposed to the concept of a bridge between the internal (cognitive) and the external (world) (Petrina, 2007).

In Sections 8.4.1 and 8.4.2, two of the expert technologists, James and Peter, identify learning experiences that are analysed using distributed cognition theory. The experiences the technologists describe enabled them to develop their learning as designers and problem solvers. In Section 8.4.3, one of the technology teachers, Kevin, describes a learning experience he provides for his students to develop their learning as designers which is also analysed using distributed cognition theory. Each of the three quotations is presented in full, then analysed in detail. The key points of distributed cognition theory (DCT) are indicated in brackets (using the notation DCT 1, DCT 2, etc.) where they apply to specific sections of the data.

8.4.1 Technological expertise and distributed cognition: James ET, 2

In this extract, James described how both conceptual ideas and practical activity contribute to solving problems. He recalled how he “designed” a very complex machine that produced a fibreglass spring for use on a trampoline. He described his design beginning as “a clean sheet of paper”. James recalled having an initial overall mental concept of the machine and then, with a group of machinists, he built a prototype of the core part of the machine.

I designed that [complex machine] from a clean sheet of paper. ... For a thing like this for instance. ... you have to have a concept of the overall machine. How am I going to take this fibreglass rod and put a 25mm spherical ball on the end of that so it won't fall off?... You come up with some ideas for a moulding assembly. We started with this and we had one of those. ... It was rough and ready ... was largely similar in concept and ... started the extruder and we came with a knife and chopped it ... so we could put the ball on the end ... So now how do I do that automatically and how do I do it at one per second. You make these decisions. ... I just had to come up with a way to slice off these lumps of plastic and get the weight very, very consistent and deliver them ... we figured it would have to be a rotating moulder would be the best way. I wanted it to be a continuous process so we wanted to feed rods in one side, add a piece of plastic as it went round, shove the rod into [it]. ... you do a lot of prototyping digitally ... you develop your ideas and refine them (James, ET, 2).

Through physically building this machine model, tapping into others' skills and using his "concept of the overall machine" both in his mind and through drawing models, James was able to clarify the detail required to build parts of this complex machine (DCT 1). The learning that enabled the machine to be designed was distributed across James' mental concepts and understanding, the drawing models of his ideas, technologies (physical and virtual) enabling the building of models, plus the support of other peoples' knowledge bases (DCT 2).

A "rough and ready" model mediated between the mental "concept" and physical aspects. It provided James with a springboard that enabled him and his team to work *manually* through some of the more specific detail that the machine was required "automatically" to perform (DCT 1). By utilising this model, James and his team thought about the best ways to slice off the plastic lumps that formed the "spherical ball on the end of" the "fibreglass rod" (DCT 2). They decided "the best way" to do this was to utilise a "rotating moulder" and "a continuous process". These details were thrashed out as the design evolved but were supported by building the model that enabled discussion between James and his team (DCT 2). The physical model informed the mental decision making that contributed to further design aspects of the overall machine (DCT 3).

James described how he arrived at a stage where he could further extend his model by using his computer programme to develop digital prototypes which allowed him to address the electronics that enabled the machine to work automatically. As James described, "prototyping digitally ... you develop your ideas and refine them". He tried various ideas, including pumping cooling water through the rotating assembly. Again, the concepts began in the mind and developed by building digital prototypes (using technology) that fed back

and forth, further developing and enriching the mental concepts of the group (including James) interacting with this problem (DCT 4).

Distributed cognition theory is about using technologies in parallel with concepts in the mind of an individual or a team of like-minded individuals (DCT 5). Each stimulates the other and contributes to learning and understanding. The use of a physical prototype and, later on, digital prototypes helped James and his engineering team to develop and eventually to build a complex machine that was required automatically to take a “fibreglass rod” and melt a “25 mm plastic spherical ball on the end” of it that would not “fall off”. It provided an example of how technologies, including artefacts such as prototypes, supported and stimulated the cognitive processes involved in the designing of James’ machine (DCT 1).

8.4.2 Technological expertise and distributed cognition: Peter, ET, 5

In this extract, Peter described working with a stakeholder and identifying “the constraints”, which include having only “12 hours” to replace an existing railway bridge. Peter’s bridge-building episode identifies how the unique environment and circumstances surrounding the bridge installation act as a stimulus for Peter and other interested parties to design a solution to this problem.

We’ve been working with [name supplied] because they know the constraints that they have and we know the constraints that we have ... [what] we plan on doing is we’ll take this to site ... [We’ll] bolt everything up on the side and then get two big cranes and lift them up onto a carriage. The carriage will drive over the existing bridge ... then we’ve got a special lifting frame we’re going to make and then we’re going to suspend it up there ... we’re going to demo the old bridge while this is still suspended and then just jack it down in position ... That [bridge] stops the main artery throughout the country. So we’ve got 12 hours to put that into position and pull the old one out of the way (Peter, ET 5).

The complexity of the installation that Peter discussed evolved as a result of the specific and quite unique constraints of the project and the particular “site” where the installation was to take place (DCT 3). The environment and “constraints” constitute the stimulation for Peter and his team to design a solution to the problem with the least amount of disruption possible. They did this working cooperatively with their clients, the stakeholders (DCT 1).

Peter and his team designed a plan that requires a group of skilled workers to operate machinery precisely, which includes “two big cranes”. He also identified having to make “a special lifting frame” to “suspend” the new bridge ready to “just jack it down in position” once “the old bridge” has been demolished (DCT 3). Each member of his team needs to do this job efficiently for his plan to work (DCT 2).

This example of learning explained through distributed cognition theory indicates that learning is not confined to one individual (Peter) but is distributed between the problem posed by the bridge replacement in a very difficult environment, the technologies that mediate to solve the problem (DCT 1) and the group of individuals and interested parties (stakeholders) that have “been working with” Peter and socially interacting to plan the solutions to the problem (DCT 5).

As well, there is the team of people who will be required to bring their knowledge to use the tools safely and effectively during the bridge’s installation. As Hutchins (2001) explains, cognition involves the whole system (environment, artefacts and other people with whom a person operates); it is not limited to the “skin and skull” of one individual (DCT 4).

The bridge in this context, has the constraint of having “12 hours to put” the bridge “into position and pull the old one out of the way”, provided Peter with this learning opportunity that enabled him to produce his plan of action and work with the various groups of people. Technologies such as the cranes, the bridge acting as the artefact and the unique environment are the external factors in this learning situation (DCT 3). The cognitive processes, such as Peter’s solution to replace the existing bridge, provide the internal factors. Both internal and external factors work in parallel (Hutchins, 2001), enabling a learning situation where unique solutions to problems evolved that could then be implemented (DCT 5).

8.4.3 Pedagogy and distributed cognition theory: Kevin TT, 2

The learning in the following quotation from Kevin’s interview is analysed using the learning theory of distributed cognition. The extract describes students making a sand-board, then testing and implementing their sand-boards on sand dunes. Later on, the students are encouraged to draw on both these experiences to think about and critique how successful their artefact is as a human intervention. That is, the impact of their artefact on

the sand-dune environment and any ongoing impact it may have on the wider social community.

When we construct our sand-boards, we actually implement the outcome by taking all the students to the beach for the day and sliding down the hills and getting them to interact with the product. ... It's supposed to be a humanist intervention. Is it going to have an impact on lives? It's going to have an impact on these sand dunes and it's going to have effects and outcomes. So for me that kind of means that [students] have the ability to interact with technology ... and decide what its impact is going to be on themselves in the wider community ... they can critique it (Kevin, TT, 2).

Distributed cognition acknowledges how learning is distributed across artefacts, minds, the environment and the context. In this example, students design and “construct sand-boards”. They then “implement” their “product” (sand-board) to interact within a suitable environment and investigate how successful it has been in terms of technological design and as a “humanist intervention”. Kevin takes “all the students to the beach for the day” and they get to slide down the sand dunes and “interact with” their sand-boards (DCT 1).

The learning experience does not finish there. Kevin uses this activity to provide a broader learning experience for his students. He uses the activity to stimulate his students to think about and discuss broader issues associated with the experience (DCT 2). The sand-board is a human intervention that impacts at several different levels. Kevin believes that for students to interact with technology they must “critique” their sand-board’s “impact on these sand-dunes”, the impact “on themselves” and “in the wider community” (DCT 3).

The students’ activity can be interpreted to demonstrate the holistic nature of their learning experience. Distributed cognition describes learning as involving whole systems (Hutchins, 2001), that is, environments, artefacts and other people. In this example of learning, students design and make an artefact, experiment with it in a suitable environment and they are then encouraged to identify how their technologically designed artefact affects themselves, others, the environment and the wider social community (DCT 4).

Students are stimulated to think beyond their experiences of making and using their sand-boards to slide down sand dunes. They are encouraged to see the artefact they produce, the sand-board, and the activity it enables (sand-boarding) in a much broader context. This includes the environmental “impact” on the sand dune as a result of this type of activity, and, ultimately, how that may affect a community of people (DCT 5).

8.5 Activity Theory

Activity theory is a learning theory that considers a range of aspects that interact and impact to stimulate, contribute to, and support learning. The factors working together include people, the rules of an organisation or system, tools and technologies, the object (possibly an artefact), the outcome and the division of labour (Engestrom, 1991). Activity theory is discussed in Section 2.9.4, p. 61 of the literature review.

The key points of activity theory are:

1. An activity system includes social aspects, actions and operations and the activity is considered to be governed by social and cultural rules, organisational systems, history/traditions of people, what is made and the environment it is made in.
2. Activity theory provides a framework that enables an understanding of how the cognitive, physical and social aspects (internal and external) interact and contribute during the performance of a task or activity (Engestrom, 2001).
3. The factors that work together to influence an activity and an outcome and help to transform each other include, specifically, the subject (people), the rules in an organisation or system, the community, the instruments or tools (technologies), the object (can be an artefact), outcome, division of labour (e.g. between apprentice and tradesperson) (Engestrom, 1991).
4. Continually, knowledge is being refined enriched or completely revised by experiences and actions of the whole social activity system.
5. Previous knowledge and previously made objects provide information about time, effort and financial constraints, skill level and materials available and input into future activities.

The two following experiences, described by expert technologists, James and Peter in Sections 8.5.1 and 8.5.2, are analysed and theorised using activity theory of learning. James and Peter recount two significant learning experiences contributing to their expertise as designers. These learning experiences required many factors to work together. In Section 8.5.3, one of the technology teachers, Matthew, describes a learning experience he provides for his students that is also analysed and theorised using activity theory. The learning experience he provides for his students supports their learning to design with hard materials. Each of the three quotations is provided in full then analysed in detail. The key

points of Activity Theory (AT) are indicated in brackets (using the notation AT 1, AT 2, etc.) where they apply to specific sections of the data.

8.5.1 Technological expertise and activity theory: James ET, 2

James described his experience in the “semi-conductor industry” “designing” computer chip- making equipment and how he worked as a designer within a complex system. This complex system included a research and development team.

In the semi-conductor industry ... we were designing ... stuff they use for making computer chips. They had these \$2b factories and the machines all cost millions each. I spent nearly nine years working on the lasers they used for imaging the circuits and chips, it's a shortwave length laser and we designers in the research group we designed ... built and tested stuff and when it was right we threw it over-the-wall into engineering and it was put into a product so we generated technologies and they were then used as necessary by the product development people so they'd say well we want the laser to go twice as fast on the pulse rate, we figured out how to make a laser that goes twice as fast and ... we do all sorts of different things, adding, cooling and you come across problems along the way and you solve them and your ideas generate new techniques and technologies ... you've tested all these things and proved that they work well enough to be used in a product because they have to be reliable by the time it gets in a chip factory, bring a line down and you're talking a million dollars an hour and if your machine is the one that did that [company name supplied] isn't very happy so absolutely you have to have the whole loop to understand whether or not your ideas are good, building it, testing it, being involved in it, breaking it, fixing it, making it better is all part of the process (James, ET, 2).

The complex system in which James worked formed a key part of his learning pathway to becoming expert. This quotation illustrates comprehensively learning as theorised by activity theory. Activity theory utilises subjects who do various kinds of work, an object which may be an artefact to produce, rules or constraints, divisions of labour, and communities who all have some stake in the product being developed (Engestrom, 1991). These factors interact and contribute to an outcome (AT 3).

The subjects in the workplace described by James include “the product development people”, the “designers in the research group”, the “engineering” group who made the “product” and the computer “chip factory” that used the designed product in a production line that produced computer chips (AT 1). In this learning environment, James worked in the research and development team “designing the lasers” used for “imaging the circuits” and computer chips. The product development people in his organisation would identify

and communicate the changes they wanted. James' team "generated technologies" to produce these changes (AT 2). The team "designed, built and tested" their new technologies. For example, to make the laser go "twice as fast", they might try using different bearings or change gas flows (AT 4).

When they thought their technologies worked well enough they were passed back to the product development team and onto their engineering department to be put into a product (AT 3). "Over-the-wall" is a term associated with product development where each aspect of the overall product development is performed and then the product is passed over to the next department, in this case, "into engineering".

James' organisation required the technologies to be very "reliable" by the time they arrived at the computer chip factory, as any interruption in production at this stage could result in the loss of "a million dollars an hour" (AT 3). At this stage, the computer company would not be "very happy" if the designed technologies failed. The demand of reliability by the computer chip factory requirement is one of the "rules" or constraints that influences each of the teams (product developers, research and development, engineering) that contributes to the object and outcome of the final product (AT 4).

James considered that being able to see a product go into production successfully is an "absolutely" critical part of learning as a designer. He acknowledged that this closes the design "loop" and validates design ideas. That is, it allowed him to find out the success, or not, of an outcome and how well a product has worked.

In the above situation, James was able to achieve this from the whole system and environment in which he worked as a designer. The rules of the organisation required successful technologies to be produced for the company to stay competitive as millions of dollars were at stake if technologies failed. The various communities within the organisation (research group, engineering, product development team, machinists) acted separately but formed part of an overall structure that relied on each other to produce the computer chips (the overall outcome) successfully (AT 3).

These various communities divided the labour involved in the product development between them, for example research and engineering. Technologies already in place stimulated the development of new or improved technologies and, simultaneously, technologies were an essential component in developing new design ideas. Many different technologies came together to produce the final product or outcome. James described how

this activity system provided him with feedback about his design ideas. That is, through being involved in a whole variety of processes, he was provided with understanding he could apply in future designs (AT 5).

Absolutely you have to have the whole loop to understand whether or not your ideas are good, building it, testing it, being involved in it, breaking it, fixing it, making it better is all part of the process (James, ET, 2).

This example of learning recounted by James identifies how his knowledge and development as a designer was being refined, enriched and in many ways transformed by the experiences and actions of this whole working environment and system (AT 4).

8.5.2 Technological expertise and activity theory: Peter ET, 5

Peter recounted how he works more successfully as a designer when he is able to bring together all parties involved with a design. Peter's company builds very large one-off structures that often involve architects and engineers in their design. In most cases, the division of labour is defined clearly. The architects come up with a design and the engineers adapt the design to ensure it functions and can be built safely using materials that are strong enough. Peter and his company design ways to manufacture the product provide the transport infrastructure and place it in its final situation. Peter noted that when all three communities are able to work together, the outcomes are likely to be more successful.

When [engineers and architects] are designing it we're helping them with the buildability. ... It's like there's a nice picture how are we going to build that, how are we going to transport it ... once we get it there how do we get it into position. ... I would always err on the engineer's side normally because they're the ones that sign it off. ... We always get around the table and there will be 10 or 15 of us and two or three engineers and it becomes more of a thrash out, a debate that is what we've got to do and we'll say we want to do this and they'll say this and you slowly get a compromise. That's how it works. ... When you look at something practically, to build it they [the engineers] would just say so you can make that for 60 man hours a tonne but the reality of it is to be in a competitive market you might have to get that down to 50 man hours a tonne or 45 ... We're doing a job like these acoustic barriers ... an engineer is saying we need to beef up that top pipe and I said well can we go to a heavier wall thickness and they said no ... it's got to go to 220mm, well that will make it look a bit different. ... then we have the architect who steps in and says I want to see a nice pipe. So you've got us saying well we can build it like that but it won't look any good and the architect is saying well I want something that looks good and the engineer is saying you can't so somebody has got to give (Peter, ET, 5).

When working together the three groups (engineers, architects and manufacturers) represent the components of activity theory. As identified in Section 8.3, in activity theory, there are subjects, rules or constraints, divisions of labour, communities or groups and an overall object that provides a goal or outcome (AT 3). Each of these three groups, the architects, the engineers and the manufacturers (the subjects), belong to institutions or organisations, with their own cultural and social identities. In the experience described by Peter, these three groups come together and contribute to the overall design outcome (AT 2). The three groups represent three different communities and three divisions of labour or roles that they contribute to the project. Peter's job is to address the building problems and design solutions, what he referred to as the "buildability". However, the certified engineers' job is to "sign it off" as a completed project so they have to be satisfied with the final details, hence Peter will "err on the engineer's side" rather than the other experts involved.

Peter identified how each of these groups (engineer, architects and manufacturers) has a part to play. By physically sitting around a table they are able to "thrash out" and "debate" ideas and "slowly get a compromise" each having contributed their part to the design and as Peter noted "that's how it works". Each of the parties is governed by its own sets of rules and regulations but have an outcome (the building of a product that functions and that is aesthetically pleasing and cost-effective) as their common goal (AT 1). Peter related that the interaction of the three groups involves thrashing out ideas, debating and compromising. He noted that this type of social interaction and commitment by all three parties (engineers, architects and manufacturers) facilitates the effective and successful completion of a project (AT 2).

As an experienced manufacturer of very large structures, Peter is always aware of constraints such as, "how are we going to build" and "transport it" then "get it into position". Likewise, he is aware that his role is governed and constrained by the cost of building something "in a competitive market", in terms of "man hours a tonne". Peter utilises his previous knowledge and experience to address these constraints that act as further rules governing his part as the manufacturer in such an activity (AT 5).

Peter recounted a specific situation where the architect had wanted something that looked "good" and "to see a nice pipe" which formed part of a design for "large acoustic barriers". The engineer was saying "we need to beef up that top pipe" and Peter as the manufacturer was saying that the only way to do that was to weld a plate on the pipe and cover it which

would “make it look a bit different”. Eventually, they arrived at a compromise through their social interaction that satisfied the issues arising from these three different groups’ perspectives (engineers, architects and manufacturers) to produce a practical, aesthetically-appealing and buildable outcome (AT 4).

When this type of interaction does not occur early on in the projects in which Peter has been involved, he often encounters problems when it comes to building or fabricating the product. The product may be built several months and sometimes years after the “architect” and “engineer” has designed the product. When there is little social interaction amongst these groups of experts, it is far more difficult to address design issues at the manufacturing end, where Peter and his company are involved. This illustrates how activity theory can identify the breakdown when very limited social interaction occurs between the three representative groups (AT 3).

Peter identified the three groups as representing their specific CoPs. They work together to provide successful outcomes sharing, building-on and contributing to each other’s expertise and knowledge (AT 4). Peter noted that when working in isolation, outcomes are never as successful.

8.5.3 Pedagogy and activity theory: Matthew TT, 3

Activity theory identifies learning that results when many different elements interact. In the following quotation, Matthew described how students learn within the complex system of competitive “Robotics”. This is a competition where Matthew’s students compete in teams against other students. The competition has rules and prescribes the problem that motivates students to design a working robot that plays a programmed game.

Robotics incorporates all the aspects ... of hard material technology disciplines and mechanical engineering materials, electronics, software ... all those things are integrated together so it's a real microcosm of what's going out there in the world. ... It's good socially as well because all the kids from all the different schools know each other really well now. They're sort of on the robotics circuit if you like and they all Facebook and Tweet ... It's a little community there. ... all the robotics forums and the Vex forums have problem solving tips and the kids are always on there scouring through for examples ... that they can use and ideas. ... because we have our monthly school competition our kids are all competing and when they see someone else's robot and oh that's a really good idea, why didn't I think of that so they tear back and pull theirs apart and add things on and they're constantly modifying their design all the way through right up to the [New Zealand] nationals. ... They design a product they're constantly refining it all the time and improving it and scrapping it and starting from square one again (Matthew, TT, 3).

The purpose or outcome of “Robotics” is for students to learn how to design using “integrated” hard materials technologies. As Matthew described, it is “a real microcosm” of what is going on in design and problem solving in the real “world”. In other words, students are encouraged to tap into existing information and knowledge from “hard material technology disciplines and mechanical engineering materials, electronics, software” and to integrate these into their robotic projects (AT 5).

To enable this learning of design, students become part of a system, a “robotics circuit” that supports their learning. The competition is part of a much broader social network as it generates a specific “community” of learners who access information via face-to-face in regular competitions, “Facebook”, they “Tweet” and access relevant websites that provide “problem solving tips” which the kids are always “scouring through for examples” that they can utilise in their own projects. A significant part of the learning is through these independent social networks. To access this knowledge, students have to learn the language of robotics, the acceptable conventions and values of social networks as well as the rules of the competition, to become a part of this “little community” (AT 1).

The students that Matthew works with have competed in local, national and international competitions. Matthew describes the value of students competing in competition and how motivated as learners they become through their physical participation. As Matthew noted, the knowledge of students who build robots is challenged constantly through their participation. For example, when competing, they “see” others’ designs and this generates new ideas resulting in students “constantly modifying their design”. Even after the local “monthly school competition”, students are “constantly refining” and “improving” their

robots and sometimes “scraping it and starting from square one again”. The competition is a key element or social structure that contributes to students refining, enriching and in some cases, completely revising their design ideas (AT 4).

The learning in this situation requires the interaction of students with the rules of the competition, the learning community of students, the Robotics organisation that sets the competition tasks and organises competitions/websites, the technological disciplines used to create the robots, the robots and the teachers using their technological background (for example, Matthew’s avionics and mechanical engineering background) (AT 3). As Engestrom (2001), recognises, knowledge in an activity system is constantly being refined, enriched and changed by experiences and actions within the whole system. In the Robotics programme, the learning is not only supported by Matthew’s teaching, but also by a system that constantly enriches and refines students’ understanding and learning through social learning networks such as Facebook, physical face-to-face social interaction that includes competitions at a local, national and international level (AT 2).

8.6 Summary

In this chapter, four learning theories have been utilised to analyse both expert technologists’ experiences supporting their learning to design and problem solve and the learning experiences teachers provide for students to develop students’ learning to design and problem solve. The findings in this chapter have utilised four learning theories based on activity and experience: ELT, situated cognition theory, distributed cognition theory and activity theory as analysis tools. As noted previously, three of these learning theories emphasise particularly the social nature of learning through these various experiences.

Selected experiences of the expert technologists have been analysed by utilising one of these four learning theories that provided a theoretical framework of the ways in which learning occurs in each of the recounted experiences. Such an analysis also indicates the relevance of the rich diversity of learning experiences that contributed to these experts’ knowledge and understanding. For example: watching a barge disintegrate as it traverses a sand-bar; practical experiences in a range of engineering workshops; utilising knowledge, models and digital technologies to design a complex machine; installing a bridge (the artefact) utilising technologies and a range of expertise to address the constraints of the environment; designing as a member of a research and development team within a complex structure that made computer chips.

Like the experts, the teachers also did not specify any of the four learning theories when recounting experiences they considered contributed to their students' learning even though they discussed the learning and value of particular experiences for their students. In other words, intuitively they knew these experiences had value and relevance to learning to design and problem solve. Such student experiences included learning through: making a novelty hammer to experience the concept of tolerance; working in a workshop environment; participation in a workshop (CoP) learning environment; designing, making, implementing and critiquing the use of a sand-board; participation in a Robotics competition. The findings of the teachers' data has utilised four learning theories to analyse examples of students' learning experiences provided by their teachers and explain their relevance and importance from a theoretical perspective.

Chapter 9: Discussion

9.1 Introduction

This research is focused on the ways in which experiences with hard materials influence the development of learning to design and problem solve with hard materials. To investigate this overarching question, expert technologists who design and problem solve with hard materials and hard materials secondary technology teachers were interviewed to ascertain their understanding of the role experiences with hard materials play in learning to design and problem solve.

Six sub-questions emerging from the literature review identifying gaps in current literature and research were formalised to investigate the overall key research question that guided this research:

In what ways can experiences with hard materials influence the development of learning to design and problem solve in the context of hard materials?

9.1.1 Chapter structure

The six sub-questions used to investigate the overall key research question are examined and discussed in turn in this chapter. First two sub-questions relating to the findings of the expert technologists are discussed in Sections 9.2 and 9.3. Then three sub-questions relating to the findings of the technology teachers are discussed in Sections 9.4–9.6. In Section 9.7, the discussion is focused on the last sub-question concerning theorising the role of experience in learning to design and problem solve. The conclusion to this chapter is presented in Section 9.8.

9.2 Ways expert technologists consider experiences with hard materials developed their current expertise to design and problem solve

The sub-question: **In what ways do expert technologists consider experiences with hard materials developed their expertise (knowledge and understanding) to design and problem solve with hard materials?** is relevant to this thesis because understanding how designers and problem solvers approach design in the real world may inform technology education of ways to support novice student designers and problem solvers in technology education. Indeed, Daly et al. (2012) note that by trying to understand how

expert designers attempt design may inform educators as to how novice designers may become more like expert designers.

The analysed data of these technologists considered how their experiences helped shape their learning, expertise and journey from novice to expert designers and problem solvers. This learning included early and ongoing informal learning through experience (Section 9.2.1), learning about materials through experience (Section 9.2.2), practical understanding through experiencing processes of materials (Section 9.2.3), developing learning through feedback (Section 9.2.4), learning through directly sharing others' experiences (Section 9.2.5) and discussion identifying in what ways the experts draw on their learning of knowledge, understanding and strategic skills to enable effective knowledge deployment to design and problem solve (Section 9.2.6).

9.2.1 Early and ongoing informal learning through experience

The findings of these five technologists described their first informal learning experiences with materials occurring in their adolescent and teenage years as particularly significant. All five experts recalled participating in a range of experiences involving hard materials that included making things, pulling things apart, fixing things, building things and using tools. All of the experts acknowledged having an intrinsic motivation driving them to engage in these early experiences. In their descriptions of these experiences, they used words that reflected this motivation—for example, “mechanical aptitude, inquiring mind, inclination, always made something, wanting to build things, a passion for pulling motors apart, and a passion for working with tools” (see Section 4.4).

Analysis shows that these early experiences seeded the development of learning various types of useful knowledge and understanding. These initial informal experiences with materials contributed very significantly to the development of the experts' early or beginning *tacit knowledge*. As noted earlier, tacit knowledge is key knowledge required in technological design (Middleton, 2005). It is described as knowledge that grows, develops and accumulates through activities that include many and varied learning experiences working with materials over long periods of time (Custer, 1995; Ropohl, 1997; Solomon & Hall, 1996).

Other knowledge developed through these early experiences likely to have contributed to experts building their tacit knowledge includes *procedural knowledge*, *device knowledge* and *conceptual knowledge*. For example, the experts recalled pulling apart bicycles, cars

and motorbikes, primarily to find out how they worked, and later on to modify and rebuild them. Early experiences begin as procedural knowledge because pulling things apart and putting them back together requires doing so in a particular sequence. This sequence is learnt through experiencing the actual activity first-hand. However, these activities also link to developing knowledge to help understanding about how mechanical things work, referred to in the literature as device knowledge (see Section 2.8.3, p. 53). This is a key component of much mechanical designing and problem solving with hard materials. Vincenti (1991) notes that, knowledge of how devices operate develops implicitly in the beginning through experiences that may include procedures and, consequently, builds procedural knowledge. Later, a conceptual understanding regarding the operating principles underpinning the operation of a device (device knowledge) may develop.

Another key aspect relating to these early experiences is that the objects they interacted with were perceived as having relevance and importance to them. In other words, they were involved with experiences with real objects in authentic contexts, not the created experiences often provided in schools. Because of these authentic contexts, these experts were often able to obtain feedback on the quality and effectiveness of their design ideas. Brown et al. (1989) recognise that learning through an experience is important but, crucially, the context and situation of the experience also contributes to the learning. Lave (1988) notes that a key element of authenticity in a learning situation is when the problem solver is involved “emotionally” in the problem. In other words, a problem has a purpose and meaning that is relevant and important to the problem solver, as was the case in several of these early, practical learning activities experienced by the experts. For example, George (ET, 1) described making a water wheel and then being able to evaluate its effectiveness in a creek. James (ET, 2) recalled chopping up and rebuilding his bicycle and later building a car. No doubt James (ET, 2) rode his modified bicycle and drove in his car, which provided a crucial part of his motivation for engaging in these activities, at the same time, provided him with feedback on his design modifications. Peter (ET, 5) raced motorbikes, so learning to pull engines apart and getting them to function more effectively was hugely motivating for him. It also provided feedback on the effectiveness of the motorbike modifications in a racing context. Brian (ET, 4) recalled learning to use real tools in his father’s workshop as his initial pathway to being able to build things. He acknowledged the use of tools was not learning simply a skill; rather, it opened a whole world of being able to make real objects, with real materials, for purposes that he considered important.

As these experiences involved real contexts and situations that were meaningful and sustained motivation for the experts, they enabled and reinforced the experts' learning and provided them with valuable feedback. The resulting feedback from building or redesigning various objects and then testing the effectiveness of these design ideas, consolidated their learning.

Indirectly, this learning developed an integration of knowledge that included finding out how things work (device knowledge), learning about materials (conceptual knowledge), how to make things (procedural and conceptual knowledge), how to pull things apart and how to put things back together again (procedural and device knowledge). As identified in the literature, it is the integration of many different types of knowledge that experts utilise to design and problem solve (Section 2.8). The integration of many different types of knowledge builds a *strategic knowledge*; a knowledge that enables a designer and problem solver to know "how to decide what to do and when" (Gott, 1989, p. 100). Likewise, developing tacit knowledge occurs initially through practical activities working with materials and finding out how things are made and work. It is conceptualised over time so it can be utilised in many and varied new design and problem-solving situations (Custer, 1995; Herschbach, 1995; McCormick, 1997; Solomon & Hall, 1996).

The second type of informal learning experience identified in the experts' findings is provided by their everyday environment. As designers and problem solvers, they analyse, absorb and evaluate constantly how other people design interesting mechanical objects and how problems have been solved in order to build things in particular ways. As these real experiences for a designer and problem solver are available, ongoing and everywhere through their awareness, observation, reflection and analysis, experts' knowledge of designing and problem solving is being constantly informed and reformed. James (ET, 2) described this type of viewing the designed world as follows: "everything I see I look at as an engineer". Sorensen and Levold (1992) describe this type of knowledge building as developing "practical intuition" and characterise the way engineers look at the world with "a developed engineering gaze" (p. 20). They consider both these aspects to be as important for an engineer as calculation and analysis in developing their engineering and technological design capabilities.

Tacit knowledge also has been described as absorbed and intuitive and occurring over long periods of time. Therefore, it would be reasonable to conclude that experts are continually able to develop their tacit knowledge through these types of informal and ongoing learning

experiences and encounters in the real world (Custer, 1995; Solomon & Hall, 1996). In a similar way, Carlson and Gorman (1992) describe how famous inventors often develop new ideas through seeing and handling existing designed objects, illustrating very clearly how design often builds on others' ideas.

To summarise this section, it can be stated that the expert technologists recognised the importance of their early informal experiences with hard materials that began developing their learning expertise to design and problem solve. The knowledge built through these initial experiences with hard materials included tacit knowledge, procedural knowledge, device knowledge, conceptual knowledge and strategic knowledge. The experiences were situated in real contexts and situations that contributed to their learning because they were authentic and relevant at the time for them. From these experiences, they obtained feedback on how effectively their designs performed in real contexts. Concurrently, they continued to build their tacit knowledge through their informal learning experiences. Building tacit knowledge continues to develop the experts' design and problem solving learning and expertise. It is proposed that the experts' learning occurs all the time through their developed engineering awareness and curiosity, as they absorb the way problems have been solved, and design executed, through ongoing experiences of their everyday designed world.

9.2.2 Learning about materials through experience

Like Faulkner (1994), the analysis of these five experts' data acknowledges the crucial significance of knowing about materials when designing and problem solving. They described various experiences with hard materials that they considered important in developing this knowledge. The first of these involved exploring materials in a laboratory. For example, a practical experience such as stretching and breaking a steel rod is observed and the de-contextualised concrete experience is used to initiate learning about the descriptive (theoretical) and the conceptual knowledge about how steel behaves in tension. From the perspective of ELT, this type of concrete sensory activity, and the observation and reflection it stimulates, can be seen to develop conceptual knowledge that subsequently can be applied to new situations (A. Kolb & D. Kolb, 2005). Although experts utilise mathematical calculation and consult manuals to find out how steel performs in tension, actually observing and hearing steel fail in tension helps to develop this concept of material limitations in a much more meaningful and applicable way. A laboratory test

such as this provides a sensory and powerful concrete proof that if enough tensile force is applied to steel, it will stretch and eventually fail and break.

The experts' findings recognise experiences that involve working with materials used in *real* design situations over "working lifetimes" developed their knowledge of which materials to use for particular design applications (Brown et al., 1989). They recognised that these ongoing experiences develop their understanding of what works well, and were built on their successful and, in some cases, unsuccessful past experiences. Therefore, their knowledge compounds through many experiences over a long time period. Knowledge built through a lifetime of experiences links to tacit knowledge, which Ropohl (1997) acknowledges evolves over a long period of time through both successful and failed experiences, and requires much practice. As Brian (ET, 4) noted there is "no substitute for experience and experiencing the *real* thing".

Experiences of designing and problem solving over many years with hard materials also provided the experts with what they described as a "feel" or intuitive understanding for the right use of materials in various aspects of design. For example, they identified knowing when a design is made from too thick a material, knowing the right material to use in a particular environment, knowing when to use an extra gusset to strengthen a design or when to use a certain diameter bolt in a particular application without having to calculate its load ratings. They recognised this as knowledge built through years of experiences seeing how design detail enables design to function effectively. These experiences developed their tacit knowledge and built their prescriptive knowledge about the size and dimensions to use in design situations. These contextualised learning experiences in real design situations are explained by situated cognition theory, where the relevance of the context and situation is emphasised as contributing to the learning (Brown et al., 1989).

These experts recalled experiences of material failure in *real* world design situations as pertinent to developing their ability to design and problem solve. Two of the experts had been involved directly in the design of projects where design had caused materials to break and, as a result, the design outcome failed. George (ET, 1) recalled actually being present and seeing a barge he helped to design break up on a sand bar as "one of the most instructive days I ever spent" as an engineer (see Section 4.4). James (ET, 2) recalled designing a pre-tensioning anchorage that failed, "went bang and took a wall out" as an experience that became firmly "lodged" in his memory. Both George (ET, 1) and James (ET, 2) had been designers involved in these projects and therefore they had been

responsible in part for these design failures; both design situations generated significant safety issues as a consequence of their failure. In other words, George (ET, 1) and James (ET, 2) were connected emotionally with the failures and, after the events, were responsible for finding out what went wrong. At a later date, they described reflecting on and analysing these incidents to rectify the causes of these failures in their future designs.

Three of the other experts also recalled witnessing material failure in design concepts that had been created by other people. For example, John (ET, 3) recalled how an extra-thick flat end welded onto the end of a cylindrical pressure vessel had been tested by a marine surveyor. When the cylinder was filled with water, “it split and he just about got washed out the door because it was a catastrophic failure”. Clearly, the experts believe that having an actual sensory experience in the real situation of seeing materials fail was invaluable for their learning. As a consequence of experiencing these incidents, the experts developed their knowledge of materials, choosing suitable materials, and also realised the consequences and detrimental impact bad design can have on materials. As Faulkner (1994) notes, knowledge and understanding of materials when designing is of crucial importance. The experts’ experiences also taught them that the limitations of the materials are sometimes exacerbated through inadequate design. In other words, materials must fit the design and design needs to fit the materials.

The failures experienced by the experts provided feedback that built their knowledge and understanding that could be applied to new learning situations, mostly as a result of observing and reflecting on the concrete experience, thinking about the experience and using their previous knowledge and understanding to help them to comprehend what went wrong. These learning components are reflected in ELT, where a concrete experience can be transformed into new knowledge through thought and reflection and the adaptive use of previous knowledge (D. Kolb, 1984; A. Kolb & D. Kolb, 2005). Likewise, these experiences continued to develop the experts’ tacit and conceptual knowledge of design and materials in these real contexts where they experienced materials failing (Ropohl, 1997).

Because each of the situations described by the expert technologists involved authentic and situated experiences in specific contexts, their learning reflects characteristics of situated cognition learning (Brown et al., 1989). In the situated experiences described by the experts, the actual sensory nature of the real experiences provided much of the learning and knowledge, in particular, about the potential for materials to fail.

The technologists identified many experiences with materials that helped them to develop their knowledge and understanding of how to use suitable materials with specific mechanical properties. Although data about the mechanical properties of materials can be found in books, awareness of how to use these materials effectively develops through experience. Seeing many and varied applications of materials with different properties provided the experts with a database of knowledge. In other words, their experiences over many years built and deepened their *descriptive* knowledge of materials (Anderson & Felici, 2012; de Vries, 2012; Herschbach, 1995; Ropohl, 1997; Vincenti, 1991). That is, factual information about the properties of materials in contexts of use is developed through witnessing successful and different applications requiring use of materials with different mechanical properties. For example, a shaft will likely use a particular type of steel that is tough and strong and able to be heat treated after machining. In different applications, this will vary depending on the loading (for example, torsional or shear) on the shaft. Because the experts' experiences were situated in real and very authentic contexts, they were able to develop useful and relevant knowledge and understanding of the properties of materials that they can utilise in new design situations.

At the same time, the expert technologists built their *prescriptive* knowledge. This enables them to prescribe with some confidence a suitable material with the right mechanical properties to new and different design and problem-solving applications. As Mokyr (2002) notes, prescriptive knowledge depends to a large extent on the tacit knowledge built from the previous experiences and practice of the designer and problem solver. James (ET, 2) identified how this knowledge-building occurs over a period of time: "as time goes by, you end up with an understanding of the detailed properties of quite a lot of different materials".

In summary, it can be stated that the experts identified and described five ways in which experiences built their knowledge and understanding about materials and therefore contributed to developing their expertise to design and problem solve. Throughout all these experiences, the experts were provided with both direct and indirect feedback through seeing and experiencing materials in many different design situations.

First, was learning about materials through decontextualised laboratory experiments intended to deepen understanding about some of the properties and limitations of different hard materials. These experiences extended the experts' descriptive knowledge of materials through sensory concrete experiences. Second, seeing materials used in real

design situations and applications developed the experts' understanding of what materials to use and where to use them. The third way was experiences developing a "feel" for designing with hard materials. In other words, the experts' tacit knowledge developed over many years through experiences that built an intuitive sense of appropriate sizes and ways to use materials in design situations. The fourth included experiences seeing materials fail unintentionally in different design situations and contexts. The feedback from seeing these experiences helped to reinforce the specific limitations of materials and the potential catastrophic consequences when materials are used incorrectly in-situ. Finally, through a variety of experiences designing and problem solving, the experts deepened their knowledge and understanding of the specific properties of different materials, and built a knowledge base of the properties of different materials and their effective application in design. For example, this type of knowledge of materials enables an expert to prescribe a material with suitable mechanical properties when designing a component such as a shaft.

9.2.3 Practical understanding through experiencing processes

The findings identified experiences learning to *process* materials that developed knowledge and understanding that they considered vital to both design and problem solving with hard materials. They stated that to design a realised functioning product requires practical knowledge of how to process materials and the accessibility of processes. Faulkner (1994) recognises that expert designers require knowledge relating to the final product; that is, knowledge that enables the production and manufacture of designed artefacts. Vincenti (1991) also identifies this essential technological knowledge as *practical considerations*; it includes knowledge of production and how best to make a component or artefact.

Integrated with knowledge of processes is an understanding of the descriptive knowledge of a specific material's key characteristics. Such knowledge determines which process is most suitable to use. Indirectly, knowledge of a material's characteristics is developed through learning to process materials. As John (ET, 3) acknowledged when "rolling a plate or bending a beam ... you start understanding [the material] by working with it".

Since part of the manufacturing process often includes the assembly of a range of component parts, device knowledge and procedural knowledge are also relevant. For some of the technologists, building this knowledge often began with direct experiences learning

to process various materials. Indirectly, experience also contributed through simply being in environments and seeing materials processed.

Several of the expert technologists recalled how initially they had learned processes in a procedural way by following instructions from an experienced tradesperson who scaffolded these learning experiences for them. Such learning experiences are interpreted readily via situated cognition, where learning is experienced through an activity situated in a real context and supported by other experts who belong to a specific CoP (Brown et al., 1989; Collins et al., 1991; Lave & Wenger, 1991).

These activities provided these experts with first-hand procedural knowledge of how things are made as well as how to address the many practical subsidiary problems that require solving during the making of a product (McCormick, 1997; 2004). Such activities also built the experts' conceptual knowledge of what types of procedures and processes are available and feasible to use. This conceptual knowledge is essential for the experts when it comes to their own designing because they have to engage this knowledge to ensure designed objects can be made. In situated cognition learning theory, both procedural and conceptual knowledge are component parts of the whole learning and considered to be integrated and inseparable (Brown et al., 1989). Vincenti (1991) identifies this type of key technological knowledge (knowledge of suitable processes) as the *practical considerations* in design (see Section 2.5), reflected in the words of George (ET, 1) when he states that design "has to be practical". The learning of this technological knowledge is ongoing and, as Peter (ET, 5) described "often it just comes to experience". Therefore, the knowledge of processes and manufacturing of the experts is a form of tacit knowledge; that is, personal knowledge built through experience over a long time period (Herschbach, 1995).

For two of the experts, their knowledge of processes developed from being in environments where they observed various processes being used to build a range of different artefacts. As James (ET, 2) reflected, to design effectively, "you've got to be able to make it and then if it's an assembly you've got to be able to put it together". This design constraint requires knowledge of processes and the manufacturing associated with specific materials. It developed through ongoing, and often practical, experiences for them. For example, the assembly element in many designs also requires device knowledge of how components work in relation to each other (Gott, 1989). In some instances, this was obtained initially through the experts' hands-on procedural experiences, which later

transformed into a conceptual understanding of the operating principle of the device that was required (Vincenti, 1991).

In summary, it is important to note that the experts' data identified the ways in which experiences built knowledge of how to process materials and why this is essential knowledge for designers and problem solvers. Specifically, learning how to process materials in different ways (procedural knowledge) built the conceptual knowledge they utilise when considering whether or not a design can be manufactured practically into a functioning artefact. This practical aspect requires choosing, then prescribing the most suitable processes for the materials used in a design to ensure a safe and functioning realised outcome. Initial procedural activities of processing materials and putting components together often develop device knowledge, including a developing understanding of a device's operating principles (Vincenti, 1991).

9.2.4 Developing learning through feedback

A key aspect of learning obtained through experiences with hard materials, and identified in the experts' data as relevant to developing their expertise, is receiving feedback through seeing and experiencing how a design outcome functions in real situations. In some situations, this includes how well a design outcome has solved a particular overarching problem. This feedback is obtained primarily through the experts being able to observe how their designed products solve real problems and/or function effectively in-situ. Situated cognition identifies how learning experiences are fruitful because they are situated in real situations and actual specific contexts (Brown et al., 1989). It also identifies how learning is embedded in a social and physical world, which was described by these experts when they discussed how feedback provides them with knowledge and understanding. They noted this feedback is valuable because it results from being able to observe how well the design functions in a real context and situation; in a sense, the context and situation co-produce the knowledge with the artefact (design outcome) itself.

Likewise, feedback from experiences designing outcomes in real contexts builds designers' and problem solvers' tacit knowledge. That is, if the design works, it validates a design idea and therefore informs future designs, because those ideas can be reused in different applications (Custer, 1995; Solomon & Hall, 1996). As James (ET, 2) described, seeing one of his designs manufactured and functioning in-situ presents "the whole loop" of design and provides feedback on its effectiveness. James (ET, 2) also acknowledged that

the design loop helps you to “understand whether or not your [design] ideas are good”. Feedback also builds knowledge of the *practical considerations* identified by Vincenti (1991) as one of six key components of technological knowledge. While outcomes “validate” designs, also, they build expert designers’ conceptual knowledge that enables them to improve and change their future designs.

Often the expert designers and problem solvers described tapping into other experts’ knowledge in order to obtain feedback on their design ideas. In other words, they tapped into what could be described as other experts’ tacit knowledge accumulated from working within a related CoP over many years (Lave & Wagner, 1991). This process requires social interaction and communication among experts, which results in being able to access and utilise others’ technological knowledge built through experience. For example, James (ET, 2), described going to visit an expert machinist with his design ideas to obtain feedback: “I used to go up with my concepts ... and he would say to me well you can’t make it quite like that, but if you did this it would be better”. In other words, experts provide and receive feedback from each other, thereby comparing, contrasting, evaluating and, as a result, developing and improving their ideas. This learning is transferred from one expert to another through discussion and social interaction (Vygotsky, 1978), in contrast to the apprenticeship model (see Section 2.9.2) of learning where activity and experiences within a CoP are a more central and directive component of the learning (Lave & Wagner, 1991).

In summary, it should be noted that the experts acknowledged two ways in which experience provided them with feedback that developed their expertise. Not only did they utilise the feedback obtained through their personal experiences of designing and problem solving in real situations, they also tapped into other experts’ feedback from their years of practical experiences. Further, the experts often utilised feedback from others on which to build their new or modified designs. In other words, feedback resulted from knowledge built through previous design and problem solving experiences.

9.2.5 Learning through directly sharing others’ experiences

The apprenticeship model of learning was experienced by three of these technologists in their respective pathways to becoming experts. Experience played a vital role in developing these technologists’ learning and expertise. This learning involved active participation working alongside an expert, utilising a scaffolded learning model situated in industrial contexts (Brown et al., 1989). These experts described entering a CoP as novices

and, through practical experiences with hard materials, gaining confidence and knowledge that enabled them to participate more fully and independently in their respective CoPs. Their descriptions reflect what Lave and Wenger (1991) describe as increasing participation in a CoP as learners become more proficient through experiences in it. As Brian (ET, 4) noted, “When you start you really don’t have much idea but as you learn ... from tradesmen and test in practice, you slowly gain in confidence”. The learning begins as a result of peripheral engagement in an authentic context, which in the case of these experts included a marine engineering workshop, a large general engineering company, a jobbing workshop, a boilermakers’ workshop and a hydro-electric power project.

In summary, it can be said these experts’ findings identified that directly experiencing and/or working with hard materials in authentic contexts helped them to build knowledge and confidence that contributed to their learning to design and problem solve. This scaffolded model of learning enabled them to build their knowledge and confidence through practical experiences in authentic contexts that began their journey to expertise.

9.2.6 Strategic skills enable the deployment of knowledge and understanding

In this section, three strategic skills of designing and problem solving with hard materials identified from analysis of the expert technologists’ data are discussed. The knowledge and understanding required to engage in each of these three skills are described in Sections 4.4–4.8. The way these experts describe using their knowledge and understanding links to *strategic knowledge*, that is, “knowing what to do and when” (Gott, 19899). They do not use just one kind of knowledge or set of skills but must be able to choose whatever is appropriate for the design and/or problem-solving task at hand. The three strategic skills discussed in this section are: (i) addressing design constraints, (ii) making informed decisions, and (iii) using functional modelling, including computer modelling and calculation to explore and evaluate design concepts. These skills are neither hierarchical nor sequential. Rather, they are cyclic as each occurs at repeated stages throughout the process of designing and problem solving; often interacting with one or more of the other two skills. For example, constraints may occur at all stages of a design and will require decisions about actions to counter these constraints. Likewise, functional models of a design may throw up new constraints that require further decisions to be made.

The first strategic skill was that of addressing design constraints. For example, Peter (ET, 5) described how design constraints imposed by a *stakeholder*, where a bridge project has a

very restricted timeframe in which it can be placed in-situ, are able to be addressed because of his accumulated knowledge. His *know-how* resulted from tacit knowledge built through working with large structures such as bridges over many years, including his years as an apprentice. To solve the problems relating to this type of project, Peter (ET, 5) is also able to draw on his procedural knowledge of many different processes learnt through his practical experiences with hard materials and his resulting conceptual knowledge. Conceptual knowledge allows him to utilise the most suitable processes to address the time constraint of the stakeholder in this situation. His knowledge has accumulated through his experience and participation in situated and like contexts, reflecting a situated cognition framework of learning (Brown et al., 1989).

A second constraint is that of *compliance*. Experts have to comply with outside authorities' prescribed knowledge represented in compliance codes. For example, George (ET, 1) described those used in marine engineering to enable a sea vessel to be accepted into a marine class. To address these constraints, George (ET, 1) needed experience of seeing how this information was applied to designing a marine vessel. To be able to apply these rules and constraints, first, he requires prescriptive knowledge of them and, second, experience of how they are applied in marine engineering. How to apply these rules and constraints requires tacit knowledge which George (ET, 1) acquired through his experience working in a shipyard. Here, he witnessed repeatedly the rules and constraints being applied. Likewise, when designing products to meet safety standards, the expert designers and problem solvers identified requiring prescriptive knowledge of several different safety standards that they apply to each new design situation.

Two further constraints identified from the expert designers' and problem solvers' findings are developing a design concept that is capable of being built and manufactured into a physical outcome and the practicality and cost-effectiveness of a design. To address these constraints, the designers and problem solvers use their strategic knowledge, described by Gott (1989), as knowledge that enables them to know "how to decide what to do and when". In the case of these experts, this strategic knowledge was built from their experiences over time. It consists of a combination of procedural knowledge of available processes, conceptual knowledge of what types of processes are best to utilise, descriptive knowledge of materials, prescriptive knowledge and tacit knowledge. The experts' knowledge was built through their situated experiences in commercial and real environments using hard materials. As Petrina (2007) points out, knowledge and learning

occur through enculturation in specific environments. Knowledge of material processes and descriptive knowledge of materials enable designers to choose the most suitable process to accommodate the different properties of materials used to design and problem solve (Faulkner, 1994). Vincenti (1991) acknowledges these two types of technological knowledge in design as: (i) practical considerations, and (ii) criteria and specification.

A second key element identified is the capacity of the experts to be able to *make decisions* that reflect good judgement. As Ahmed et al. (2003) note, experts in engineering design try to evaluate and make decisions about design concepts prior to implementing them because they acknowledge trial and error is not a feasible strategy in the majority of design situations. James (ET, 2) recognised that this capacity requires belief in your own ability and the courage of your own convictions. Brian (ET, 4) identified this happening after he gained confidence through working with others and through “practice” on the job. It would seem that being able to make decisions based on sound technologically informed judgement, believing you are able to design something, and having the confidence and courage to carry it out, require substantial previous experiences and extensive knowledge in related contexts.

As James (ET, 2) noted, such decision-making expertise requires time. He stated that his ability to design has improved as his knowledge and experience have increased. When pointing to a complex machine he had designed recently from a “clean piece of paper”, he identified how his expertise has developed over time: “I get better at this [designing] as time goes by”. In fact, he stated: “I couldn’t have done that [design a complex machine] 20 years ago”.

These technologists acknowledged often building on and using the feedback from others’ previous design ideas to help inform their decision making in finding a good design idea. In other words, they use the knowledge of others as a base to which they add their own knowledge to develop more effective design solutions. This often includes modifying others’ designs to improve their function. As James (ET, 2) noted, often “you build on what other people have done before”. Prescriptive knowledge results from continuous efforts to achieve better results in design and reflects the view that prescriptive knowledge continues to be adapted and modified over time, depending on the specific context and application (Herschbach, 1995; Mokyr, 2002).

A third strategic skill is their use of *technological modelling*. Although the various technological modelling processes described do not as a general rule produce the final functioning product, they do provide some representation of aspects that contribute to a final functioning outcome. Therefore, it can be described as *functional modelling*, testing design concepts that incorporate research, knowledge and supporting evidence to inform decision making for the development of a new outcome (Compton & France, 2007). These experts described making mock-ups and building something quickly and roughly to test an idea. These functional models not only reflect but also utilise their knowledge and expertise; they are not something a novice could produce with limited experience, knowledge and understanding. For example, being able to use a 3-D engineering computer modelling programme requires considerable engineering expertise and was described by James (ET, 2) as a “tool”, not something that did the actual engineering for a designer. It should also be noted that, in some situations, a designer makes digital drawings of a model with sufficient technical detail to be sent directly as a computer dxf file to a machine tool to be manufactured. James (ET, 2) described this as: “I’ve got that model [digital], I then make a drawing [on the computer]... the drawing is views of the model ... then you create a dxf file ...which you can feed into a machine tool”. The digital model in this situation could be likened to a prototype model.

In stark contrast, George (ET, 1) described drawing up a sketch (functional model) of a \$7 million marine vessel on the “back of a fag packet”. This ability relied on his considerable background knowledge and understanding. As Cross (2004) reports, several studies identify experts as being able to develop some “type” of solution to a problem relatively quickly because they are able to consider the problem and the solution together. Jones et al. (2013) note, knowledge in design and problem solving often requires ways to transfer knowledge that cannot rely solely on propositional knowledge. It requires the ability to act appropriately but adaptively, which entails being able to build functional models, sketch ideas and utilise computer programmes to create 3-dimensional models and FEAs. However, as noted by the experts, there are many experiences and much knowledge and understanding contributing to the development of any purposeful technological model.

In summary, the technologists’ data identified how the many different experiences building knowledge and understanding described in Sections 9.2.1–9.2.6 contribute to three strategic skills required to design and problem solve. In other words, the experts’ ability to utilise these skills (addressing constraints, making decisions and building functional

models), helps them to function as designers and problem solvers. They are skills developed through many different types of experiences with hard materials.

9.3 Experts' conceptions of design and problem solving

The sub-question: **In what ways do expert technologists conceptualise the relationship between design and problem solving in the context of hard materials?** is relevant to this thesis as it helps to unravel the differences between, and the interrelationships of, design and problem solving from the perspective of experts in technologically specific environments that use hard materials. Therefore, it helps to build a more comprehensive picture of the underpinning of design and problem solving with hard materials that may be utilised in technology education.

An overall finding is that problem solving is interrelated strongly with design in the context of mechanical engineering and working with hard materials. Six of the key findings are discussed to show the ways in which these experts conceptualise design and problem solving with hard materials.

The conception of design identifies that an initial problem defines a need for design. While this is not the sole reason for design, the technologists identified it a significant reason. This conception of design reflects the first step of the problem-solving process as presented in much of the early technology education literature (see Section 2.3.1), which commences with defining a problem and continues with devising solutions (design) to solve the problem (Savage & Sterry, 1990). Although these technologists did not focus solely on the problem-solving aspect, they stated that solving an overarching problem often constituted the reason to design, described by Brian (ET, 4) as a “problem needing to be solved”.

The second finding focused on how the purpose for design is often turned into what James (ET, 2) described as a “big” problem before the design begins. Once the design process commences there are many further subsidiary problems encountered that may require a design solution. In their study of “better-than-average” expert engineering designers, Cross and Cross (1998) describe how creative designers will often pose a task as a problem to make it ill-defined and more challenging, rather than solve it via the easiest route. Likewise, in many of the current design processes presented in engineering design texts, the design process will very often commence with a problem (Jack, 2013). The stated overall “unfulfilled need” initiating a design can often be formulated into a problem (Mital et al., 2010), described by James (ET, 2) as the “big problem” in a design and problem-

solving activity. In other words, the process of design may be manipulated and viewed as problems which are solved by developing a design as a solution.

The third finding identified that the many subsidiary problems are not just production or manufacturing problems necessarily but, in a complex design, are problems that may require further minor design solutions to enable the overall design or solution to the “big problem” to function. These experts emphasised that for a design concept in engineering to “practically work”, there is a myriad of minor problems that also must be solved. James (ET, 2) explained these as “a problem within a problem”; to solve the subsidiary problems, “you drill down through the overall problem into all the detail”. As Vincenti (1991) points out, an engineer’s design includes both the plans of the design and the production processes and detail associated with the design to produce a realised outcome. George (ET, 1) stated that in real estate it’s “location, location, location” but in engineering design with hard materials it’s “detail, detail, detail”. In other words, the design must incorporate the detail to accommodate the subsidiary problems encountered as part of the overall design. It could be stated that designing with hard materials as conceptualised by these experts, regardless of whether or not it is solving an overarching problem or meeting a need, incorporates subsidiary problem solving as a key and essential component that enables a design to function effectively.

A fourth finding, which overlaps with this concept of solving subsidiary problems as a design develops and providing detail within a design, is the conflict of design providing extensive detail while striving to be innovative. In other words, the interrelationship of design and problem solving can create a tension between innovation and practicalities. This concept of design mirrors literature acknowledging the tension between technological design as conceptual and innovative at the same time as systematic, functioning and addressing the constraints around being able to be produced and manufactured. As a consequence, design has to account for and incorporate a wide range of technological details (Barak & Goffer, 2002; Hill & Anning, 2001; Mioduser & Dagan, 2007). George (ET, 1) described this tension as: “If you’re going to provide an innovative design to get to the practical stage you’ve got to solve all the problems”.

A further finding from the experts’ data is recognition of a situation in which a relatively straightforward problem that would under normal circumstances be solved by a standard procedure, and not require a design solution, can sometimes generate new problems that require solving with a design solution. For example, Brian (ET, 4) described a situation in

which machinery being fixed in his workshop often required specific jigs or fixtures to be designed and made to enable machining operations to be implemented safely.

In a sixth finding, the expert technologists noted that many problems associated with engineering design do not require solving by means of a design solution. These types of subsidiary problems are often encountered in the processing and manufacture of others' designs and are a component of design where an outcome is a product. As Brian (ET, 4) commented, in his work sometimes "someone ... has already created the design ... the problem is how do we perform the process?" McCormick (2004) also describes how practical problems sometimes arise during the making of a product and notes that this type of problem solving receives limited acknowledgement in technology classrooms.

To summarise, the expert technologists' conceptualisation of the relationship between design and problem solving is that design is a problem solving process that tries to find the optimum design but in doing so must address many and various subsidiary problems within the design. These expert technologists acknowledged that problem solving with hard materials may not always be associated with design. However, they believe that design with hard materials cannot stand alone, without the inclusion of problem solving. In other words, their conception of design includes both innovation and creativity, but also acknowledges the practicalities, including the subsidiary problem solving, in order to realise the design into a functioning product. Likewise, it may include the practical subsidiary problem solving that is often necessary to manufacture a design. To enable this to happen, technologists have to be able to solve many and various problems that arise. The expert technologists' conceptualisation of the relationship between design and problem solving reflects the view of McCormick et al. (1994) on the interconnection of design and problem solving as design being the "manifestation of the problem-solving process". Likewise, the experts' view also reflects the position of Middleton (2005) and Taylor (2000) that design is seen often as a defining component of technological problem solving and the view of Mital et al. (2010), who define designing in engineering as a "special form" of problem solving (p. 28).

9.4 Technology teachers' conceptions of design and the role of problem solving

A further sub-question: **What are technology teachers' conceptions of design and the role of problem solving?** is significant as it endeavours to ascertain a group of hard materials technology teachers' understanding of two key elements (design and problem

solving) central to this thesis. As acknowledged in the literature (Section 2.3), since the introduction of design and problem solving in technology education, there remains some confusion as to the differences, similarities or interconnectedness of these two elements (Johnsey, 1995; McCormick, 1997; Mawson, 2001). Therefore, it would seem pertinent to find out teachers' conceptualisations of design and problem solving before investigating the learning activities they provide for their students. Also, it is relevant to look for similarities between the teachers' conceptualisations of design and problem solving and those of the experts, as one key purpose behind the introduction of design and problem solving in technology education was to replicate what *real* technologists do (MoE, 1995).

The findings of the five hard materials technology teachers' conceptions of design and problem solving indicate several similarities to those of the expert designers and problem solvers. That is, the teachers' findings revealed that they identify an interrelationship between design and problem solving. For example, three of the five teachers described design as solving an overarching problem in a specific technological context. This interrelationship reflects Morrison and Twyford's (1994) concept of design arising from problems and issues, and echoes the view of Stein et al. (2003), who consider design in technology education as a form of problem solving.

Like the experts in this research, several teachers considered subsidiary problem solving as an integral part of designing with hard materials and acknowledge that designing often requires further practical subsidiary problem solving as a design is realised. Two of the five teachers had backgrounds in engineering-related fields prior to becoming teachers, which no doubt impacts on their understanding of design and problem solving with hard materials. Two of the teachers acknowledged the practical manufacturing-type subsidiary problem solving when realising a design. They acknowledged these problems do not require necessarily a design solution. As noted previously in Section 9.3, the technologists identified this type of problem solving as sometimes being separate from the initial design. Nevertheless, for a design to become an outcome, it is necessary to address and solve these subsidiary practical problems. McCormick (2004) points to manufacturing-type problems occurring frequently in technology classrooms, although it is not a type of problem solving that receives much acknowledgement in curriculum documents.

Two of the five teachers noted *optimisation* as a factor in design and problem solving with hard materials. As noted in the research of Merrill et al. (2008), optimisation is identified as one of three key elements (constraints, optimisation and predictive analysis) that expert

engineer designers utilise. The expert technologists also acknowledged the necessity of developing an optimum design incorporating the many different design constraints (see Section 9.3).

The five teachers' conceptions of design and the role of problem solving differed somewhat. In some instances, they reflected the influences of their technological background. For example, problem solving did not feature strongly in Kevin's (TT, 2) conception of design. Instead, his view of design focused very heavily on design concepts and exposing his students to innovative and creative design. A possible reason for this difference is Kevin's (TT, 2) background in boat designing and building, which prompts a stronger focus on form and design. Kevin's (TT, 2) view contrasted significantly with that of Henry (TT, 4), who believed problem solving at quite a prosaic, practical level is in fact a key component of technology education if the aim is for students themselves to be able to design and produce an outcome. Matthew (TT, 3), a former aviation technologist, considered design as problem solving at a "higher level" and his design conception included problem solving as a key element, while the conceptions of Patrick (TT, 5), a former diesel mechanic, and Andrew (TT, 1), a former architect and building technologist, focused on the practical problem solving enabling a design to be realised. Interestingly, none of the five teachers acknowledged troubleshooting or fault-finding as problem solving although, as McCormick (1997) observes, this is a major type of problem solving practised by workplace technologists.

The technology teachers' conceptions of design and the role of problem solving may be summarised as: design solving an overarching problem; design requiring inspiration and creativity; design as problem solving at a higher level; design requiring components of practical problem solving as a design is realised; and design including optimisation as a factor that considers constraints such as time and cost.

Both the expert technologists and the technology teachers provide a rich and broad explanation of design and problem solving and their interrelationship in the context of hard materials. It would seem important for technology education to try and clarify how design and problem solving are distinctive and how they interrelate, particularly in the context of hard materials. While the expert technologists' data findings enrich these explanations, they cannot be transformed completely into school programmes without some modification. From the technology teachers' data, it would appear that problem solving receives less emphasis in terms of how it is integrated within the whole design process.

From the technologists' findings, problem solving is not just defined as an overarching problem that is solved by a design solution or solving the practical manufacturing-type problems. Instead, design is a problem-solving process that requires ongoing solving of subsidiary problems within the design to provide the detail that produces a realised functioning outcome, including solving the subsidiary practical manufacturing-type problems.

9.5 Traits of successful novice student designers and problem solvers

The fourth sub-question: **What are technology teachers' conceptions of the key traits of successful novice student designers and problem solvers working with hard materials?** is relevant in that it identifies traits as important for students to have and to acquire to be successful novice student designers and problem solvers. By considering these traits, this research can also consider how experiences with hard materials might develop these traits in students. Analysis of the technology teachers' data findings identified seven key traits of novice student designers and problem solvers. Teachers' responses to this research question indicate the interaction of three components of pedagogical context knowledge (PCtK): (i) teachers' classroom knowledge of students, that is, being able to identify the key traits of successful student designers and problem solvers; (ii) teachers' academic and research knowledge about how students learn; and (iii) teachers' professional knowledge represented by their unconscious reflection and discussion concerning why students are successful as novice student designers and problem solvers (Barnett & Hodson, 2001).

The key focus of the first trait, *awareness and curiosity*, can be summarised as students who are aware of the physical world in which they live and are thinking constantly about and questioning how and why things are made in a particular way in their quest to build their knowledge. Words such as "attuned, observant, interested, wondering how and why" were used by the teachers to describe these students (see Table 6.11). These descriptions link to the views of the expert technologists, who described how their knowledge of designing and problem solving constantly is being informed and reformed through awareness, observation, reflection and analysis of their everyday world. As noted previously, Sorensen and Levold (1992, p. 20) describe this type of knowledge building as developing "practical intuition" and identify the way expert engineers look at the world as "a developed engineering gaze". It would appear that "an engineer's gaze", or equivalent,

is desirable for all students, so teachers should consider the ways in which different types of experiences can help their students develop this trait.

The second trait, *risk-taking/creativity*, can be expressed as students who are focused and confident to take risks because they have some ability that enables them frequently to come up with better ways to do things. The teachers recognised that this trait is often triggered after students have acquired some practical skills and knowledge. Words such as creative, thinking and ability were used to describe these students (see Table 6.11). Likewise, the expert technologists considered creativity is embedded in experiences with hard materials. For example, design and problem solving cannot *just* be creative because a design must also address the myriad of subsidiary problems if it is to become a realised functioning outcome. As the experts' data recognised, the creativity of a design is constrained by the cost, available processes, expertise and available materials. In the real design world of the expert technologists, risk-taking was also constrained by safety standards and compliance regulations. However, the experts did acknowledge that they tried to be "innovative" and develop "smart ways" to design and solve problems.

It is interesting that the third trait, *confidence*, was regarded widely as arising from producing a successful outcome in hard materials technology classrooms. This validation provided students with good feelings and built their confidence. Patrick (TT, 5) noted that students who learn practical skills are empowered with a can-do attitude to turn out "viable designs of their own", therefore utilising a kind of internal confidence or self-efficacy. This confidence often enables them to find out further information when required. Key words used to describe these students included a can-do attitude, personal belief, high quality, validation and good perceptions (see Table, 6.11, p. 187). Confidence was highlighted also by Brian (ET, 4), who described how he "slowly gained in confidence" from his working experiences when supported by tradespeople and practical learning in-situ. The experts described also gaining confidence from feedback obtained when their actual design outcomes prove to be successful and effective. Decision making was described in Section 9.2.5 as a key skill of designing that experts are required to perform. This requires confidence on the part of the designer that has been developed through many experiences and successful design outcomes with hard materials. This experience results in the development of sound technological knowledge on which to base judgement and decisions.

The fourth trait, *anticipation of problems*, is described as students being able to integrate different pieces of information or knowledge about a problem and its design solution and

anticipate the impact of changes made to a design. In other words, students being able to think ahead and anticipate the subsidiary and nested problems in a design idea and therefore be aware of the constraints such as time and cost when designing. The key words and phrases used by these teachers to describe these traits include thinking like engineers, do this/affect that, thinking ahead, consequences, decision making (see Table 6.11). This reflects an early ability to use strategic knowledge, described by Gott (1989) as knowing what to do and when to do it. As discussed in Section 9.2, the expert technologists gained this knowledge through practical experiences where they have practised thinking ahead, anticipating subsidiary problems within the design, identifying causes, effects and consequences before making final design decisions. In Section 9.3, analysis of the expert technologists' data identified the experts' view that design with hard materials included anticipating and solving the many subsidiary problems that occur if a design is to become a functioning outcome.

The fifth trait was *evaluation*. Students who manifest this trait were described by the teachers as critical thinkers who are able to evaluate and reflect on their own work and are keen to find ways to improve it. In addition, they are able to build on others' ideas and incorporate these into their own designs. This metacognition or understanding that design can always be improved upon was described by Henry (TT, 4) as "the hallmark of the top students". It also links to confidence as this provides students with the "can-do" attitude that often enables them to try and improve their initial designs. Key words and phrases used by the teachers to describe this trait in students included reflective practice, critical thinking, modifying design, refining and improving (see Table 6.11). Likewise, the expert technologists identified the importance of constantly evaluating both their own and other's designs, which provided them with feedback to help them to create and build better designs and to solve problems more effectively. As well, design failures provided them with opportunities to reflect and evaluate why these occurred and to use this information to inform and change their future designs.

The sixth trait identified was *conceptualisation and communication in three dimensions*. Two of the teachers identified students who could either think in three dimensions and/or express their ideas through sketching or drawing in three dimensions as much more able to design ideas to make with hard materials. Patrick (TT, 5) summed up the purpose of graphics or design and visual communication as a means to develop students' visual literacy. In other words, this meant being able to study drawings to visualise what a

product actually might look like in real life and, if a mechanism is involved, how it might operate. Middleton (2005) identified one of three representations of knowledge when technologically designing as *visual*; that is, developing a realistic mental 3-dimensional image of an object. The key words and phrases that teachers used to describe this trait in students includes thinking in 3-D, draw ideas, work in 3-D and implement ideas (see Table 6.11). As Jones et al. (2013) note, non-propositional knowledge is an essential component for design and includes aspects of technological knowledge such as the use of drawings. However, Schunn and Silk (2011) observe that modelling is in fact a skill and can provide a challenge to many learners. For example, they observe that students may fail initially to see models as a representation of design; rather, they see models as isolated things with no other purpose. As noted in Section 9.2.5, the expert technologists relied on knowledge developed through experiences with hard materials to produce useful and purposeful *technological and functional models* of their designs.

The final trait identified was *intuition*. This trait refers to those students who have intuitive skills when designing and making things with hard materials. These teachers commented that some of these pupils are not skilled particularly at completing the associated book work usually required in students' design folders. The academicisation of technology education, partly through the inclusion of design and problem solving, has required students to complete a lot of associated recorded and written work, often referred to in New Zealand schools as "folder work". Several of the technology teachers acknowledged a concern for those students who want to design and make products and who use the workshop environment in a purposeful way. However, frequently these students feel alienated and often fail when it comes to completing their written work, despite being identified as talented novice student designers and problem solvers possessing intuition. The words and phrases used by the teachers to describe intuition among students included intuitive skill, can see it straight away, talented and instinctive (see Table 6.11).

It would seem that technology education in its present format fails to meet these students' needs adequately. Perhaps there is a place in technology education that considers the knowledge and understanding of a student as represented in a designed and functioning outcome or artefact (without the folder work). In other words, recognition that artefacts in technology not only integrate a wide range of necessary knowledge but embody knowledge in their own right (Compton & France, 2007). To paraphrase Custer (1995), the production of a designed artefact is a distinguishing component of technological knowledge that

represents activity, experience and practice. This notion is also recognised by Baird (2002), who notes that a functioning artefact contains knowledge that distinguishes it from other forms of knowledge.

Five of these seven traits identified from the findings of the teachers' data (awareness and curiosity, risk-taking/creativity, anticipation of problems, evaluation, intuition) link to Williams' (2011) identification of nine *thinking dispositions* that he posits are teachable to students: seeking understanding; metacognition; lateral thinking; carefulness; being constructive; imaginative; taking risks; making connections; and critical reflection. Williams makes a strong case for the teaching of these thinking dispositions through suitable learning experiences as an achievable goal in technology education. Williams further notes that the "generality" of these dispositions may in fact "build" upon more situated and context-dependent skills and abilities (p. 101). This research inquiry identifies how these traits may be supported and developed through learning experiences with hard materials.

In answer to this research sub-question, the teachers' findings conceptualised seven key traits of successful novice student designers and problem solvers: awareness and curiosity; risk-taking/creativity; confidence; anticipation of problems; evaluation; conceptualisation and communication of ideas in three dimensions; and intuition. The technologists' data has also highlighted parallels with experts' acknowledgement of utilising similar traits to design and problem solve to those identified from the teachers' data. In the following Section 9.6, the analysis of the teachers' data provides links to the ways in which these teachers implement pedagogy to enhance and develop these traits in their students with experiences using hard materials.

9.6 Ways teachers consider learning experiences with hard materials can influence and support students' learning

The sub-question: **In what ways do teachers consider learning experiences with hard materials can influence and support students' knowledge, understanding and learning to design and problem solve with hard materials?** is relevant as it finds out information from teachers regarding how they consider experience with hard materials relates to learning to design and problem solve in technology education. By considering both the experts' data and technology teachers' data, a detailed overview can be presented of learning design and problem solving with hard materials through experience. Three issues were identified from analysis of the teachers' data as influencing the teachers'

pedagogy that relate to this question. In Section 9.6.1, these three experiential issues are revisited and discussed. Section 9.6.2 discusses the learning experiences teachers provide through their pedagogy that they consider can support students' learning design and problem solving.

9.6.1 Experiential issues relating to teaching design and problem solving

Three issues identified from the analysis of the teachers' data regarding students learning to design and problem solve with hard materials. These issues relate to teachers' identification of students' prior experiences, knowledge and understanding as they begin their post-primary school technology education. While each of the teachers identified problems arising with students in their own schools, these problems can be categorised into three key general issues. Through identification of such issues associated with technology education, these teachers were able to deepen their understanding of their students. As noted in discussion of PCtK, classroom knowledge and pedagogical content knowledge (PCK) require teachers to know the students in front of them, including key background information (Barnett & Hodson, 2001).

The first issue relates to students' *lack of experiential learning* with hard materials. Teachers articulated this lack of experiential learning in different ways. For example, Andrew (TT, 1) noted that in his single-sex girls' school, the female students rarely query how everyday things are made or from what they are made. Matthew (TT, 3) considered that at his school, many of the students lack understanding because they spend little time playing or getting out and making things in the physical world. This differed considerably from the memories Matthew had of his own childhood. Henry (TT, 4) noted that many of the students in his school live in situations where generally someone is paid to fix anything that goes wrong. In addition, he considered that students' constant playing of computer and video games, where they spend their spare time being "entertained", as contributing substantially to this issue. Patrick (TT, 5) noted that many of the students in his single-sex boys' school have absent fathers and, as a result, a dad playing in the garage "making stuff" with his son is the "exception not the norm". In fact, he noted this situation was a rarity even if fathers are part of a family unit. This contrasted quite distinctively with the expert technologists' recollections of playing, making and fixing things during their childhood and later as teenagers (see Sections 4.2 and 9.2.1) and likewise, the activities Matthew (TT, 3) and Andrew (TT, 1) recalled experiencing during their childhood (see Sections 6.2.3 and 6.2.1). Dixon and Brown (2012) acknowledge that if what students have

experienced is very limited, child-centred learning is difficult and students may require new experiences to broaden their limited experience of the world.

The second issue linked clearly to the first issue, is students' *lack of experiential knowledge of hard materials*. In other words, students who have had limited experiences working, playing or tinkering with hard materials have very little knowledge or understanding of hard materials when commencing their post-primary technology education. As expressed emphatically by the technologists (see Section 4.3) and discussed in Section 9.2.2, knowledge of materials is a key element necessary to design and problem solve with hard materials and much of this knowledge is developed through rich experiences. The research literature acknowledges that knowledge of materials is an essential element that experts require when designing and problem solving (Faulkner, 1994; Vincenti, 1991).

The third issue is that many students have *no experiences of designing, problem solving or ever making something with hard materials*. This issue relates to both students' lack of experiential learning in the real world, and their lack of experiential knowledge of hard materials (first and second issues). Unlike what the expert technologists identified as important in Section 4.2 and discussed in Section 9.2, students do not have the extensive procedural, conceptual and tacit knowledge bank of expert technologists to draw on when designing and problem solving. Often students have no idea where to begin and have no experience of how to proceed or anticipate problems in a design.

After reflecting on matters relating to these issues, teachers acknowledged that a component of their learning programmes and pedagogy developed in response to these three key issues. Initially, this resulted in providing students with "catch-up" introductory experiential learning activities with hard materials to build their knowledge and understanding of materials and of designed products. As noted previously, these teachers' reflections on the three issues concur with the literature and research of teachers' PCK and classroom knowledge components of PCtK identified in Section 2.10 of the literature review (Barnett & Hodson, 2001).

9.6.2 Technology teachers' pedagogy supporting the learning of design and problem solving with hard materials

Throughout this section, the technology teachers' pedagogy is discussed and the background influences on the teachers acknowledged. PCtK posits that teachers' academic

and research knowledge is influenced by their content, cultural and historical knowledge surrounding a subject (Barnett & Hodson, 2001). This is relevant particularly for four of these teachers who had been practising technologists prior to becoming teachers. Likewise, recognition of the key traits considered as evidence of successful novice student designers and problems solvers identified from the teachers' data (see Section 9.5) are also influential in their pedagogy. As well, the teachers' pedagogy provides ways in which the three issues identified in Section 9.6.1 can be addressed. Consequently, in this section, this discussion acknowledges in teachers' pedagogy: (i) the technology teachers' background influences; (ii) teachers developing key traits of successful novice student designers and problem solvers in all students; and (iii) addressing the three issues identified from the analysis of the technology teachers' data of students learning to design and problem solve.

The teachers stated that a first key purpose for many of the experiences with hard materials they provide for their students is to try and raise the awareness and curiosity by getting them to reflect on the world. Initially, the teachers do this by showing students or making them aware of designed products in their real world, and trying to get them to evaluate what materials these objects are made from, and why. In contrast, the expert technologists acknowledged their long-lasting preoccupation with observing and questioning how things are made and what materials they are made from in their everyday world.

Because the students often have such limited experiences of how to make objects with materials, these teachers provide experiences through which they can deconstruct objects to help develop some initial awareness of how things are made, including how materials can be formed, manipulated and transformed to make functioning objects. Matthew (TT, 3) described how he takes his students to visit the design office and the many different workshops where various components of a super-yacht are built which enable his students to witness the "deconstruction" of a super-yacht. He believes the many components of construction made from various combinations of materials provide students with an authentic global picture of super-yacht production. This learning experience reflects situated cognition as the activity is situated in the real context of super-yacht production and students get to see and experience this real-world designing and problem solving first-hand. The context, situation and the culture of the experience is central to the learning process in situated cognition (Brown et al., 1989; Hendricks, 2001). For example, first, the component parts of the super-yacht reflect a very high quality of expertise using a wide range of hard materials, complex innovative design and problem solving and a key focus

on functionality associated with design and building an expensive luxury sea vessel. Second, the culture surrounding super-yacht production of expensive high-quality, cutting-edge technologies and aesthetic design is likely to be evident and witnessed throughout this experience.

Like the expert technologists (see Section 9.2.2), these teachers also considered that knowledge and understanding of hard materials is essential and necessary to design and problem solve. Knowledge and understanding of materials is also identified in the research literature as a crucial element of what expert designers utilise (Faulkner, 1994). The teachers considered that an initial key way to get students to learn about materials is to teach them to use tools and to process materials. While these skills are not an end in themselves, they assist students to have purposeful experiences with materials at the same time as developing their initial knowledge and understanding of materials. As noted in the analysis of the teachers' data (see Section 7.2), many students have very limited, if any, previous experiences with hard materials.

These teachers believe that by introducing students to tools and processes they are given the skills to engage with materials, and through these sensory experiences build some initial knowledge. As Kevin (TT, 2) noted, you can't really describe a material or show students how to work with a material in the "abstract"; students have "to get in and use" the material. Likewise, Henry (TT, 4) noted that when using tools and processing material, students "can't help but learn about materials". Interestingly, Andrew (TT, 1) commented "the brain" connects with the material through physically feeling it. This is supported by research that shows how distributed cognition theory identifies a physical experience that stimulates the brain and the brain is thereby stimulated into thinking what it can do through the experience, in this case, working physically with real material (Vvidis, 2002). Likewise, McCormick (2004) identifies how students think through doing and the feedback they experience affects their thinking. Furthermore, these initial experiences with materials build students' beginning tacit knowledge of materials (Custer, 1995; Herschbach, 1995; Solomon & Hall, 1996).

Students can obtain an understanding of basic properties of materials through processes; for example, the brittleness of certain acrylic plastics or the hardness and machinability of aluminium as opposed to mild steel. Henry (TT, 4) noted that when making something, students will need to know about how to process a material and so their motivation is high because their "knowledge and understanding" has come from a situation that has

“emotional cachet with them”. In other words, they are doing something that is meaningful for them, which Lave (1988) refers to as *authenticity* in a learning situation—that is, when the problem solver is involved “emotionally” in the problem. As students learn how to work independently with materials, their confidence also develops.

Once students develop an initial understanding and knowledge of materials, teachers can use experiences with hard materials to demonstrate knowledge about their more complex properties. For example, when heat treated, many metals will look exactly the same on the outside, although their internal structure may be altered significantly and, as a result of the heat treatment, their properties and usefulness as a material change. While much of this knowledge is available in textbooks or manuals as descriptive knowledge, these teachers believe that students’ experience of activities that display this conceptual knowledge helps them to deepen their understanding of the associated concepts. As Dixon and Brown (2012) note, students are able to transfer knowledge when they have understood it, rather than when simply memorised.

For example, Patrick (TT, 5) described demonstrating to students the case hardening of steel (a process of applying heat to steel in a particular way that increases the hardness of the outer surface) through the application of an oxygen-acetylene carburising flame. Case hardening is used extensively in hard materials design where it is desirable to have a hard-wearing outer surface while retaining the toughness of the body of the object, as in an engine crankshaft. At the end of this practical exercise, Patrick gets students to try and file the steel; it still looks the same but now has a hard thin outer casing. As Patrick notes, after this type of case-hardening heat treatment, the steel “doesn’t file so good”. Patrick considered this kind of practical learning experience, beginning with observation of an initial concrete experience, develops into “a whole understanding” or conceptualisation. He further notes that students learn through reflection and discussion of how heating a metal such as steel can change its molecular structure and consequently its *properties*, including its hardness.

As James (ET, 2) commented: “I think reading about something and learning by doing it are different”. Earlier, George (ET, 1) noted that finding out the molecular changes and subsequent property changes brought about by heating steel has been essential knowledge that he utilises in marine design. As with ELT, the initial concrete experience develops through thought and discussion into concepts that can be applied to new situations (A. Kolb & D. Kolb, 2005). Likewise, this initial physical sensory experience can introduce

students to learning about the conceptual descriptive knowledge of the molecular changes occurring in steel resulting from heat treatment.

In terms of addressing the issue of students having no previous design and problem-solving experiences, these technology teachers' identified ways in which they introduce design and problem solving to their students through experiences. For example, teachers described taking students through a scaffolded project from beginning to end to show them the process of a designed object and the various problems that need to be addressed in order to produce such an artefact. Here students have a minor design input into the initial project but the project is scaffolded to provide enough support for students to produce a successful outcome that builds their confidence and self-efficacy. This learning is a clear example of students working in a ZPD (Vygotsky, 1978); they occupy a cognitive space in which they can act successfully and develop understanding with teacher support and encouragement although they could not do so unaided. Often the learning begins through a physical activity and knowledge is abstracted from the activity with support of a facilitator or teacher. As Schunn and Silk (2011) note, "scaffolding and fading" assist students to develop and retain a "self-efficacy" about their capability when solving problems.

The teachers believe that these scaffolded projects build students' procedural knowledge of how to process materials into a functioning artefact, demonstrate to students the relevance of anticipating each step in an appropriate order, illustrate the subsidiary practical problems encountered when manufacturing, and indicate the complexity of design and problem solving when working with hard materials. The experience of carrying out a project also develops students' conceptual knowledge of the most suitable choice of materials to enable an artefact to function effectively. For example, Kevin (TT, 2) described how producing an actual artefact such as a sand-board enables his students to evaluate the effectiveness of the outcome by actual trialling of it on a sand dune. Technological knowledge necessary to design and problem solve requires both conceptual and procedural knowledge (McCormick, 2004). Although these scaffolded projects do not necessarily have *true authenticity* for each individual student (because, for example, it is the teacher who has decided all the students are making sand-boards), the learning is situated in a context that utilises real materials and real processes in a workshop environment, resulting in the production of an actual artefact (Brown et al., 1989).

These teachers considered that empowering students to make actual objects with hard materials enables them to address the subsidiary problems sometimes encountered when a

design is manufactured. These problems make students think about and also build their procedural knowledge and tacit knowledge of how design generates subsidiary problems, often relating to the manufacturing processes, to be addressed within the design. For example, in the real world, designs with hard materials are manufactured into practical artefacts which often includes additional and sometimes unanticipated problem solving. Some of the teachers considered that getting students to engage in lots of this type of “hands-on problem solving” in the workshop contributes to their learning to design with hard materials in what could be viewed as a reverse order. Henry (TT, 4) described this as getting students to “think with their fingers”. In other words, learning about processes and materials, and working out how to deal with practical problems, builds knowledge relevant to designing with hard materials. This reflects the experts’ views that it would be impossible to design with hard materials if the problems encountered during the manifestation of the design are not acknowledged and addressed. They referred to this as the design “details” and the “myriad of little problems”.

As students learn about different available processes, become familiar with a wider range of materials, and learn through basic projects the issues and problems they must address when designing with hard materials, “fading” of the scaffolded learning becomes important. As this occurs, the teachers note that their students are able to take more control of the design component within particular projects. For example, Patrick (TT, 5) noted that his students have built enough knowledge and understanding relating to hard materials that he can hand over “85–90 percent at Year 13” of the design component in their projects. This enables those students with intuitive practical skills (see Section 9.5) the opportunity to extend their learning.

A last but very important learning experience teachers develop in students is the ability to model their project. As described by the teachers, modelling is a form of scaffolded learning. The type of modelling described by these teachers, accords with functional modelling as described in the New Zealand Curriculum: Technology (Compton & France, 2007; MoE, 2007). Students are taught to sketch some basic design ideas, beginning often in two dimensions. Teachers then support students working using 3-dimensional sketching tools such as isometric. As noted previously, the teachers state that students who can think, visualise and sketch in three dimensions generally find it easier to design using hard materials (see Section 9.5). Mioduser and Dagan (2007) also recognise that skilled problem solvers, including experts, are considered to have powerful, dynamic and flexible mental

models of design ideas. In some schools, students have the opportunity to work their design ideas on 2- and 3-dimensional computer CAD programmes. As discussed by Jones et al. (2013), much of the knowledge in design is non-propositional, which includes students being able to sketch, draw and model their ideas. This type of functional modelling encourages and supports students to visualise and design in safe environments. However, the teachers also emphasised that this type of modelling should not replace working with real materials. Teachers stated that these skills develop in tandem with students' practical experiences, especially for those students who have had limited previous experiential learning in the real world. Their sentiments reflect what Schunn and Silk (2011) note: that novice designers need to be taught the skills to be able to model, and the reasons for modelling. Patrick (TT, 5) noted that when his students reach Year 13, the focus is on "design" because now his students know "how to draw" and "how to do things" in the workshop.

As noted in Sections 9.6.1 and 9.6.2, the teachers considered the ways in which learning experiences with hard materials can influence and support students' knowledge, understanding and learning to design and problem solve. Teachers noted that when students begin secondary school, they often do not have any early experiences that involve either working with or making things with materials. In order to address this lack of experience, teachers provide students with initial experiences that both encourage them to become aware of materials in their everyday world and provide them with tactile experiences with real hard materials. Teachers described using practical experiences with their students to build their conceptual knowledge and to deepen understanding about the important properties of different materials. Later, through learning how to process materials, students find out ways to manipulate and form materials in a procedural way. Although this learning begins as procedural knowledge, the teachers believe that it also builds students' conceptual knowledge necessary to design and problem solve and produce a realised functioning outcome. For example, students require conceptual knowledge to be able to choose which processes will be most appropriate in terms of cost, time and availability in the manufacture of one of their own design outcomes. Teachers also acknowledged the relevance of students learning skills that build knowledge of materials and processes to enable them to make actual outcomes that validate their design concepts and ideas. Validation of a design outcome provides students with feedback they can utilise in further design and problem-solving exercises.

Teachers noted that they initially scaffold projects for students. Scaffolding enables students to make decisions in small increments if they have had no previous experience to inform their judgement when making design decisions, and thereby builds their confidence. Scaffolding also raises students' awareness of constraints and subsidiary problem solving that need to be addressed when a design concept is developed into a functioning outcome. Likewise, teachers considered functional modelling as a way to scaffold learning to enable students to explore their design ideas through 2- and 3-dimensional sketches and later using 2- and 3-dimensional computerised drawing programmes. The teachers believe that students build much of the knowledge that enables them to develop these modelling skills through experiences with hard materials. Finally, as a result of all these experiences with hard materials, the teachers believe it is possible for students to start developing the traits of successful novice student designers and problem solving identified in Section 9.5.

9.7 Theorising learning to design and problem solve through experiences

A final sub-question: **In what ways can experiences with hard materials be theorised regarding learning to design and problem solve with hard materials?** utilises four learning theories to explain learning through experiences. The experiences identified from the findings of the expert technologists' and the technology teachers' data could be analysed using four different learning theories based on experience.

ELT emphasises the impact of real concrete experiences in initiating and developing learning, and the role of subsequent observation, reflection and eventual abstraction of the knowledge gained from the experience in developing new learning that can be applied to new situations (D. Kolb, 1984). For example, in Section 8.2.1, George (ET, 1) described graphically an experience where he observed a barge he designed break up on a sandbar as "one of the most instructive days I ever spent". In Section 8.2.2, John (ET, 3) described a concrete experience where he witnessed a cylindrical pressure vessel split open accidentally when it was pressure tested with water. Through observation, reflection and his prior theoretical descriptive knowledge, he abstracted new learning and deepened his conceptual knowledge from the situation. The "one-off" concrete experience enabled John's (ET, 3) knowledge and understanding to deepen and his subsequent learning be accelerated.

In a similar way, in Section 8.2.3, Patrick (TT, 5) described a project where his students experience making a project with two interconnecting parts. If the tolerance on the

measurements is not adhered to when making the two separate parts of a hammer, then the parts will not connect. Through reflection and discussion, the experience teaches students about the concept of tolerances when designing with hard materials (A. Kolb & D. Kolb, 2005). Understanding tolerances and being able to implement them in design are part of what a designer must do. It is often described as prescriptive knowledge (Herschbach, 1995; Mokyr, 2002). However, if there is no understanding of why tolerance is required in an engineering design, it would be difficult to prescribe it. As Patrick observed, this experience, combined with reflection and discussion, “puts a very, very *tangible* understanding on why you have a measurement plus or minus so much”. These three examples show how a learning theory such as ELT identifies how practical experiences can enhance learning that includes building knowledge and understanding.

In the analysis of expert technologists’ data in Section 8.3.1, Brian (ET, 4) described the apprenticeship model of scaffolded learning through working alongside an expert tradesperson. In this analysis, notions of situated cognition were used to acknowledge the role of situatedness, social context and culture in supporting the learning. The novice apprentice begins participating in a CoP on the periphery and gradually, as the novice gains confidence and builds knowledge, he or she is able to participate in a more central role (Lave, 1988). The learning is centred in an authentic social working environment which not only supports the learning but also helps the learner to acquire the culture, including the appropriate ways to behave, within a specific workplace context (Collins et al., 1991).

In the data analysis reported in Section 8.3.2, George (ET, 1) described his early experiences situated in a large engineering company where he had real experiences working in the workshops, design offices and a metallurgy laboratory. These experiences helped build his knowledge and understanding of processes, production techniques, materials and how design occurs. As in Brian’s (ET, 4) case, the culture, the social context and experiences all contributed to George’s knowledge, understanding and ultimate learning (Collins et al., 1991).

While George’s (ET, 1) and Brian’s (ET, 4) experiences are those of experts in a real workplace, Patrick (TT, 5) described how his school workshop provides students with opportunities to work with real hard materials and tools. In this workshop environment, he is able to teach students about the culture of safety and appropriate behaviour that contributes to them being able to work safely and independently to design and build real

artefacts. In other words, through these experiences situated in a workshop context, students have access to real materials and processes. Henry (TT, 4) described the workshop set up in his school, though significantly different from Patrick's, as enabling students to work towards independence as they design and make things using a range of different hard materials. These social learning spaces provide a unique and specific context in which students experience a culture, develop skills that enable them to design and problem solve with real materials, develop traits of successful novice student designers and problem solvers as identified by the technology teachers (see Section 9.5) and develop the knowledge and understanding essential to successful designing and problem solving.

James' (ET, 2) description of making a very complex machine to manufacture a fibreglass spring (Section 8.4.1) provides a clear example of learning based on experiences, as theorised in distributed cognition theory (Hutchins, 2001). Learning experiences based on distributed cognition acknowledge the value of physical activity and experience in stimulating cognitive thinking, which then feeds back into the physical experience. First, through working on design ideas using "rough" models to check his ideas, James was able to develop his design ideas into more detailed design embodiments. The prototype mediated between the concept and physical requirements of the machine. He also utilised non-propositional knowledge in these prototypes, which often led to him refining his initial design idea. Later in this process, James included the use of digital technologies to produce prototypes to stimulate his and his team's mental concepts and design ideas. The use of these models and prototypes supported, stimulated and often helped to refine James' (ET, 2) initial design ideas.

Peter's (ET, 5) description of the experience of putting a new railway bridge in-situ within a specified timeframe was analysed using distributed cognition (Section 8.4.2). The description of the environment, the set of circumstances and the nature of the artefact (40 tonne steel bridge) provided the stimulus for Peter (ET, 5) and others to design a unique solution to the problem presented. Consequently, the learning from this situation relies on the co-ordination and distribution among many factors working in parallel: the unique situation posing the problem, such as the demolition of the old bridge and restricted timeframe to put in the new bridge; size and weight of the old and new bridge; unique geological environment and setting; effective use of technologies such as large cranes; technical cognitive input of Peter (ET, 5) and his colleagues; and social interaction of many different groups of people. The factors that enable this example of designing and

problem solving to achieve a functioning railway bridge in-situ are both internal (mind and cognition) and external (artefacts, technologies, environment, other people) (Hutchins, 2001).

Kevin (TT, 2) described a student activity that has also been analysed using distributed cognition learning theory (Section 8.4.3). In this school activity, students design and build a sand-board as a functioning artefact, then take their artefact and trial its effectiveness by sliding down a sand dune. Kevin utilises these experiences of designing, problem solving, and building and trialling the artefact to get students to reflect on and critique the impact of their sand-boarding activity on the sand dunes and the wider community living close to the sand dunes. As Hutchins (2001) points out, in the theory of distributed cognition, learning and thinking involves a broad system that can involve artefacts, environments, technologies and other people. In the experience described by Kevin, students learn through working and thinking in parallel with technologies that build artefacts, testing the effectiveness and impact of a sand-board in a specific environment (sand dunes), designing and building an artefact, and considering the impact sand-boarding might have on people in local communities.

In Section 8.5, data extracts from two of the expert technologists, James (ET, 2) and Peter (ET, 5), and one of the technology teachers, Matthew (TT, 3), were analysed using activity theory. The analysis illustrates how learning experiences are sometimes supported by complex networks that include a subject, rules, communities, technologies, an object, an outcome/goal and divisions of labour (Engestrom, 1991). Success in each of these situations requires an understanding of how different social groups influence, direct and therefore have impact on the purpose, production and constraints surrounding design.

In his description of designing within the semi-conductor industry (Section 8.5.1), James (ET, 2) noted that while he must utilise his design and problem-solving skills within a research and development team, he must also be aware and understand the whole complex nature of the industry in which he is participating as a designer. At the same time, his knowledge is refined, enriched and transformed continually as a result of working within such a complex structure. The complexity of the semi-conductor industry acts as a giant constraint as each individual department or section is, in a sense, dependent on all other departments if it is to function successfully as a whole unit or system.

Likewise, in the analysis of Peter's (ET, 5) description of working on design projects with engineers, architects and the manufacturers who build and implement the artefacts (Section 8.5.2), it is noted that each group's contribution and expertise collectively enables the successful outcome. Peter (ET, 5) acknowledges that when all three groups, each with their own design perspectives, get around the table and thrash out the design details, it is much more effective in solving the immediate problems, resulting in a more successful design outcome. Successful design and problem solving involving these three representative groups (architect, engineer and manufacturer) exemplifies the tension described in the literature review of design having to be aesthetic at the same time as having to be technically functional (Barak & Goffer, 2002; Hill & Anning, 2001; Mioduser & Dagan, 2007).

Activity theory was also used in the analysis of Matthew's (TT, 3) description of his school Robotics programme and was indicative of how activity theory can be used to analyse learning through experience and activity in a technology education school environment. Student learning occurred through experiences within large social communities involving several different key elements. The whole system of the Robotics programmes, which includes the competitions, the social media networks and the integration of different hard material technologies, provides and supports the rich motivating learning environment that constantly enables knowledge to be refined, enriched and changed through these experiences (Engestrom, 2001). Consequently, an activity system which is based on activity, often occurring over a long timeframe, takes learning beyond what could be achieved by individuals who may decide to build a robot on their own.

As noted in the summaries above and in the detailed analysis of the expert technologists' and teachers' data presented in Sections 8.2–8.5, it is possible to analyse and theorise learning through experience as described by both the experts and teachers in this research using the four identified learning theories: experiential learning theory; situated cognition theory; distributed cognition theory; and activity theory. Analysis utilising these four learning theories recognises the crucial importance real experiences play in learning to design and problem solve, as described by both the experts and the technology teachers.

9.8 Summary of key findings on learning through to design and problem solve

This section provides a summary of the key findings relating to learning to design and problem solve through experiences from analysis of both the expert technologists' and technology teachers' data.

9.8.1 Experiences build technological knowledge

The expert technologists' findings identified that there are many different types of technological knowledge required to design and problem solve with hard materials. Knowledge developed by these technologists included procedural knowledge, tacit knowledge, device knowledge, conceptual knowledge, descriptive knowledge and strategic knowledge.

Knowledge building for the experts began in their early childhood and continued into their adolescence. By way of contrast, the teachers identified how students often do not have any of these early experiences that involve either working with materials or making things. Consequently, a significant part of teachers' pedagogy requires them to provide these initial learning experiences to develop students' knowledge.

9.8.2 Experiences develop knowledge of materials

The technologists' analysed data identified the crucial significance for designers and problem solvers of having knowledge and understanding of materials used in their designs. While they noted that much of the key information about hard materials is available as descriptive knowledge in catalogues, they acknowledged that it is much better if a designer and problem solver can have practical experiences, as it clarifies and deepens knowledge and understanding of materials.

Teachers noted that students have very limited experiences or awareness of hard materials in the real world. In order to address this lack of knowledge, and to build knowledge identified by the experts, teachers provide students with initial experiences that encourage them to become more aware of materials in their everyday world.

While many of the experts' experiences of materials began as procedural knowledge processing materials, these experiences also developed the tacit, conceptual and strategic knowledge essential for design. This finding was reflected also in the teachers' data as they described initially teaching students about processes to introduce them to hard materials

and working with materials in a procedural way. However, they believe that such experiences also build conceptual knowledge required when students want to design their own products.

9.8.3 Feedback on design through experiences

The experts' analysed data identified clearly feedback as a result of design and problem solving experiences with hard materials as a key element in developing learning to design and problem solve. Feedback was a thread that ran through all experiences described by both experts and teachers. James (ET, 2) described how a successful outcome validates his design ideas and the necessity to receive feedback on how well a design idea works. The experts described how failed outcomes also provide "lasting feedback" that informs their future designs. Another form of feedback utilised by the expert designers is tapping into others' experiences from working in relevant CoPs. Teachers also acknowledged the relevance of students learning skills and building knowledge that resulted in them being able to make actual outcomes that validated their design concepts and ideas.

9.8.4 Experiences develop technological knowledge and understanding, strategic skills enabling effective deployment of knowledge

As noted in Section 9.2.6, experiences build knowledge and understanding and the strategic skills to deploy knowledge required for design and problem solving. These strategic skills include: skills to deal with various design constraints, strategic skills to effectively deploy in decision making; skills that enable experts to develop technological models of their design ideas.

Teachers noted that, initially, they scaffolded learning for students in their classes. Scaffolding enables students to make decisions in small increments as they have little previous technological knowledge, experience and skill to inform either their judgement or design decisions. Scaffolding also raises students' awareness of constraints that need to be addressed. Teachers taught most students 3-dimensional sketching techniques and introduced them to lots of practical experiences with hard materials before introducing them to 2- or 3-dimensional computer programmes. These teachers believe the development of such functional models is supported through experiences with hard materials.

9.8.5 Experiences develop character traits relevant to design and problem solving with hard materials

The seven traits identified from the teachers' data (Section 6.4) concerning successful novice student designers were also reflected throughout the experts' data as traits of successful expert designers and problem solvers. For example, successful novice student designers and problem solvers were identified by the teachers as being aware and curious of the world around them and constantly asking questions. This reflected what the experts described as always looking around with an engineers' gaze at the designed world to find out how other designers use ideas.

9.8.6 Learning through experience can be theorised

Both experts and teachers' data could be analysed using four learning theories to explain learning to design and problem solve through experiences.

9.9 Conclusion

This chapter has discussed findings from both the expert technologists' data and the technology teachers' data and linked these findings to the literature review presented in Chapter 2. In this chapter, the six sub-questions have been answered in support of the overall research question: **In what ways can experiences with hard materials influence the development of learning to design and problem solve in the context of hard materials?** The following and final chapter of this research identifies the educational significance and implications of the key findings answering the six sub-questions and the overall research question presented in this chapter.

Chapter 10: Significance and Educational Implications

10.1 Introduction

With the goal of subjecting some current practices in technology education to critical scrutiny and identifying some ways forward, this thesis has investigated the ways in which experience can contribute to learning to design and problem solve with hard materials by interviewing both expert designers and problem solvers who work with hard materials and secondary hard materials technology teachers. Design and problem solving are key and unique elements of technology education and particularly relevant in the context of hard materials technological practice.

In recent years, there has been much debate about the value and purpose of practical experiences in technology education. To explore learning to design and problem solve through experiences with hard materials, this research sought to ascertain expert technologists' views and insights on the role of experiences in their own learning to design and problem solve as well as their conceptualisations of design and problem solving. It was anticipated that as practising experts, the technologists' views could provide rich insights into design and problem solving. This research also sought to find out technology teachers' conceptions of design and problem solving in the context of hard materials, technology teachers' views of the key traits of successful novice student designers and problem solvers, and teachers' views of the influence of experiences on students' learning to design and problem solve. Because many technology teachers are key providers who enable students to learn in this context, it was considered important to investigate their views and understanding. Lastly, this research identified the ways in which key learning theories can be applied to analyse and describe learning to design and problem solve through experiences.

This avenue of research was premised on the view that investigating how learning occurs can inform curriculum development and pedagogical practice. Through these six aspects, this research sought to answer the key and overarching research question: **In what ways can experiences with hard materials influence the development of learning to design and problem solve in the context of hard materials?** This chapter utilises key findings in response to this overall research question to make a series of specific recommendations for curriculum and pedagogy in technology education. In Section 10.2 of this chapter, learning to design and problem solve in the context of hard materials is characterised including the

key role of experiences. In Section 10.3 how learning through experiences can be theorised and rationalised and the implications for curriculum and pedagogy are presented. Section 10.4 identifies the limitations of this study and in Section 10.5 a concluding statement is presented.

10.2 Characterising learning to design and problem solve

Because design and problem solving are complex and wide ranging spheres of human activity, they draw necessarily on a number of disciplines to generate a complex body of knowledge, understanding and skills that is distinctively technological. Moreover, given the extensive context variables and uncertainties, there is a need for balance and prioritisation which adds further layers of complexity. In consequence, this research shows there is no simple means to learn design and problem solving, particularly in the context of hard materials. These expert technologists described their learning as ongoing and constantly being modified and adapted to new situations. The teachers also directed attention to this complexity and consequent difficulties of teaching design and problem solving to their students. Despite this complexity, this research has identified key overarching elements from the findings of both the experts' and the teachers' data that together enable more effective learning to design and problem solve with hard materials to be characterised. These three characterising elements are identified as:

- Recognising the multifaceted complexity of, and interactions between, design and problem solving in the context of hard materials.
- Identifying a range of knowledge, understanding and strategic skills needed to design and problem solve and developing character traits of successful designers and problem solvers.
- Defining a broadened construct of experience with hard materials required to learn design and problem solving.

10.2.1 Multifaceted complexity of interactions between design and problem solving

Existing curricula often regard design and problem solving as discrete, generic processes. Data collected in this thesis tell a very different story. The first key overarching element from this research characterising learning to design and problem solve is the role of *subsidiary* problem solving as an integral component contributing to the multifaceted and complex nature of design with hard materials. This interrelationship of design and problem

solving extends beyond the notion of design solving an overarching problem posed. Instead, it indicates a myriad of subsidiary problems, nested and sequential.

The findings of this research identify subsidiary problem solving as a key and critical component of designing with hard materials. The experts' conception of the interrelationship of design and subsidiary problem solving includes predicting, addressing and solving the many subsidiary problems within a design so that the design *detail* can be mapped out appropriately to enable the production of a final realised functioning product or system in-situ. This subsidiary problem solving includes predicting and addressing the practical problems that may arise in the manufacture of a design and installation in-situ. It recognises that subsidiary problem solving also acknowledges the detail required in a design such as an awareness of tolerances, the selection and processing of materials and, where applicable, issues relating to mechanisms. As identified throughout this thesis, much of the experts' knowledge and understanding of problem solving within design developed as a result of their experiences with hard materials. Although this construct of subsidiary problem solving within design was reflected in some of the teachers' data, it was not expressed as strongly as in the experts' data.

As noted previously (see Section 9.3), this construct of the interrelationship of design and subsidiary problem solving creates a tension between design innovation and the practicalities of developing a functioning design that can be made. It mirrors literature acknowledging the tension between technological design as being conceptual and innovative while providing enough detail that enables a design to function and all the while addressing the constraints associated with production and manufacture of an artefact. In other words, design with hard materials requires a balance between innovation and imagination and subsidiary problem solving that deals with the constraints, technicalities and practicalities of producing a realised functioning outcome.

The current view in New Zealand schools does not acknowledge or identify specifically the integral role of problem solving within design, including the tension between design as innovation and subsidiary problem solving as it relates to the practicalities and detail of the design. A key implication for technology education is the necessity for teachers to identify clearly the integral nature of subsidiary problem solving within design. Students also need to understand this construct of subsidiary problem solving in design to be able to understand more clearly the requirements and complex nature of design in the context of hard materials. To implement this construct of design and problem solving requires the

acquisition of knowledge and understanding, strategic design skills and the development of key traits of successful designers and problem solvers.

10.2.2 Knowledge and understanding, strategic skills and key traits relevant to designing and problem solving

From the data analysis of interviews with both the expert technologists and the technology teachers, it can be concluded that learning to design and problem solve requires the development of: technological knowledge and understanding; strategic skills to enable effective knowledge deployment; and the traits displayed by successful designers and problem solvers. These three components can be further detailed as follows:

1. Developing key types of technological knowledge and understanding:

- Building procedural, conceptual, tacit, descriptive, device, prescriptive, and strategic knowledge
- Building descriptive and conceptual knowledge and understanding of materials.

2. Developing strategic skills to enable effective knowledge deployment in decision making when designing and problem solving:

- Addressing constraints
- Making decisions based on informed judgements
- Developing technological models.

3. Developing the traits of successful designers and problem solvers:

- Awareness/curiosity, risk-taking/creativity, confidence, anticipation of problems, evaluation, conceptualising in 3-dimensions, intuition.

It is the contention of this thesis that these components contain many attributes, and that all three interact with and feed off each other. For example, technological knowledge and understanding is required to develop strategic skills that enable effective deployment of knowledge. Technological knowledge is required to make informed decisions, to be able to address design constraints and to develop technological models. Likewise, engaging in these activities develops traits of successful designers and problem solvers such as confidence and risk-taking identified in the data analysis (see Section 9.5) that builds further knowledge and understanding. In turn, traits such as confidence and risk-taking are key traits to acquiring technological knowledge and understanding and developing

strategic skills. All three are interacting components necessary to design and problem solve with hard materials using the construct of design that includes the integral role of subsidiary problem solving, as identified in Section 10.2.1. A key outcome of this thesis is that the learning of these components (building technological knowledge and understanding, developing strategic skills that enable effective deployment of knowledge and acquiring the traits of successful designers and problem solvers) is facilitated through a wide and broad range of experiences with hard materials.

10.2.3 A broadened construct of experience

Because the purpose of this research was to investigate the ways in which experiences with hard materials influence the development of learning to design and problem solve, a key component of this investigation is to establish a construct of what constitutes experiences with hard materials. Initially, this inquiry sought to investigate experiences that were confined to hands-on experiences with hard materials to find out in what ways these supported learning to design and problem solve in this context. However, the data analysis of both the expert technologists and the technology teachers has broadened considerably this initial construct of experience with hard materials. This broadened construct encompasses:

Informal experiences

- early and ongoing informal experiences through play and tinkering in the real world, fixing, building, pulling things apart
- observing and reflecting on how hard materials have been utilised and realised in real world design
- working with and observing how hard materials perform in various situations and environments.

Sensory experiences with materials

- deconstructing (pulling things apart) to identify how they are made and/or operate
- seeing and experiencing first-hand the processes in contexts that develop and make design concepts into realised products

- working directly with a wide range of different materials to build knowledge of materials
- using tools to access and build knowledge of materials
- seeing materials change through experiences, e.g., laboratory experiences, heat treatments, environmental impact such as the corrosion of mild steel.

Situated experiences

- experiences in a variety of industrial environments
- working directly in a hands-on way with hard materials in practical workshop-type environments to develop an understanding of subsidiary problem solving
- learning situated in a practical workshop-type environment
- learning situated within complex social systems and organisations, including competitions.

Feedback experiences

- experiencing first-hand concrete experiences of both successful and failed functioning design outcomes in different contexts
- experiencing design (incorporating the subsidiary problem-solving component) with hard material from its conception to a functioning in-situ outcome
- sharing and utilising experiences of others who belong and work in relevant CoPs.

Scaffolded learning experiences

- developing a designed object into a functioning outcome through guided and supported learning experiences with hard materials
- working alongside an experienced designer and problem solver to facilitate learning
- supporting ways to communicate and explore ideas and concepts through technological models.

This broadened construct of experience is a major outcome of this research. The findings bring together experiences identified by the expert technologists as developing their design and problem-solving expertise with the experiences that technology teachers believe support students learning to design and problem solve in the context of hard materials. Recognising this broadened construct of experience should help teachers plan and provide more effective learning experiences with hard materials. It is the contention of this thesis that learning to design and problem solve develops through a combination of broad-ranging experiences as identified in this research.

While the limitations of a school environment prevent students from replicating the experiences described by the expert technologists, technology education can look to a broadened construct of experience when developing a pedagogy for student education. If students' experiences are to be rich and purposeful in the ways outlined here, technology educators need to tap into the diverse opportunities available in industry and various relevant communities of practice. It is contended that technology students require different types of experiences to develop their learning to design and problem solve with hard materials that are situated in contexts that are authentic as possible.

Students also require diverse experiences to develop their technological knowledge and understanding. They need experiences that begin to build all types of the technological knowledge identified in both the literature review (see Sections 2.5–2.8) and in the discussion chapter (see Section 9.6). This includes conceptual, procedural, device, descriptive, prescriptive and strategic knowledge. While some initial learning experiences, such as processing materials, may build students' procedural knowledge, these experiences may also develop students' conceptual knowledge where decisions have to be made about what processes are available to use for a specific design. In other words, experience of processing materials may not only be considered as enabling students to carry out a procedure or skill but also contributing to the building of their conceptual knowledge and understanding relevant to design and problem solving.

Further examples of experiences include students having sensory experiences using different types of materials in specific applications to build and deepen their descriptive knowledge and understanding. The ability to choose the right materials and understand the complex properties and behaviour of hard materials have been identified in this research as crucially important in effective design and problem solving with hard materials.

Students need experiences to develop skills to address design constraints. These may include designing and making a project from start to finish. However, it is clear that students will require scaffolded learning experiences as they begin building their knowledge, skills and understanding of the complexity of design and problem solving with hard materials. This may require students to be supported through an initial project, with increasing opportunities for them to make design decisions as their experience, strategic skills, knowledge and understanding develop. It is proposed that when students have opportunities to produce functioning design outcomes that validate their design ideas, it provides feedback that informs their future understanding and design and problem-solving skills.

A major priority of learning through experiences should take into consideration the development of the key traits of successful designers and problem solvers (both novices and experts) including: awareness and curiosity; risk-taking/creativity; confidence; anticipation of problems; evaluation; conceptualisation and communication of ideas in three dimensions; and intuition, as identified in Sections 6.4 and 9.5. For example, through a broadened range of experiences, students are assisted to develop their 3-dimensional visualisation skills that enable them to create technological models in the form of functional models such as sketches, drawings or digital models.

In conclusion, a key outcome of this thesis is that a broadened construct of experiences is necessary to facilitate the learning of knowledge and understanding, strategic skills and the development of key traits of successful designers and problem solvers. Likewise, it addresses the complexity and multifaceted nature of design especially the integral role of subsidiary problem solving.

10.2.4 Diagrammatic characterisation of design and problem solving with hard materials

The three key elements of a richer and more complex view of learning to design and problem solve discussed in Sections 10.2.1–10.2.3 can be encapsulated in Figure 10.1. This diagram synthesises key findings of the ways in which experts learn to design and problem solve through experiences and the teachers' interpretation of learning to design and problem solve through experiences. For such a characterisation, the starting point of the diagram is the inner circle depicting learning to design and problem solve with hard materials. The outside linking circle illustrates the interconnectedness of the three key

elements (Sections 10.2.1–10.2.3) that achieve the learning presented in the inner circle. These three key elements are: subsidiary problem solving as an integral component of the multifaceted complexity of design; building and developing knowledge and understanding, strategic skills and key traits of successful designers and problem solvers; and a broadened construct of experience. Likewise, a second use of this diagram (Figure 10.1) is for curriculum planners and teachers to consider the interaction of these key elements in order to bring about learning to design and problem solve indicated by the two-way arrows in Figure 10.1.

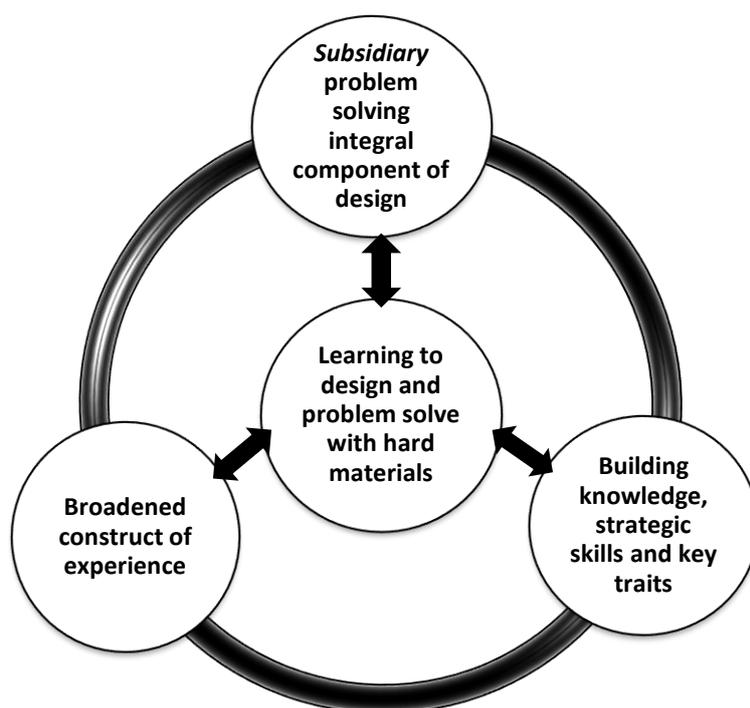


Figure 10.1: Characterisation of learning to design and problem solve in the context of hard materials

The three outer elements are placed equally around the outside circle to create a sense of balance indicating the importance and equal status of *each* element in supporting learning. Although this diagram has been simplified to three key elements identified by three key statements, within each element are many different and interconnecting components contributing to the inner learning circle. In this way, this diagram illustrates that learning to design and problem solve is multifaceted and is not just discrete generic processes.

When planning a curriculum, the complexity of each element within Figure 10.1 needs to be considered as well as an understanding of the interconnectedness of all elements. While it is possible for curriculum planners and teachers to begin with any of the three elements when considering learning activities, they must also identify in what way any learning

activity contributes and interconnects to the other elements. For example, to develop activities/experiences that build different types of knowledge, it is necessary to look to the broadened construct of experiences while at the same time understanding in what ways this knowledge might contribute to addressing the multifaceted and complex nature of design (including the integral component of subsidiary problem solving). Alternatively, when providing a learning experience from the broadened construct of experiences identified in this thesis, it is important for curriculum planners and teachers to consider how this might develop students' knowledge, strategic skills and key traits, and, ultimately, how this may contribute to the multifaceted and complex nature of design, including the integral component of subsidiary problem solving.

Because the role of experience in learning to design and problem solve with hard materials is the key focus of this thesis, it has been essential to identify in what ways experiences facilitate learning by considering learning theories that describe learning through such experiences.

10.3 Theorising and rationalising learning to design and problem solve through experience to inform pedagogy

In order to construct a curriculum and propose a pedagogy incorporating the characterisation of the complexity and multifaceted nature of learning to design and problem solve with hard materials, as presented in Section 10.2.4 and Figure 10.1, some theoretical tools to explain learning through experience are required. In Sections 8.2–8.5, examples of the learning activities and experiences of both the expert technologists and technology teachers were *analysed* using four learning theories: ELT, situated cognition theory, distributed cognition theory and activity theory. This thesis considers that because designing and problem solving with hard materials is complex and multifaceted, all four learning theories are necessary to analyse experiences supporting learning to design and problem solve.

The analysis utilising these four learning theories recognises and explains the crucial importance experiences play in learning to design and problem solve, as identified from analysis of both the expert technologists' and technology teachers' descriptions. Given that these learning theories can be used to analyse learning to design and problem solve through experience (see Sections 8.2–8.5), it follows that these four learning theories can be used as a theoretical framework to *theorise* and *rationalise* learning to design and problem solve through experience and to underpin curriculum building, pedagogy and lesson planning. In

short, the four learning theories provide the theoretical tools that draw attention to the usefulness, purposefulness, relevance and importance of many different types of experiences required to develop the knowledge, understanding, strategic skills and key traits of successful designers and problem solvers and to address the complexity and multifaceted nature of design and problem solving with hard materials (as characterised in Figure 10.1).

The dominant pedagogical idea is the importance of learning through experience to design and problem solve. This research acknowledges that a pedagogy rationalised from each of these four learning theories will incorporate experiences and activities that build many different types of knowledge, understanding, strategic skills and key traits relevant to learning to design and problem solve. In this thesis, learning theories have theorised the importance of experiences teachers provide for their students. These experiences have been further enhanced by analysing experiences that have developed the learning of expert technologists and incorporating them into experiences to support students learning to design and problem solve. In summary, technology educators and curriculum developers can use this information and confidently incorporate experience as a key component of a pedagogy that supports learning to design and problem solve.

The four learning theories describe learning through different types of experiences. First, ELT relates learning to a concrete experience from which knowledge is identified and abstracted through reflection and observation and can be applied to new learning situations. Incorporating this learning into a pedagogy may include providing experiences where students change the properties of materials through simple heat treatments. For example, copper will anneal (soften) if heated to a cherry red colour and then quenched in water. It can be hardened again through hitting it repeatedly with a hammer. The physical concrete experience demonstrates the theoretical concept of heat treatment changing the properties of metals.

In situated cognition, learning is dependent on the context, the socialisation, the culture and the situation in which the learner is immersed. Brian's (ET, 4) description of learning through apprenticeship was analysed using situation cognition theory. Likewise, George's (ET, 1) early learning of design and problem solving incorporated situated learning experiences in a range of different engineering workshops. This illustrated that learning is situated in a real context and supported through social interaction and the culture of the environment. In terms of a pedagogical application of this type of learning, students can

experience working in environments such as school workshops. By enforcing the same safety standards as industry in terms of behaviour and equipment, students can be enculturated into this unique and potentially dangerous environment but are also able to learn in a situated practical way with the guidance and social interaction of their peers and from suitably qualified and experienced teachers. Also building a one-off scaffolded project with minimum design decisions may provide an experience and a pathway for students into this type of learning context that helps build their initial confidence.

Distributed cognition theory acknowledges learning occurring as a result of experiences where the mind interacts with, and is stimulated by, technologies, other people, artefacts and environments. The expert technologists' experiences analysed using distributed cognition theory included James' (ET, 2) designing of a complex machine to make trampoline springs and Peters' designing a solution to the installation of a railway bridge within a restricted time frame. Both experts worked with teams of people and utilised technologies to develop their designs. In terms of a pedagogical application, students working in teams to design and make a larger scale project such as a go-kart may be a theoretical application of distributed cognition. In such a project, students learn through their minds (cognitive), socially interacting with other students and their teachers, the technologies incorporated within the project or artefact and the physical artefact. The possibility of racing the go-kart provides further stimulation between the artefact and the mind as students try to get the best performance from their go-kart.

Activity theory concerns learning situations where experiences are embedded in larger social structures that support learning over extended periods of time. The factors working together include people, rules of an organisation, the community, technologies, the object, the outcome such as an artefact and division of labour. The two expert technologists' examples of learning analysed by activity theory included James (ET, 2) designing lasers in the high stakes computer chip industry and Peter (ET, 5) working with engineers and architects to design and manufacture an aesthetic and functioning acoustic barrier. Students' learning experiences through entering and participating in Robotics competitions were also analysed using activity theory. In terms of translating these types of learning experiences into a pedagogy, this may include students investigating case studies of experts to understand the complex systems in which experiences supporting learning to design and problem solve occur in industry. Likewise, it may include students being involved in competitions such as Robotics where they are supported in their learning to

design, problem solve and build artefacts through social networks such as websites and able to evaluate these designs in face-to-face competitive environments where they learn from observing and seeing others' similar projects.

Learning theories provide deep understanding for educators regarding the value of experiences and provide guidance on how to incorporate and legitimise such experiences into a pedagogy of learning to design and problem solve. Students can build knowledge, understanding and strategic skills, and acquire key traits of successful designers and problem solvers, through a range of experiences that are rationalised and theorised using these four learning theories. The four learning theories are not necessarily hierarchical or of equal importance, but together they provide a comprehensive framework that underpins and supports curriculum developers and technology educators to consider the ways in which learning can occur through the use of a broadened construct of experience. To summarise, some experiences provided for students may be one-off concrete experiences, some will be set in a social situation and context that supports the learning, some experiences will utilise technologies, people and environments to support the learning and some experiences may be set in more complex social systems that support students' learning.

This range of experiences may also provide learning opportunities for students across a much broadened spectrum of abilities. For example, it could provide learning opportunities for students who may require practical concrete learning experiences before they are able to conceptualise knowledge and understanding to apply to new design and problem-solving situations. Likewise, some students may learn by being in a situated learning environment such as a school workshop where their learning develops over a period of time as they become more confident social participants in a CoP.

Figure 10.2 represents the theorising role learning theories provide between the analysed data of both experts and teachers describing learning through experiences and the rationalisation and legitimisation of learning through experience in building a curriculum and pedagogy. A curriculum and pedagogy to support learning to design and problem solve through experiences in the context of hard materials can be underpinned by the use of learning theories. The four learning theories can also be utilised to analyse learning through a broadened construct of experiences as characterised in Figure 10.1. Likewise, the learning theories can be utilised to rationalise this characterisation of learning to inform

technology curriculum and pedagogy on ways in which learning to design and problem solve through experiences develops in the context of hard materials.

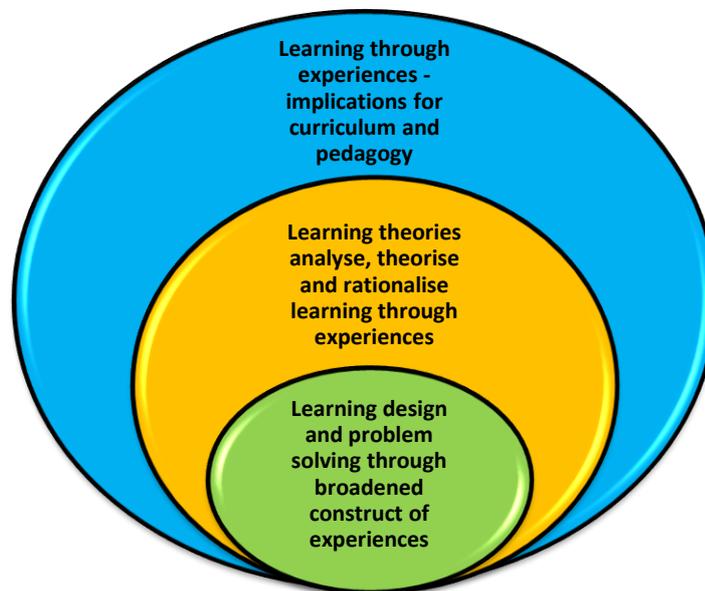


Figure 10.2: Learning theories analyse and theorise learning to design and problem solve through experience

Figure 10.2 provides a conceptualisation of how learning theories (yellow zone) can be used to theorise and legitimise curriculum development and teacher pedagogy based on learning to design and problem solve through experiences (blue zone). Likewise Figure 10.2 conceptualises how learning theories may be used also to analyse learning to design and problem solve through experiences (green zone).

Although key issues relating to learning to design and problem solve through experiences may be implicit in some technology education classrooms, curriculum documents and technology educators' teaching practice, this thesis has made them explicit by utilising four specific learning theories (ELT, situated cognition, distributed cognition and activity theory) to analyse learning, theorise learning and rationalise a pedagogy of learning to design and problem solve through experiences in the context of hard materials. Underpinning this learning through experiences is the characterisation of learning to design and problem solve (see Figure 10.1) that identifies the pivotal role of experiences as a key element in building knowledge and understanding, developing strategic skills and acquiring the traits of successful designers and problem solvers required to address the complexity and multifaceted nature of design, specifically the integral role of subsidiary problem solving.

Together, Figures 10.1 and 10.2 provide theoretical tools for curriculum planners and teachers to justify incorporating experiences enabling students to learn to design and problem solve in the context of hard materials.

10.4 Limitations of study

This research was confined to in-depth data gathering and subsequent analysis of 10 participants' views, understanding and conceptions of the role of experience in learning to design and problem solve with hard materials. The research participants included five expert technologists and five hard materials technology teachers. While these research participants' understanding, knowledge and conceptions of design and problem solving presents a coherent sample, it could be suggested that they are not representative necessarily of all technologists in the field of mechanical engineering or hard materials technology teachers. However, the expert technologists are experienced technologists with high reputations in their respective specialisations and the teachers considered exemplary within the teaching profession. As such, they provide an eminently suitable sample of these two groups' conceptions of the role of experience in learning to design and problem solve with hard materials for academic study and theorising. The findings constitute a trustworthy and authentic foundation on which to base recommendations for technology education and practice.

A desirable refinement may be to link the expert technologists' understanding of the role of experience in learning to design and problem solve and the technology teachers' views through an investigation of tertiary students' views of the role of experience in developing their learning to design and problem solve with hard materials. These tertiary research participants might include university engineering students studying mechanical engineering, engineering apprentices and those students in tertiary level study to become engineering technicians. In other words, novice and in-training hard materials technologists from three similar representative groups from which this research drew its experts (university degree qualified engineer, engineering tradesperson qualified through the apprenticeship model, and technician level qualified engineer). A further qualitative research of this nature would be helpful to deepen understanding and refine the implications obtained from this research thesis. Likewise, a survey with more participants might reveal further nuances, but is not expected to shift the thesis findings substantially.

Finally, it is important to note that this research has not included many aspects relating to technology education such as assessment, environmental issues relevant to technology education, design brief development and gender issues as it is focused on learning to design and problem solve.

10.4.1 Concluding statement

This research investigated the role of experience with hard materials in learning to design and problem solve with hard materials. As this thesis investigated the role of experiences in learning to design and problem solve in the context of hard materials, it seemed practical to ask expert technologists in what ways experiences contributed to their learning. Likewise, it seemed pertinent to back up these findings by consulting teachers as to how they considered experiences contributed to students learning to design and problem solve. The findings indicate clearly there is an important role for experiences in learning to design and problem solve especially in the context of hard materials technology education.

This thesis showed that learning experientially to design and problem solve is complex and needed to be analysed using four learning theories. These four learning theories can be employed to analyse current teaching practice and develop pedagogy, to inform and plan future curriculum, and to inform and develop effective learning programmes for students in technology education.

This thesis has presented an in-depth reflection on the role of experience in learning to design and problem solve with hard materials. As learning through experience is central to this thesis, Dewey's observation is a fitting end to this study:

We do not learn from experience ... we learn from reflecting on experience (Dewey, 1938).

Appendices

Appendix A: Guide Questions (Expert Technologists)

Title: The role of experiences in learning to design and problem solve in the context of hard materials.

Researcher: Patricia Potter

Tell me about your work.

Tell me about your background experiences that have supported your present career e.g. qualification, interests, experiences, career pathway.

Tell me about the materials you work with.
What properties do they have?

Could you explain your ideas about designing?
How do you use design in your work?
Explain your ideas about problem solving.
How does problem solving relate to your work?
Do you consider design and problem solving linked in any way?
If so, how are they linked in the type of work you do? Please tell me some examples where this occurs in your work.

Are there specific types of experiences you have had with hard materials that have been particularly influential in helping you to design and problem solve with these materials?
How do you consider your knowledge of hard materials has influenced your ability to design and problem solve? Please explain.
Where do you consider you acquired this knowledge?
How do you consider you acquired this knowledge?
Please explain.
Do you consider there is generally any link between knowledge about the properties of these materials and your ability to design and problem solve with these materials?
Are there any examples you can recall to illustrate this link?

What other significant factors do you consider have influenced your learning to design and problem-solve?
Can you tell me something about these factors?

Can you tell me about some other significant learning experiences you have had that have contributed to your expertise?

Do you have new people on your team?
How do they develop their expertise?
What do you do to give them practical expertise?
How important do you consider this to be and why?

Appendix B: Guide Questions (Technology Teachers)

Title: The role of experiences in learning to design and problem solve in the context of hard materials.

Researcher: Patricia Potter

Tell me about your technology teaching and the types of materials you use in your programmes.

Tell me about your background experiences that have supported your present technology teaching career e.g. qualification, experiences, career pathway.

Can you explain your ideas about problem-solving?

How do you consider problem solving relates to technology education?

Can you explain your ideas about design?

How do you use design in your technology programmes?

In what way, if any, do you consider design and problem solving are linked from your own learning experiences and in technology education?

Can you tell me some examples where design and problem solving learning with your students is developed or supported in your teaching programmes?

In your own background what factors do you consider have influenced or been significant in your learning design and problem solving with hard materials?

Can you tell me something about these factors?

Has this influenced the learning experiences you provide to enable your students to learn design and problem solving?

How do you consider students' knowledge of hard materials influences their learning to design and problem-solve with these materials? Please explain.

Are there any examples you can recall to illustrate this link?

How do you consider students can acquire or learn this knowledge?

How do you consider you acquired this knowledge?

Do you think there is any link between knowledge and learning about the properties of these materials and the ability to design and problem solve with these materials.

What if any value do you consider this has for your students' learning? Please explain.

What other learning or value do you consider students obtain through having experiences with hard materials?

What value, if any, do you consider there is in students being able to make and see actual outcomes in terms of learning design and problem solving?

Tell me about any other significant learning experiences you consider have been valuable and helped students to design and problem solve using hard materials?

How do you consider experiences with hard materials, in a broader sense, for students' learning design and problem solving e.g. if they were able to observe the manufacture of steel in a real context? Please explain.

Appendix C: Participant Information Sheet Expert Designers and Problem-Solvers

Title: The role of experiences in learning to design and problem solve in the context of hard materials.

Researcher: Patricia Potter

My name is Patricia Potter and I am currently enrolled as a part-time Education Doctoral student at the University of Auckland. My research is about how experts consider practical experiences with hard materials may have influenced their ability to design and problem-solve using these materials. Because you use hard materials in your work to design and problem-solve you have been identified as someone who might be interested in taking part in this research project. Therefore I invite you to participate in this research. It is intended at a future date to use these findings to investigate how students may be taught and learn to design and problem-solve within secondary school technology programmes involving hard materials.

My research will require you to be interviewed by me for about one hour. A set of questions will be used to guide the interview which will be sent to you before the interview. Your contribution will be anonymous with your employment details disguised and you will be given a pseudonym. The interview will be audio-taped and later transcribed by a transcriber who has signed a confidentiality agreement. This would provide you with an assurance of confidentiality. As a participant you can ask that the tape be turned off at any time during the interview. You will be given the option to view the transcript of your interview to verify or edit it so as to ensure it is an accurate and true record. All data collected during this research, including the audio-tapes and the transcribed texts of interviews, will be kept in a secure place for six years. After six years the data will be either shredded or electronically erased.

The interviews would be conducted at a place and time that suits you. You may prefer to be interviewed by telephone. In the written analysis of my data the identities of the research participants will remain anonymous as well as the identity of their respective workplaces and employers. There is a possibility that some information or data could be linked to the participants who provided it as there may be a limited number of experts working in their area of expertise. The findings will be written into a report for the purposes of publication in a suitable academic journal. When this research project has been completed the main findings will be offered to each participant. The findings may be used to inform, or be used as part of, a later doctoral thesis to investigate how students may be taught and learn to design and problem solve within secondary technology programmes involving hard materials.

You have the right to completely withdraw from the project at any time. This includes withdrawing information you have provided during the interview. However, it is not feasible to withdraw after the transcript has been verified and data analysis has begun. This would be one week after you have verified the transcript. If you are a member of the Institution of Professional Engineers New Zealand your standing with this organization will not be affected whether or not you decide to participate in this research.

If you agree to take part in my research project please sign the accompanying consent form and return it to me in the stamped addressed envelope. I believe the benefits of taking part in this research include being able to provide valuable information that may be used to inform how secondary technology students are supported in their learning to design and problem-solve using hard materials. After I have received your consent to participate in my research I will make contact with you by either telephone or email to organise your interview.

Thank you in anticipation of you taking part in and helping me to carry out my research project. If you require further information please do not hesitate to contact me at the following email address ppot007@aucklanduni.ac.nz.

My supervisors for this research project are:

Associate Professor Bev France
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Telephone 64 09 623 8899

Adjunct Professor Derek Hodson
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Telephone 64 09 623 8899

Yours sincerely

Patricia Potter

For any queries regarding ethical concerns you may contact The Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Office of the Vice Chancellor, Private Bag 92019, Auckland 1142. Telephone 09 373-7599 extn. 83711.

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS
ETHICS COMMITTEE ON 12 May 2010 for 3 years. Reference Number 2010/173

Appendix D: Consent Form to Participate in Research (Expert Designers and Problem-Solvers)

THIS CONSENT FORM WILL BE KEPT SECURED FOR A PERIOD OF SIX YEARS

Title: The role of experiences in learning to design and problem solve in the context of hard materials.

Researcher: Patricia Potter

I have read the Participant Information Sheet and understand why I have been asked to participate in this research.

- I agree to participate in this research
- I agree to participate in an individual semi-structured interview that will last about one hour and that is audio-taped.
- I understand that I may ask that the audio-tape be turned off at any time during my interview.
- I understand that I will be given the opportunity to check the transcription of my interview to verify that it is an accurate and true record and that I have the right to ask that aspects of it be edited.
- I understand that I am able to withdraw at any time including the information provided up until the point of data analysis which will commence one week after I have verified the transcript of the audio-taped semi-structured interview.
- I understand that this consent form will be kept by the researcher's supervisor in a secured cabinet for six years after which time it will be destroyed by shredding.
- I understand that the final written report and any subsequent reports or oral presentations will disguise my identity and that of my employer.
- I understand that my privacy will be respected at all times and that the findings will be available to me at the end of this research.
- I understand that all data will be kept by the researcher in a secured cabinet for six years and then destroyed by shredding or by electronically erasing audio-tapes.
- I understand that the information given may be used by the researcher to inform, and as part of, a later doctoral thesis by the researcher.
- I understand that there is a possibility that some information or data could be linked to me as there may be a limited number of experts working in my area of expertise.

Once again thank-you for agreeing to take part in this research project.

Name:

Signed:

Dated:

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS
ETHICS COMMITTEE ON 12 May 2010 for (3) years. Reference Number 2010/173

Appendix E: Participant Information Sheet (Teachers)

Title: The role of experiences in learning to design and problem solve in the context of hard materials.

Researcher: Patricia Potter

My name is Patricia Potter and I am enrolled in a Doctorate of Education at the University of Auckland Education Faculty. My doctoral thesis will research in what ways experiences with hard materials influence the ability to design and problem-solve using these materials. The three phases of my research will involve interviewing three different groups of participants. The three groups involved in this research will be expert designers and problem-solvers who use hard materials, secondary technology teachers who teach design and problem-solving and whose programmes provide experiences with hard materials and secondary technology students whose learning includes experiences with hard materials. At a later date this will involve students being interviewed from one school where there is a relatively large cohort of students participating in a hard materials technology programme.

The research is ultimately aimed at identifying how students may be taught and learn to design and problem-solve through experiences involving hard materials. The research also aims to characterise learning through experiences. Because you teach technology using hard materials and will likely incorporate design and problem-solving in your programme, I would like to invite you to participate in this second phase of my research.

I have been given permission by your principal to approach you about this research. The principal of your school has given me an assurance that your employment status or standing in your school will not be affected should you decide, or not, to participate in this research. The overall research question for teachers in this phase of the research is:

In what ways do teachers consider experiences with hard materials influence the development of students' learning in the context of design and problem-solving?

Research Time and Data Collection

My research will require you to be interviewed by me for about one hour. A set of questions that will guide the interview is attached to this information sheet. I will send these to you again before the interview takes place. The interview will be audio-taped or digitally recorded and later transcribed by a transcriber who has signed a confidentiality agreement. This would provide you with an assurance of confidentiality. As a participant you can ask that the tape be turned off at any time during the interview. You will be given the option to view the transcript of your interview to verify or edit it so as to ensure it is an accurate and true record. In addition to this interview, you may be asked to share some

relevant lesson or unit plan documents with me which may take an additional half hour. I may ask your permission to digitally photograph or photocopy these documents. If the information you provide is reported or published this will be done in a way that does not identify you as its source. You will be given a pseudonym however there is a possibility that some information or data could be linked to you as a participant by members within your own school community. All data collected during this research, including the audio-tapes or digital recording and the transcribed texts of interviews, will be kept in a secure place for six years. After six years the data will be either shredded or electronically erased. The interviews will most probably be conducted at your school or at a place and time that suits you.

Analysis and Findings

In the written analysis of my data the identities of the research participants will remain anonymous as well as the identity of their respective schools. There is a possibility that some information or data could be linked to the participants who provided it as there may be a limited number of teachers working in this area of expertise. The findings will form part of my written doctoral thesis. The research findings may also be used for the purposes of publication in a suitable academic journal or a conference presentation. When this research project has been completed the main findings will be offered to each participant.

Informed and Voluntary Consent

If you agree to take part in my research project please sign the accompanying consent form and return it to me in the stamped addressed envelope or email it back to me. After I have received your signed consent form I will contact you by either telephone or email to organise your interview and to share your documents at a time and venue that suits you.

You have the right to completely withdraw from the research project at any time. This includes withdrawing information you have provided during the interview and any documentation. However, it is not feasible to withdraw after the transcript has been verified and data analysis has begun. This would be one week after you have verified your individual interview transcript.

Benefits of Participating

I believe the benefits of taking part in this research include being able to provide and share valuable information that may be used to inform how secondary technology students are supported in their learning to design and problem-solve using hard materials. Thank you in anticipation of you taking part in, and helping me to carry out, my research project. If you require further information please do not hesitate to contact me at the following email address patricia.potter@pompallier.school.nz

My supervisors for this research project are:

Associate Professor Bev France

b.france@auckland.ac.nz

Telephone 64 09 623 8899

Adjunct Professor Derek Hodson

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The Head of School is:
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Yours sincerely

Patricia Potter

For any queries regarding ethical concerns you may contact The Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Office of the Vice Chancellor, Private Bag 92019, Auckland 1142. Telephone 09 373-7599 extn. 83711.

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS
ETHICS COMMITTEE ON 4/4/2011 for 3 years, Reference Number 2011/122.

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Appendix F: Consent Form (Teachers)

THIS CONSENT FORM WILL BE KEPT SECURED FOR A PERIOD OF SIX YEARS

Title: The role of experiences in learning to design and problem solve in the context of hard materials.

Researcher: Patricia Potter

I have read the Teacher Participant Information Sheet and understand why I have been asked to participate in this research. I have had an opportunity to ask any questions and these have been satisfactorily answered. I understand that participation in this research is entirely voluntary.

- I agree to participate in an individual interview that will last about one hour and that is audio-taped.
- I understand that I may ask that the audio-tape be turned off at any time during my interview.
- I understand that I will be given the opportunity to check the transcription of my interview to verify that it is an accurate and true record and that I have the right to ask that aspects of it be edited.
- I understand that I am able to withdraw from the research up to one week after I have verified the transcript of the audio-taped individual interview.
- I agree to share and to allow any relevant unit work plan to be photocopied or digitally photographed.
- I understand that the final written report and any subsequent reports or oral presentations will disguise my own identity and that of my school.
- I understand that my privacy will be respected at all times and that a summary of the findings will be available to me at the end of this research.
- I understand that all data will be kept by the researcher in a secured cabinet for six years and then destroyed by shredding or by electronically erasing audio-tapes.
- I understand that the information given will be used by the researcher to inform, and as part of, a doctoral thesis.
- I understand that there is a possibility that some information or data could be linked to me as there may be a limited number of teachers working in my area of expertise.
- I understand that the principal of my school has given an assurance that either participation or non-participation in this research will not affect my standing with my school.
- I understand I will be offered a summary of the findings at the end of this research project.

Once again thank-you for agreeing to take part in this research project.

Name:

Signed:

Dated:

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS

ETHICS COMMITTEE ON 4/4/2011 for (3) years. Reference Number 2011/122

Appendix G: Coding and Memoing example

Expert Technologist sample initial analysis of transcript

Yellow memoing Pink coding

If you know it works, often you do in our business they bring the thing into our shop and we fix it and it goes away and you never find out any more. If it was a successful job you don't hear any more but you hear about the bad ones that don't work. *Risk factor feedback validates design*

Sometimes you've got to get it out of a customer. You do something you're not sure really whether that was going to be the correct way to do it so the next time you see him, hey it worked? *And he says yeah, no problem so then you know you can use that idea again.*

There's no substitute for knowing how it's going to work. We had a job making a coal hopper arrangement with an auger in it and I can remember the engineer in the dairy factory coming here, he says this thing has been designed by a computer and he says the trouble is the computer has got no experience and he was dead right. That thing was a problem from Day One, *it got modified and modified until it eventually worked, well an expensive way to do things.* *Trial and error expensive eventually work*

Behind the computer knows yeah but if he hasn't had any, see I've had engineers, engineer is a confusing term because you've got the engineers like me that are hands on and you've got the engineers that have been to university.

What you find though is that the engineers from university, *although they learn how to design and calculate strengths of material and stuff like that, mostly they don't.*

Well I guess they do if you're designing a strength of a building or whatever but the engineer he was making up a specification for a job that was going to go out for tender and he had a pipe that had to remain full of water and he was going to put a thing like a spouting at the end of it so that it always kept the pipe full and the spouting just over flowed. So this thing, it's only round about a metre long and basically there was no pressure involved. He was going to make this thing out of 8ml stainless steel and that was going to be the specification. Heck man you don't need to go to that thick. He had **no feel for He just did the calculation and that would cover** He would sit down for hours and calculate it I suppose so it was easier to ring me. *Overdesign through theory and no practical knowledge or experience – way too thick for job no feel for*

I've got a thing here. My knowledge of hard materials has been collected over a working lifetime and over this time **one gets to know** what will work and what won't. **I don't believe I could have learned it all from a book. There really is no substitute for experience and experiencing the real thing.** When you start you really don't have much idea but as you learn from and from other **tradesmen and test in practice**, you slowly gain in **confidence**. Where did I acquire the knowledge? Well the first lessons were in my dad's shed. It was here that I gained a passion for working with tools. What followed was tech at school and the way they used to do it when it was called engineering shop work and tech drawing. I gained an immense **knowledge from these subjects** and **the experiences of the tradesmen doing the teaching**. I will be forever grateful for the knowledge they gave me. When I started work I gained knowledge from those working around me and then from the tutors on block courses and the theory was learned by correspondence. You get to a certain level and then you are to some extent **able to teach yourself as you learn from experience.** **Experience builds knowledge, confidence and self-learning**

The theory component is really important because it gives you a basis to hinge things around. When you're trying to sharpen a drill and I mean most engineering shops will just sharpen the drill by hand but when you're trying to teach somebody how a drill, how to sharpen a drill you need to know the angle that you're going to sharpen the point to and you also need to know where it's supposed to hinge around when you're sharpening it. And if you do it correctly you almost automatically get it to the right clearances and things. If you just got someone without any theory at all, they wouldn't have much hope of getting it correct.

Theory and practical compliment learning

Well firstly how do you consider you acquired the knowledge was firstly **by OBSERVING** and helping my dad and mucking about in his shed and then from tech courses at school and the mixture of theory and practical was excellent. **Without this knowledge you will have no idea what size of material is required and what problems are going to occur later in the life of whatever you are designing. You will also have little appreciation for the difficulties likely to be encountered during manufacture.**

This is why architects and engineers design things which won't work or can't be built. Architects are the worst. If they don't know, they leave it off their plans and if you then ask them they get arrogant and hedge and then generally become unavailable. **Practical experience builds knowledge required to build manufacture effectively**

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