Mental Representation and the Construction of Conceptual Understanding in Electronics Education

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Abstract

Learning about abstract electronics concepts can be difficult due to the hidden nature of the phenomena of interest. Developing understanding about electronics is therefore challenging because voltage cannot be readily observed; only the outcomes of the behaviour of voltage can be observed. Consequently modelling the phenomena of interest becomes a crucial factor in supporting learners in their development of knowledge and understanding. Visualisation skills have been promoted as important when modelling knowledge in different forms, supporting learners in their development of knowledge and understanding.

Current research about electronics education, however, has tended to focus on learners' misconceptions, experimental methods and interventions focusing on theoretical aspects of knowledge. Perspectives on learners' actual constructions of knowledge in practice are not common. The aim of this research study, therefore, was to explore the use of external visual representations in support of learning about electronics concepts, within the context of Secondary Design and Technology education.

The study adopts a case study approach and uses an interpretative cross-case synthesis methodology to explore a specific case of representation use among one class of Year 10 students. The analytical framework is designed to focus on the translation of and transition between multiple representations, including computer program code, and the representation of phenomena at three levels of representation: observable, symbolic and abstract.

Data collection involved the observation of learners engaged with learning activities, documents collected from these activities, individual semi-structured interviews and participant characteristics data collected from course records. The findings show that common processes of learning are accompanied by individual developments in meaning and understanding. Individual understanding was characterised with the creation of four cognitive profiles representing key learner constructs. Understanding about abstract concepts was shown to benefit from representations where concrete referents linked with practical experience. Electronics understanding was also shown to benefit from the explanatory use of program code as a supporting method with which to model and simulate circuit behaviour.

The research approach involving the close observation of learners engaging with learning activities was found to provide a greater understanding of learners' approaches to learning in practice. The outcomes are applied to the practice of teaching electronics and modifications to the research are suggested for future researchers interested in the issues of teaching, learning and concept development in electronics education.

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Glossary of Terms

Term	Description
Analogue	Voltage which fluctuates smoothly, often in response to a circuit input
Capacitor	Component which stores voltage
Charge	Relating to the voltage present, usually in a capacitor
Charging	Relating to the action of a capacitor when voltage is applied
Circuit	Collection of components arranged to allow current flow and functionality
Code	Term in programming representing an operational statement
Coding	Connecting codes to form a complete program
Component	Individual electronics device
Conceptual understanding	Internal representations of phenomena constructed by the learner
Current	The quantity of electricity
Design and Technology	School subject based on finding practical solutions to human problems
Dialectic	An understanding of both sides of an argument
Digital	Voltage which is either on or off, it has only one positive value
Electronic	Device using electricity for operation
High	Term used to describe the action 'switch on' in programming
Input	Circuit feature which usually allows the connection of a sensing device
Logic	A system of formal reasoning usually applied to electronic 'logic gates'
Logic Gate	A device which operates using the principles of formal reasoning
Logician	Someone who uses the principles of formal reasoning
Low	Term used in programming to represent an off condition
Microcontroller	Device forming a computer programmed interface between inputs & outputs
Multimeter	Testing instrument used to measure voltage, current and resistance
Ohm	Measure of resistance in electronics
Output	Connection on a microcontroller, usually to light or sound devices
Pin	Term relating program code with the microcontroller's physical connections
Program	Complete list of statements used to control the microcontroller
Prototype	A fully working model of an intended design solution
RC Network	Timing circuit consisting of a resistor and capacitor connected in series
Real-world component	Electronics device such as a light bulb or battery
Resistor	Device used to control voltage

Subprogram	Section of code within the main program
Syntax	In programming, rule based language structure
Technology	The practical application of resources to solve human problems
Voltage	The force value of electricity
Voltmeter	Test equipment which measures voltage levels

Abbreviations

Abbreviation	**Description**
2D	Two dimensional – a drawing or on-screen (flat) representation
3D	Three dimensional – a physical model capable of viewing from different angles
AT	Researcher
C.2	Output pin name on a microcontroller
CAT	Cognitive Ability Test
CPD	Continuing Professional Development
DCT	Dual Coding Theory
EBacc	English Baccalaureate
LED	Light Emitting Diode
PIS	Participant Information Sheet
ST	Student
UREC	University Research Ethics Committee
YELLIS	Year Eleven Information System

Chapter 1 Introduction

1.1 Introduction to area of study and focus

This research study explores the use of external visual representations in support of learning about abstract electronics concepts, within the context of Secondary Design and Technology education. My interest in visualisation, interpreted as the use of visual representations, developed because I had observed that some students were able to discuss phenomena of an abstract conceptual nature by supporting their thinking with a mental 'picture' of the phenomenon. They were able, for example, to rotate objects 'in the mind', while others would provide a perspective to illustrate phenomena not immediately associated with the discussion or linked with an external referent. I was curious to discover the nature of students' concept formation and how the role of visualisation supported its development and application in electronics education.

Abstract concepts are considered to be difficult to develop because phenomena of the type studied in electronics education cannot be readily observed in the real world; only the product of their operation can be easily observed or measured. In Design and Technology education, because the subject is concerned with the practical application of resources in the design of solutions to problems (Black and Harrison, 1994), a focus of previous research has been the creation of models of knowledge which require the learner to apply procedure in the development of their understanding (Kimbell, 1994; Kimbell and Perry, 2001). Procedural knowledge is therefore regarded as necessary and important for the development of expertise where problem solving requires learners to engage with the components of systems in a practical way (McCormick, 1997; Claxton, Hanson and Lucas, 2014). I was therefore interested to explore the role of procedure and how students applied this in the context of developing their conceptual understanding of electronics.

Electronics knowledge can be categorised in terms of its 'science' or theory, for example researchers have noted that all electronics phenomena are interpreted in relation to the concepts of current and voltage (Metioui and Trudel, 2012). This theoretical perspective is a useful starting point for exploring learners' knowledge, however what constitutes a concept is open to interpretation in terms of the electronics phenomena actually conceived by the learner (although see discussion on analogue and digital circuits below). Hiley, Brown and McKenzie Smith (2008, 13) posit a distinction between 'scientific' understanding and understanding based on 'practical application'; the distinction indicating a difference between science (theory) and engineering (application). Evidence from employee experience has indicated that in addition to conceptual knowledge, procedural knowledge linked with application are essential to support problem solving, investigating and analysing (Claxton et al., 2014). Thus, in this study, electronics knowledge is conceived in terms of technology, engineering and systems design and consequently the study aims to develop Metioui and Trudel's (2012) observation by revealing the learner's perspective in practice.

In practice electronics phenomena can be further categorised by the behaviour of voltage as either a fluctuating or fixed entity. This tends to be described in terms of either analogue (fluctuating voltage) or digital (fixed voltage) circuit types (Duncan, 1997). These contrasting conceptions have been exploited in this study, by providing a focus for the collection of contrasting data and the comparison of these different data during analysis. Therefore it was intended that focusing on different circuit types would provide a framework for designing representational materials and comparing participant responses following data collection.

1.2 The rationale for the study

I had some initial thoughts surrounding students' personalised thinking about electronics. I was interested to know whether a difference existed between 'traditional' electronics (batteries, light bulbs and physical components) and electronics based around computer programming. This is because increasingly electronic functioning in commercial products is achieved using a computer generated program and curriculum specifications have followed this development. The teaching of electronics has thus gradually followed this trend. I wanted to know more about how traditional and programmed approaches support learning within the context of their practical application, in line with the procedural approach adopted in Design and Technology. This could then lead to adjustments in the methods and sequence of activities employed to engage learners in these topics. The key purpose of the research, therefore, was to clarify learners' understandings of electronics concepts and use this to inform the future teaching of the subject.

A conceptual framework was adopted which supported the research by focusing on observable, symbolic and abstract levels of representation, as described by Johnstone (1993) and Wu et al. (2001). I was interested in the interaction between these different representations and how learners used them during the learning process. What was the role of practical experience, for example, and how did this support the interplay between electronics representations? A large body of research describes learners' misconceptions of electronics knowledge, often using experimental methodology. I wanted to find out more about the nature of learners' knowledge in the context of Design and Technology, as the literature available often presents research conducted only in closely controlled conditions.

Learners' application during their learning was therefore important in revealing the specific nature of understanding and concept development. Research on electronics learning in context (Metioui and Trudel, 2012) and procedural learning in Design and Technology (McCormick, 2004) has been noted as scarce and the interplay between representations was identified as a useful contribution to the work of others. Such research does not always recognise the learning context. Visualisation was interpreted as the interplay between representations. In practice this can be observed as the translation of (making connections between representations and attaching meaning to phenomena) and the process of transition between representations. This formed the unit of analysis, as described by Yin (2014), with which to explore the levels of representation and learning procedures. This was considered to contribute to the literature as translation and transition skills have been noted as key to the interpretation of multiple representations (Ainsworth, 2006). Similarly, the specific nature of learners' understanding has not been widely researched in relation to concept formation. Solsona, Izquierdo and de Jong's (2003) research which develops four conceptual profiles related to chemical change phenomena, and Gentner and Gentner's (1983) electronics specific models of voltage behaviour, are two exceptional examples of attempts to define learners' specific and individual ways of thinking about conceptual phenomena. This research case study, it was hoped, would build on and contribute to this area of the literature.

1.3 The research context

The research was conducted at a Boy's selective 11-18 Grammar School in the south of England which has, typically, 1650 students on role. Intake is from a wide geographical area with approximately 60 feeder schools (Ofsted, 2009). Most students are considered to be of White British heritage with about 15% from other ethnic heritages and of those students learning difficulty and/or disability is considered low (Ofsted, 2009). The school is considered to promote 'exceptionally high academic standards' (Ofsted, 2009: 4) and GCSE results, typical for the Electronics GCSE, were 100% A*-C grades (60% A*/A, 86% A*-B) in the academic year 2014-2015. Students are allocated one and a half hours of Design and Technology per week in Year 7, one hour per week in Year 8 and one hour per week in Year 9. Design and Technology is optional in Key Stage Four and the school offers Resistant Materials, Graphic Materials Technology and Electronic Products as GCSE options, with one group per option area per year typical of take-up. GCSE groups tend to number approximately 17 students for each option.

1.4 The aims of the research

The research aims can be concisely stated as follows:

- To describe the different visualisation skills students apply when using external representations (circuit diagrams, symbols, computer code) to construct abstract electronics concept understandings
- To explore the effect on conceptions of learning of using different representations, including embodied approaches to learning
- To compare 'traditional' representations (circuit diagrams, symbols) with those used to program microcontroller-based electronic systems

1.5 The approach to the research

The research study adopts an interpretative methodology with the aim of exploring learners' development of abstract concept understandings in electronics education. It focuses on learning experiences, the learning context and takes account of the researcher's role as teacher/researcher. The research study explores a particular instance of the use of external representations, such as diagrams, graphs and text, through learners' translations of and transitions between multiple representations.

1.6 Outline of thesis chapters

In Chapter 2 the literature review begins with an exploration of visualisation skills, the nature of representations and their use and theories of personalised approaches to learning. Concept formation is discussed and a working definition of conceptual knowledge relative to electronics learning is presented. Literature describing conceptual change is reviewed and discussed relative to changing and developing learning trajectories.

Chapter 3 covers the Methodology adopted in this research. It begins with a discussion of the consensus view of knowledge and learners' default positions relative to developing understanding and learning. An overview of the benefits of interpretative methodology is provided, relative to the research questions and within a case study approach. The methods used to collect data are presented and the analytical framework used to analyse the data is explained.

The findings and analysis are presented in Chapter 4. The findings consist of the themes and categories generated from lesson observations, documents collected from the lessons and interviews. As the data are presented an analysis is included which explores and adds meaning to the findings. The analysis follows the analytical framework grounded in Wu et al.'s (2001) levels of representation and notions of translation and transition between these.

Chapter 5 discusses the findings in connection with the literature review and places the analysis into the context of previous research exploring electronics learning, conceptual change theory and the theories of procedure and strategy of learning.

Chapter 6 provides a concluding synthesis of the research study. It summarises the key findings from the study which show that common processes of learning are accompanied by individual developments in meaning and understanding. Individual understanding was characterised by four cognitive profiles representing key learner constructs. Understanding about abstract concepts was shown to benefit from representations where concrete referents linked with practical experience and simulation. Electronics understanding was shown to benefit from the explanatory program coding as a supporting method with which to model and simulate circuit behaviour. The chapter suggests how the research outcomes can be applied to the practice of teaching electronics. The methodology used is also reviewed in the Conclusion chapter and modifications suggested for future researchers interested in the issues of teaching, learning and concept development in electronics education.

Chapter 2 Literature Review

2.1 Introduction

In the Introduction I outlined my '*prima facie'* question (Thomas, 2011a: 30) which asked 'how do students apply visualisation skills to learning in electronics education?'. I was curious about students' use of visualisation skills (defined below, Section 2.3) through noticing that some students were able to converse about complex spatial problems with ease (and without referents) and others adopted individualistic ways to conceive of electronics concepts, for example making links with computer programming to support their understanding. The link between representation use and concept development was therefore key to developing ideas about visualisation and how to approach the topic. An initial review of the literature on visualisation (Twissell, 2014) highlighted the value of Dual Coding Theory (DCT) (Paivio, 1986) as a method to investigate students' thinking about electronics concepts. DCT focuses on the verbal and nonverbal aspects of representation use and provided a point of departure for exploring conceptual understanding in terms of students' use of words and images. I also developed an interest in the application of computer program code as a method of representing concepts, which emerged from my teaching experiences.

The following literature review explores research and theorising related to visual representations and their use in the development of conceptual understanding. The review includes literature from a number of relevant disciplines, including psychology, education, neuroscience and engineering. I gradually taper the focus to emphasise literature which connects the use of multiple representations with electronics education, as conceived within the school subject Design and Technology. Through the review I present the background to visualisation skills, which provides a theoretical foundation to considerations of learning and teaching with multiple representations and how these can support conceptual thinking in electronics education. The review leads to a reformulation of the original question and the development of an 'analytical frame' (Thomas, 2011a: 35).

One key consideration underpinning the literature is the view that individuals process information in different ways (Dunn, Beaudry and Klavas, 2002). Larkin and Simon (1987) and Paivio (1986) consider how the synchronous processing of images and diagrams affect understanding; alternatively McKim (1978) and Mathewson (1999) have considered logical-mathematical and verbal approaches to understanding. Arnheim's (1970) theorising about cognition suggests that all thinking can eventually be traced to some form of visualisation. Whilst this position is not widely shared (Gardner, 1984), there seems to be a consensus that synchronous approaches provide benefits to learning about abstract concepts, not present in logical-mathematical and verbal approaches (Mathewson, 1999; McKim, 1978). One outcome of my initial literature review revealed that the specific visualisation approach adopted relates to context or learning task. For example, in engineering Akasah and Alias (2010) focus on spatial relationship, in electronics Pule and McCardle (2010) focus on analogy and metaphor and in science Wu, Krajcik and Soloway (2001) develop concepts grounded in Paivio's (1986) Dual Coding Theory. The context is therefore important to understanding the usefulness of any approach chosen to researching visualisation.

A second consideration when exploring the literature is the chosen level of analysis attached to visualisation. Drawing from Morton and Frith's (1995) diagnostic model, I consider visualisation in terms of three levels: biological (the learner), cognitive (the learner's thinking) and behavioural (observations of the learner's thinking). These each enable different explanations of phenomena at the different levels of analysis and are referred to as appropriate in the discussion. Morton and Frith (1995) also consider each level of analysis in relation to environmental factors, which in this research study can be related to the specific context of the learning. An alternative perspective can be taken from Johnstone (1993) and Wu et al.'s (2001) considerations of the nature of representations. These have been described as the levels of what can be observed (macroscopic level), what is invisible (microscopic level) and what is represented in symbolic form (symbolic level). This framework is a useful tool because it enables thinking about the different types of representations and how visualisation skills are used in practice. Throughout the literature review, I therefore refer to these frameworks in support of my analysis of others' research and its application to my research study.

Finally a third consideration, and one linked with the Johnstone (1993) and Wu et al. (2001) framework, is the inherent level of and relationship between concreteness and abstraction with respect to information processing and the nature of representations. Using the term concrete refers to one end of the concrete/abstract continuum; it describes specific rather than general phenomena that can often be perceived by the senses (CODCE, 1990). Abstraction on the other hand refers to ideas and concepts, often but not always in a more generalised form (*ibid*). In some cases researchers refer to surface, rather than concrete features when discussing representations and in doing this ascribe meaning to elements that can be readily observed (Seufert and Brunken, 2006). A numerical value attached to a circuit symbol is an example of an unambiguous electronics-based referential feature. In this study I adopt the term concrete for the purpose of uniformity and add clarification where necessary to explain any difference between concrete as a way of thinking and concrete as a referent for unambiguous representational features.

The study aims to reveal a broad picture of students' visualisation use (rather than isolating variables for manipulation). The literature review begins with the two sections Definition of Conceptual Understanding and Definition of Visualisation. It then discusses Constructivism and how this term is applied in this study. The review is then arranged to discuss different Cognitive Mechanisms (spatial relation, transformation, transformation and applied skills and verbal and nonverbal processing), and different Levels of Representation (embodied cognition, problem solving and modelling, representations, codes and multimodal thinking, computer programming, conceptual thinking and electronics, analogy and metaphor and learning and language). The review concludes with a discussion of the themes and the revised research questions. As the development of conceptual understanding is thought to involve a number of diverse experiences (Johnstone, 1993; Wu et al., 2001), the range of themes are considered to support a justifiably broad approach to reviewing the literature.

2.2 Definition of conceptual understanding

2.2.1 Technological concepts

Electronics knowledge can be conceptualised in terms of its science or theory, for example researchers have claimed that all electronics phenomena are interpreted in relation to the concepts of current and voltage (Metioui and Trudel, 2012). While this is theoretically accurate, what constitutes a concept is open to discussion in terms of what the learner actually conceives in relation to electronics phenomena (although see following discussion on analogue and digital circuits). A development of this position is offered by Hiley, Brown and McKenzie Smith (2008, 13) who posit a distinction between 'scientific' understanding and understanding based on 'practical application'; the distinction offered being one founded upon the difference between science and engineering fields. Thus in this study electronics knowledge is conceived in terms of the engineering, or system design and consequently the learners' perspective is considered more widely than Metioui and Trudel's (2012) current/voltage perspective.

Metioui and Trudel (2012) may be alluding to the difference between analogue and digital voltage types. Electronics knowledge tends to fall into the categories of either analogue or digital circuits (Duncan, 1997; Hiley et al., 2008) and often reference to concepts follow this distinction. Adopting a procedural (McCormick, 1997) or situated (McCormick, 2004) approach to thinking about electronics knowledge therefore may reveal how learners apply concepts, which may be different from the theoretical perspective.

2.2.2 Representations and conceptual understanding

In practice the term conceptual understanding refers to the internal representations constructed by the learner, from external representations which themselves may be constructions by teachers or originate from other source materials (Treagust and Duit, 2008). These internal representations, or concepts, have been considered to be 'abstract theories' which require 'complex metaphor [and] abstract language' to enable their communication (Pule and McCardle, 2010: 18). In this study I use the abstract concept of analogue and digital voltage types as a basis for conceptualising voltage behaviour and as a foundation for the lesson activities in the data collection phase. The abstract language, interpreted broadly, may be in the form of technical terms that describe phenomena. Alternatively abstract language may take the form of symbols, diagrams or other external referents such as binary notation. These are discussed in the following sections.

Analogue voltage means that the circuit is such that voltage is fluctuating, often in response to a timing condition, temperature/light level or audio signal acting on an input component. An audio amplifier is an example of an analogue circuit. Digital voltage alternatively means that voltage is either on or off; a score counter used at sporting events is an example of a digital circuit. The counting example may also use logic components to make logical decisions. The voltage phenomenon is abstract since it cannot be readily observed in the real world; only its effects can be observed, for example through an output component or measurement on a voltmeter. Therefore communication will draw upon the external referent when conveying a concept's meaning, which may be held differently internally when thinking about the concept.

One way to understand a concept is to compare it with its opposite. Kelly (1963) devised a theory of personality which drew on the construction of bipolar constructs (interpretations of situations) where individuals organise their thoughts on the basis of meaning developed in response to observations in their environment. In practice individuals make choices about the constructs attached to phenomena and the direction on any dichotomous scale. Choices may reflect convenience or theoretical principles and are arranged hierarchically by individuals reflecting their personal importance. Developments have permeated fields beyond cognitive psychology and therapy, such as organisational change (e.g., Rhonda et al., 1994) where Kelly's (1963) theory has supported the exploration of identity and personal construal. Here I draw on the notion of bipolarity in identifying participants' constructs in relation to electronics knowledge. The analogue/digital dichotomy is one example of thinking which relies on the bipolar comparison and I draw on the phenomenon during the analysis of the findings in Findings and Analysis (Chapter 4).

2.3 Definition of visualisation

Visualisation has been described as a process, in that it is 'the ability to generate, retain, retrieve, and transform well-structured visual images' (Lohman, 1993: 3). Implicit is Kosslyn's (2005) distinction between visual perception (viewing a stimulus) and visual mental imagery (an internal process of visualisation drawing on memory in the absence of a stimulus). Therefore visualisation describes the mental processes involved once a visual stimulus has been received by the perceptive system and interpreted by the visual association area (Martini, Nash and Bartholomew, 2012).

Conversely Hoffler (2010, 246) describes 'a visualisation' as 'any kind of non-verbal illustration (both symbolic, such as graphs, and pictorial, such as realistic diagrams, pictures, or animations)' and therefore as an artefact. Similarly 'visualisations' describe different 'graphical models of expression' (de Vries and Masclet, 2012: 46). van Garderen (2006, 497) makes the following four distinctions by describing 1) 'visual imagery' (object representation, shape and colour), 2) 'spatial imagery ' (spatial relationships between parts of objects, their spatial location and movement), 3) ‘pictorial imagery’ (representative of the object or person) and 4) ‘schematic imagery’ (representative of problem related spatial information). In the study I use the term ‘representation’ to refer to these various external stimuli, as appropriate.

Visualisation and memory have been linked to mechanisms where perceiving and processing are considered to support rapid information processing (Gegenfurtner, Lehtinen and Saljo, 2011; Larkin and Simon, 1987; Mathewson, 1999; Smith, Ritzhaupt and Tjoe, 2010). Thus this review distinguishes between viewing an external stimulus, referred to as *perception* and refers to *visualisation,* meaning the cognitive processes associated with visual thinking, image manipulation and transformation. In the following sections, visualisation is discussed in terms of the cognitive mechanisms used to support learning and development with external and internal representations.

2.4 Constructivism and learner development

According to von Glasersfeld (1989, 1), constructivism is ‘a theory of knowledge’ with two main principles: 1) knowledge is formed by individuals and 2) constructivism allows individuals to adapt to and organise their experience of the world. In this study constructivism is applied following Piaget’s (1955) concepts of assimilation (e.g., recognising patterns in new information and organising/coordinating this into existing schemata) and accommodation (e.g., adapting knowledge during interactions with new situations, i.e., translating from one representation type, such as a circuit diagram, to another such as a computer program). The term schemata (Piaget, 1955) is used to describe the established ideas of the learner, which through developmental experiences are modified accordingly. Therefore the term constructivism in this study is related to the development of understanding which can be observed differently in different individuals.

Piaget’s (1955) theories are considered to focus on the learner as an individual (Bennett and Dunne, 1994). Drawing on Vygotsky’s (1978) ideas, the role of the social setting is also acknowledged in terms of the influence on learning of others within the learning context. Consequently an important emphasis, but not a key focus, is placed on the learning context and experience of students within their educational setting to support the analysis of individual experiences.

Bruner (1977) provides a taxonomy for thinking about how the use of representations might lead to new conceptual understandings, or accommodation. Describing a learning process involving learning episodes, Bruner's (1977) taxonomy includes the three stages: acquisition of new knowledge (to complement existing knowledge), transformation (new knowledge is manipulated, analysed or converted to another form) and evaluation (consideration of the new knowledge in context, checking for generalisations or plausibility). Bruner's (1977) transformation stage stressed the need to consider how representations might need to be transformed for a full understanding of the concept to emerge. Consequently Bruner's (1977) taxonomy provided a framework for analysing students' interview responses with respect to how the knowledge portrayed by their answers developed.

However, criticising constructivism, Meyer (2009, 338) questions whether it can effectively represent reality in practice because it obscures the 'distinction between meaning, understanding and knowledge', essentially conflating 'knowledge and superstition'. It would seem that Meyer's (2009) discussion is essentially a critique of the validity of different knowledge types. Conversely, constructivism has been usefully described in terms of what's viable, collectives (Fleer and Richardson, 2008) and an authenticity based on 'consensus' (Guba and Lincoln, 1989: 86), particularly within communities of practice (von Glasersfeld, 1995) as a method to overcome the epistemological issue of constructivism's validity. The concept of conventional current for example (which is dichotomously positioned in relation to scientific evidence), is one such electronics based model of knowledge which is viable and accepted on the basis of consensus within communities of practice (Fischer-Cripps, 2005). Therefore in this study an assumption is made that constructivism underpins the cognitive development of the participants involved, on the basis that individuals construct knowledge for themselves represented by specific models and the interplay between existing knowledge, action and interaction with knowledgeable others (Ben-Ari, 2001). It was hoped that this would be evidenced during the study through participants' individualised approaches to learning.

2.4.1 Overlapping waves theory

In practice individual approaches have been shown to draw on different strategies which are context and task specific; they are the subject of 'variability, choice, and change' (Siegler, 2005: 771). Overlapping waves theory (Siegler, 2005) describes the use of different strategies by learners which overlap in time. Older strategies may be used concurrently with newer strategies, or may be replaced as learners choose between and change their approach. Where progression is impeded due to the lack of a known strategy, learners are said to choose 'adaptively' among those that they do know (Siegler, 2005: 771). Although the trend is for learners to progress towards more advanced strategies, regressions are common. A key analytical approach within overlapping waves theory is the focus on learners' strategies which are considered to vary, often within the same type of problem solving task. It may be useful, therefore, to explore the extent to which a learning strategy is used and whether it has evolved from other applications. This would assist in developing appropriate links between learning activities and problem solving approaches for learners, who may increase their autonomy in problem solving and task completion.

2.5 Cognitive mechanisms

In this section visualisation is discussed within the framework of cognitive mechanisms. Research into cognitive mechanisms emerges largely from the field of psychology. Early work on mental imagery linked with the perceived stages of child development and describe a transition from visual perception to visual imagination and anticipation (Piaget and Inhelder, 1971). Piaget's (1955) notion of cognition relies on a process of assimilation and accommodation in the development of an individual's schemata. Bruner's (1977) taxonomy, similarly, involves a process of transforming knowledge into other forms as a part of the accommodation process and includes an evaluative stage as an explicit part of the learning process (i.e., new knowledge → transformation → evaluation). Bruner (1977) emphasises experience and individual differences as key influences in the learner's cognitive development.

Elaborating on these theories of cognitive development, Kolb and Fry (1974) describe a system of experiential learning which has become known as Kolb's Learning Cycle (Figure 1). The cycle involves the application of four different abilities: concrete experience abilities (exposure to new experiences), reflective observation abilities (reflection from different perspectives), abstract conceptualisation abilities (personal theory building) and active experimentation abilities (decision making, problem solving and knowledge testing in new situations) (Kolb and Fry, 1974). The four abilities are said to operate along two dimensions consisting of polarised continuums (Figure 1): a concrete/abstract (perceptive) continuum and an active/reflective (processing) continuum. Thus learners engage with new concrete experiences, reflection on these leads to abstraction and theorising and experimentation allows testing leading to problem solving in new situations. Key to the process, and therefore of interest in this study, is how the transformation of experience works in practice in relation to teaching electronics.

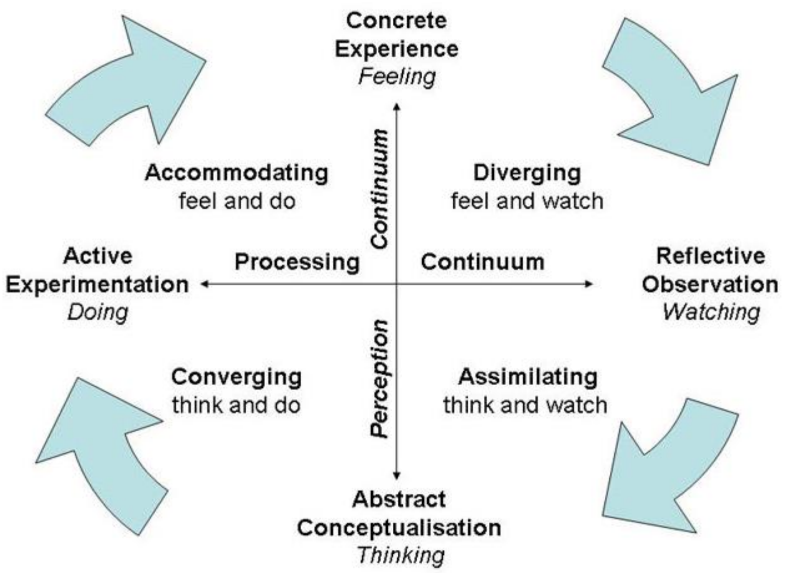


Figure 1: Kolb's Experiential Learning Cycle (McLeod, 2013)

In practice engagement in the cycle is dependent on individual differences, represented partly at the biological level. Learners are said to make choices about the degree to which an ability is applied along any of the two dimensions, and which dimension to apply in any learning situation. In doing so entry into the cycle at different points is implied and related to a range of variables which may include 'our hereditary equipment, our particular past life experience and the demands of our present environment' (Kolb and Fry, 1974: 37). Thus Kolb and Fry's (1974, 38) research involves the identification of the following four notable learning styles:

- the *converger* – strengths relate to practical application of ideas and concrete, single answer/solution outcomes

- the *diverger* – strengths relate to imaginative ability and the generation of ideas
- the *assimilator* – strengths relate to the creation of theoretical models and inductive reasoning
- the *accommodator* – opposite to assimilator. A practical experimenter, adapts to specific immediate circumstances, adopts trial and error in problem solving

The styles represent the extent to which learners exhibit a preference for an approach which involves '[moving] in varying degrees from actor to observer, and from specific involvement to general analytic detachment' (Kolb and Fry, 1974: 36). The experiential learning model is particularly useful in describing the interaction between experience and thought processes. Experience is represented in both the concrete exposure stage (CE) and the active experimentation stage (AE); processes characteristic of application in technology based activities. The acknowledgement of an integration between learner as individual, the learner's experience and the learner's environment provides a multi-faceted lens with which to view the actions and outcomes leading to growth and development.

Within the area of conceptual development, the model may present a practical approach to Bruner's (1977) notion that central to learning is the development of structure within subject matter, meaning the forming of generalisations that can be transferred between phenomena. The model may provide a basis upon which to analyse relationships between concrete experiences and the more abstract generalisations at the opposing end of the perceptual scale (see Figure 1). Of interest to this research study is the role of visualisation in moving between concrete and abstract thinking along the perceptive continuum. It would be useful to consider what the learner might conceive in an abstract sense during or following exposure to a concrete representation or experience? How do practical experiences support the reflection on knowledge suggested as necessary when generating personal theories or perspectives on experiences? And how does entering the model at differing stages effect the development of concepts?

Vygotsky (1978, 97) suggested the role of child's play and childhood experience influences the development of visual mechanisms, in that 'it is impossible for very young children to separate the field of meaning from the visual field because there is such intimate fusion between meaning and what is seen'. This has been supported by Shepard (1978) with research focusing on play and physical object manipulation. The recognition of objects also clearly relies on memory (Bruner and Postman, 1947), as does the prospective use of experience (Williams, 2012). Here the learning cycle draws on the processes manifest in concrete play-based experience and experimentation, but activated within the context of structured school-based learning experiences.

Consideration of physical experience and symbol systems has suggested that movement along the assimilation/ accommodation continuum is age related. Gardner (1984) observes that although school age children are easily able to spatially negotiate the environment, they find it very difficult to use symbol systems to re-create or communicate it, indicating that learning, language development and symbolised modes of thinking are important accompaniments to spatial ability and multimodal thinking. Therefore these are important developmental tools. Piaget and Inhelder (1971, 381) proposed the 'system of imaginal symbols' which described the creation and use of personal (internal) symbols to represent words, which are then used to memorise and evoke thinking following a visual stimulus. This resonates with Paivio's (1986) Dual Coding system, discussed in Section 2.5.4 below.

Consequently physical experience and the gradual development of personalised approaches to using symbolic representations have contributed to an understanding about the learner's use of visual mechanisms; what Vygotsky (1978, 99) referred to as achieving a 'functional definition of concepts'. This has more recently been termed embodied cognition (Davis and Markman, 2012). Thus the role of physical experience and the personal use of symbolic representations in learning are key supporting concepts in this study and discussed further in Embodied Cognition (Section 2.6.1).

2.5.1 Spatial relation and rotation

Spatial visualisation (mental rotation) and spatial relation (object relation) are key cognitive abilities which have been identified by Hoffler (2010) in a meta-analysis of largely experimental approaches to understanding physical experience in relation to visual mechanisms. Mentally rotating an object is said to generate an image in the mind, an analogue, which research has shown requires mental rotation in order to imagine a new object view (Shepard and Metzler, 1971).

Zacks (2008) supports the concept of mental analogues with research that finds a strong correlation between degree of object rotation and extent of brain activity, confirmed using neuroimaging techniques. This seems to confirm earlier suggestions of a biological mechanism which coordinates mind and body activity for this type of task. An interesting outcome of Zacks' (2008) discussion is the view that mental rotation is enhanced with the support of manual rotation, when that rotation is directionally complimentary. This links mental and sensori-motor facets of the brain and supports the view that seeing and doing are complimentary to learning experiences, providing further support for the concepts of embodied cognition discussed above in relation to active experimentation as a part of the learning cycle.

2.5.2 Transformation

Kosslyn (2005) supports the view that areas of the brain responsible for perceiving are also responsible for the visualisation abilities discussed so far. Kosslyn (2005, 336) describes a 'visual buffer' which processes visual thinking drawing on multiple areas of the brain. Thompson et al. (2009), describing spatial relation and spatial transformation processing, also believe multiple areas of the brain contribute to the ability to use mental transformations. However when and how these mental images are used to aid thinking, a key interest in this study, seems unclear (Kosslyn, 2005). Other research, as with spatial relation and rotation, has shown that visualisation links closely with the body's perceptive, sensori-motor and auditory systems and suggests that how and why imagery is used can be explained in terms of a whole body approach to the task at hand (Kosslyn, Ganis and Thompson, 2001). This would support a collective focus on these processes when considering how and why imagery is used by learners when forming electronics concepts using external representations, and the role of practical application in building circuits and handling the components of electronics.

2.5.3 Transformation and applied skills

The mechanisms discussed so far have particular applications within applied skills fields of education such as technology and engineering. In these fields the transformation of visual material may take the form of a conversion from two dimensions (2D) to three dimensions (3D). Translating between modes thus requires an additional imaginal or anticipatory ability which allows the new object view to be 'seen' in another way, and widens the learner's ability to use a range of representational forms. In electronics this might be represented by the learner transforming a circuit diagram into a component-based prototype model. Drawing from Bruner's (1977) taxonomy, this should indicate that the transformational activity provides a learning opportunity for the leaner.

Exploring translation within engineering education, Akasah and Alias (2010) found that instruction commencing with 3D forms instead of 2D accelerated students' ability to visualise and carry out the transformation, due to the existence of a more recognisable referent. Of particular interest to this study is Basson's (2002) finding that the 3D to 2D model (known as whole-to-parts) benefited students' learning of concepts in mathematics and physics. This may indicate that any electronics-based transformation be carried out, at least initially, in the direction of 3D to 2D (i.e., real life representations to circuit diagrams).

The trainability of visual skills to improve 3D spatial awareness has been a particular focus of research in engineering (Potter et al., 2009). Nguyen and Khoo (2010) report an improvement in the learning of and interaction with abstract engineering concepts when the training links learning with computer graphics. The use of domain related drawing strategies (orthographic projection, isometric views and section drawings) were found to relate to specific problem solving strategies in engineering (Hsi, Linn and Bell, 1997) and correspond with visualisation strategies in science education, such as the use of metaphorical representations (Mathewson, 1999).

In electronics education, transformation from one representation to another is a common problem solving strategy, which may compliment other means such as the use of metaphor (see Analogy and Metaphorical Modelling, Section 2.6.6). Information in the form of a circuit diagram is often accompanied by tabularised information and graphs, which when taken together represent an electronics concept. Therefore in electronics education, transformation from one representation to another requires the manipulation of spatially located objects, which embody the electronics concepts. This type of visualisation ability is very different to that conceived by spatial rotation and location researchers, but as the review so far has revealed is likely to draw upon the same mechanisms in its operation, including an underlying embodied cognitive capacity.

As a practical example, Figure 2 includes an electronics concept represented by circuit diagram, truth table and Boolean expression. It illustrates the different ways electronics concepts might be represented and the type of transition learners need to make to achieve a full understanding of the concept of the operation of a logic AND gate. Transitions from one representation to the other require both an understanding of the information presented and methods with which to operationalise the transition. It is the identification of these methods which forms the key focus in this study.

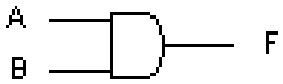
<table>
<tr><th>Circuit Symbol</th><th>Truth Table</th><th>Boolean Expression</th></tr>
<tr><td>
</td><td><table><tr><th>A</th><th>B</th><th>F</th></tr><tr><td>0</td><td>0</td><td>0</td></tr><tr><td>0</td><td>1</td><td>0</td></tr><tr><td>1</td><td>0</td><td>0</td></tr><tr><td>1</td><td>1</td><td>1</td></tr></table></td><td>F=A.B</td></tr>
</table>

Figure 2: Logic AND gate represented in three different ways

Visualisation has so far been conceived as a cognitive ability which has biological origins, and which develops through childhood physical experiences. Researchers have shown that the ability is capable of training and development, particularly in fields such as engineering where visualisation ability is key to understanding concepts (Nguyen and Khoo, 2010; Potter et al., 2009). Visualisation has been considered as an individual mental mechanism, and one which draws from several cognitive mechanisms suggesting interconnectivity between mental processes during learning. Some types of visualisation processing relate well to object manipulation, while conceptual understanding seems to require the application of additional cognitive approaches, which I now move on to discuss.

2.5.4 Verbal and nonverbal processing: Dual Coding Theory

To explore conceptual understanding and mental processing more fully, I consider in the next section the concept of verbal and nonverbal processing which emerges from Paivio's (1986) Dual Coding Theory (DCT). Within Morton and Frith's (1995) framework, DCT can be considered at both the biological and cognitive levels of analysis. Paivio's (1986) seminal work suggested a strong link between verbal and nonverbal mental processes and continues to gain support with useful and varied learning applications (Reed, 2012). The DCT processes are considered separate, but closely associated functions of thinking, which support memory and mnemonic (memory aid) development by coding the two types of referent (verbal/nonverbal) accordingly. DCT proposes a dual conception of information representation and processing (Paivio, 1986; Clark and Paivio, 1991), as presented in Figure 3 below. Firstly words (sequentially processed arbitrary symbols) and images (synchronously processed visual imagery) code information and form associative networks (i.e., association by naming images and representing words with images). Secondly, within the coding system associative networks link representations, for example linking words with other associated words and images with other imagery (which might also relate to other modalities such as sound, smell or experience).

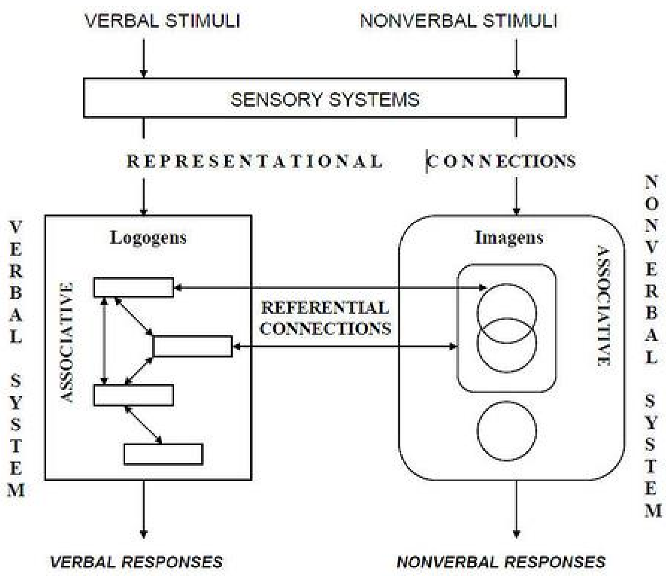


Figure 3: Dual Coding Theory system outline (Paivio, 1986: 67)

DCT therefore represents the more developed skills which support an individual's constructions of knowledge. They represent the observable referrals and associations which develop as a result of using the coding system (Paivio, 1986; Clark and Paivio, 1991). Beyond the practical applications of combining words and images within the learning context, two key features of DCT therefore emerge. Firstly is the recognition that representation use is affected by a broad range of sensory inputs, such as visual, auditory and of particular interest here, kinaesthetic modes, and that individual experiences and differences affect the way word/image associations are made by the individual.

Secondly multi-object perspectives (such as the logic gate representation in Figure 2) are represented by imagery which aid memory in supporting 'dynamic spatial transformations'; which means that imaginary thinking is possible with combinations of verbal and nonverbal referents, but not verbal referents alone (Clark and Paivio, 1991: 152). The notion that individuals use images and words in personalised ways is illustrated by Piaget and Inhelder (1971) with their number sequence representation example and Hoffler's (2010) counting strategy example which demonstrate these personalised approaches. Therefore words *and* images allow an enhanced depth of personalised thinking, which may also be affected by a number of sensory influences; sensori-motor influences being of particular interest in this study. The transition task presented above in Figure 2 is an example of an electronics concept which may draw on DCT as a strategy to support learning and understanding using the verbal and nonverbal referents shown.

DCT has however been criticised for inadequately explaining links between cognition and the processes of DCT thinking (Randhawa, 1978). The concept of a dual system seems to be contended and open to interpretation. Lloyd et al. (1984) particularly highlight the difficulty of judging the significance of imagery in cognitive processes, since research shows the considerable variability in individuals' image use. Arnheim (1970, 3), a proponent of visual thinking, has been particularly critical of the dual mechanism approach, suggesting that without visual thinking 'productive thinking is impossible in any field of endeavour' and views verbal language as a 'one dimensional sequence' (*ibid,* 232). In support of imagery, using tasks based on Dienes-type blocks (physical representations of number bases to support the teaching of numeracy), Steiner (1974) found that iconic media (coloured blocks), rather than symbolic (words representing the blocks) significantly improved identification, possibly as verbalisation processes were avoided. However support for aspects of language use includes categorical naming, organisation of thoughts and enabling communication through verbal codes (Arnheim, 1970). Pinker's (1998) discussion highlights the need for something more than imagery, however, to support conceptual thinking which he suggests requires abstract symbols and caption-like instructions to aid interpretation (see section on Language as a Representational Model, Section 2.6.7).

The DCT concept has been explored in research focusing on visualisation and verbal learning in relation to the use of concrete and abstract words (Blakemore and Frith, 2005). Referring to research from brain injured patients, Blakemore and Frith (2005) describe how visual and verbal areas of the brain, and memory, are used to support object and image based recognition. Consequently, research from neuroscience is suggesting that recognising and recalling concrete words makes use of visual processes and abstract words draw upon language based processing, including auditory processes (Blakemore and Frith, 2005). In this study this notion will be explored through a focus on students' use of nonverbal representations (circuit diagrams) and verbal representations (computer code) and the extent to which these are combined in a dual system to represent concepts.

Paivio's (1986) position has been strengthened by a number of studies which draw upon the original theory (Griffin and Robinson, 2005; Suh and Moyer-Packenham, 2007; Sadoski and Paivio, 2004; Wu et al., 2001). Griffin and Robinson's (2005, 24) geography education based study is particularly interesting, as it explores 'visuality' and 'spatiality' and finds that icons more effectively aid recall of textual features, compared with spatial positioning based recall. DCT has therefore made a significant contribution to the development of and approach to this study as it provides a helpful foundation for thinking about visualisation processes and learners' concept development. It is thus considered a useful tool for analysing associations between words (e.g., linking technical terms), images (e.g., linking different images such as symbols/pictures/diagrams) and referents between words and images and supports the development of the analytical framework discussed in Analytical Procedure below (Sections 3.7 and 3.8).

2.6 Levels of representation and modelling

Earlier I made the distinction between visualisation as process (Lohman, 1993) and visualisation as artefact (Hoffler, 2010). In this section the nature of different representations are discussed and related to the process of visualisation. I draw on the levels of representation emphasised by Johnstone (1993) in relation to the teaching of chemistry: macroscopic (observable phenomena), microscopic (invisible, atomic level) and symbolic (symbols and equations). These can be straightforwardly adapted to modelling electronics phenomena.

2.6.1 Embodied cognition

A common theme underlying the discussion in this chapter is the concept of sensori-motor engagement with the objects of learning. Embodied cognition, or thinking which relates to actions performed using physical means, has been suggested as a 'necessarily broad' field of endeavour (Davis and Markman, 2012: 685). Practical experience and metaphor have been considered to play a combined role in cognitive development (Lakoff and Johnson, 1980). More recently embodied cognition has described 'the consequences on thought and emotion of existing as a human body' [*sic]* (Davis and Markman, 2012: 690). Thus embodied cognition grounds a way of thinking, but not exclusively, about learning which draws on a particular type of knowledge, known as tacit knowledge. This relates to knowledge that emerges through contact with representations in the real world, through sensory experience. Closely aligned with embodied cognition is the notion that meaning is attached to experience through the use of a foundation metaphor, which in the context of electronics, for example, could mean drawing on the learner's first experiences of water when engaging with learning using the 'water-in-a-pipe' analogy. Thus practical application appears to enhance the process of learning with visualisation (Kosslyn et al., 2001; Shepard, 1978; Vygotsky, 1978; Zacks, 2008).

Learning through doing has been described as an applied learning context, because knowledge and understanding are normally engaged with using a material, practical vehicle as the representation. As I discussed in the Introduction (Chapter 1) technology education is such a subject, as it deals with outcomes relating to human problems, solutions and the creation of 'things' while in science, conversely, the focus is on the 'explanation' of phenomena (France, Compton and Gilbert, 2011: 383). Therefore technological thinking is often embodied in the representative modelling which enables product development, and this thinking is 'carried and validated by the materiality of the outcome itself' (*ibid*).

2.6.2 Problem solving and modelling

The contrasting conceptions of knowledge have an impact on the way information is processed. Research has shown that even in domains such as mathematics and science learners construct their own understandings on the basis of intuition (Hennessy and McCormick, 1994). In Technology education understanding has been referred to as the 'practical organisation of knowledge' (Smithers and Robinson, 1994: 37) and as such the problem solving approach can be referred to as procedural (McCormick, 1997) as it requires flexible and appropriate application to the problem in a practical context (Hennessy and McCormick, 1994). This procedural approach has often been associated with a linear design process (Chidgey, 1994), however critics highlight the interaction between design stages and emphasise the interacting elements that connect problem identification with solution generation (Kimbell, 1994). Middleton's (2000) model of design activity suggests that information processing revolves around an iterative process of search and knowledge construction within a 'space' between problem and solution. The observable outcome of this iterative knowledge construction process is often an external model in the form of drawing of physical prototype.

Problem solving more generally may follow similar patterns and include iterative periods of practical trial and error. In the world of problem solving a heuristic is an approach providing adequate but often imprecise solutions (Kahneman, 2012), based on procedures such as experimenting, evaluating or trial and error. The parallel with designing and technological endeavour is grounded in this iterative process and supports the relationship with procedural knowledge. A heuristic approach to knowledge construction is therefore a familiar phenomenon in Design and Technology and one commonly applied by students following the subject in the form of tangible models as representations of phenomena.

2.6.3 Representations: Symbols, codes and multimodal thinking

Learning can be described as 'the development of cognitive systems [which] depend on signs and representations as mediators' (Hoffman, 2012: 185) and which allow the communication of personal knowledge. To enable the engagement with and communication about knowledge and concepts in electronics education, that knowledge requires an external referent. Sinha (2004) has considered that evolution and the need to communicate complex information has led to signals and symbols evolving into more complex representations, complex grammar and language use. This view emphasises a link between visual thinking, the social-cultural practice of communication and constructions of personalised knowledge, as discussed by Hoffman (2012).

Others have supported the use of symbols in learning, which aid the construction of new knowledge, but only at and beyond certain stages of development (Bruner, 1977). Hoffman (2012, 193) links the sensori-motor engagement with 'concrete objects and representations', supporting cognitive development using concrete symbols and physical manipulation of objects in mathematics. Thus learning and the use of representations is here conceived as a combination of perception, visual symbolic thinking and the manipulation of symbols and objects (Bruner, 1977).

The field of mathematics has provided a good deal of research related to visualisation and the use of symbols. It has been suggested that children commence with an understanding about object permanence, which leads eventually to the use of complex symbols and abstract conceptual reasoning (Eysenck, 1996; Gardner, 1984). Mathematical problem solving is considered to draw upon object recognition, perceptual organisation and structural representation, the difficulty often being the transfer between these phases and beyond object recognition (Gal and Linchevski, 2010). Children's play is thought to support the mathematical problem solving process. Drawing on visual-spatial problem solving, play has been found to enhance later mathematics ability (Assel et al., 2003). Spatial structure leading to object recognition, called 'subitising', is supported as a means to quickly perform calculations based on object arrangements (Bobis, 2008: 6). For example instantly recognising groups of objects in terms of their total number. This is supported by the research using Dienes blocks highlighted earlier (Steiner, 1974). However Bobis (2008) also finds support for verbal coding, alongside nonverbal means, in the form of pattern-name associations, which practically allow the attachment of meaning and its communication. This finding is important in clarifying the role of visualisation in terms of practical experience (manipulation of spatial elements), representation type (verbal/nonverbal) and their combination using cognitive concepts such as DCT and embodied cognition.

Pictorial and schematic imagery has also been explored, in relation to mathematical ability and achievement (van Garderen, 2006; Edens and Potter, 2008). Schematic imagery was preferred by high mathematical achievers, while pictorial imagery was preferred by low achievers (*ibid*). Of interest to this study are the individual differences suggesting preferences for either object appearance (pictorial), or spatial relation and concept (schematic) within the mathematical problem. Both studies found positive correlation between successful mathematics problem solving and the use of schematic imagery.

Chen et al. (2011) exploit these representation types in a study grounded in electronics education. Their research combines pictorial imagery with concept models (schematic representation) and suggests that this combination enhances learning because learners can more easily 'verify and clarify the existing knowledge' (*ibid*, 269) attached to abstract concepts with familiar referents (pictures) and symbolic representations (schematics), particularly when this reflective stage is built into learning schemes. Research supporting this has suggested that good existing knowledge is needed to enable representation combination and where combination is not successful, learners often focus on a single concrete representation (Seufert, 2003). Similarly where a representation is unfamiliar learners tend to focus only on surface or concrete features (*ibid*).

Larkin and Simon's (1987) discussion emphasises that imagery, diagrams and schematics allow access to information almost instantly. One of the skills that learners need to do this include the identification of elements of the representation to enable referential connections and therefore learning (Seufert, 2003). Since the information is grouped or spatially located, as in the subitising example, meaning can be extracted simultaneously using a 'search-recognition-inference' strategy (Larkin and Simon, 1987: 69). Text (sentential) representation on the other hand requires a sequential (and slower) search-recognition-inference strategy (Larkin and Simon, 1987). The ability to make referential connections is particularly important in electronics education, as much information is presented as a circuit diagram. Larkin and Simon's (1987, 82) research emphasises that individual differences dictate how efficiently the search, recognition and inference processes are performed and suggest that 'A good deal of skill acquisition in any domain can be attributed to the gradual acquisition of domain-specific inference procedures'.

In support of this, and perhaps a development of the Larkin and Simon (1987) work, Zhang and Norman (1994: 89) describe the 'distributed representational space' attached to representations in problem solving. This means that a distributed cognitive task would draw upon the external 'real world' representation and the internal representation 'in a person's mind' which will have evolved drawing on a variety of referents in its construction (Zhang and Norman, 1994: 3). Therefore when considering learning with a representation, instruction should take account of the interrelation between internal constructions and external representations. In addition, Zhang (1997) suggests representations carry a degree of determinism, which describes the extent to which the representation leads to certain (fixed) perceptions and particular information that can be extracted from it. This would suggest that a particular representation leads to particular ways of thinking about it and its content and that this is different for different learners.

In a study focused around scientific systems (whole or gestalt) thinking with symbols, Eilam and Poyas (2010) found multiple visual representations more useful to students than textual displays. However the researchers found that as representation manipulation activity increased, the performance of some students decreased, possibly due to the need for additional transitions between representations, therefore increasing cognitive load on complex tasks. Cognitive load can be reduced by coding multiple elements of representations as one element, by automating tasks and by presenting information in several ways (Kirschner, 2002).

Consequently learners who are familiar with visual representations have been found to increase performance and reduce cognitive load where text has been removed (termed *redundancy*) from the familiar visualisation (Ainsworth, 2006). Another study, however, reports that learners tend to merge text and image into one internal representation, and concludes that image/text redundancy has not been shown to either support or hinder learning (Schuler, Arndt and Scheiter, 2015). This may relate most readily to simple representations; conversely complex information may benefit from multiple representations as learners can make use of 'complementary processes' in relation to individual differences (Ainsworth, 2006: 188) and the presentation of information in several ways (Kirschner, 2002).

Thus codes and symbols appear to accelerate, or automate (*ibid*), cognitive processing and enable thought about abstract concepts and their communication. Using and manipulating a code or symbol may be context bound and appears also to be affected by individual differences. However a problem highlighted by de Vries and Masclet (2012) relates to whether a nonverbal representation leads to an understanding of content, or whether understanding of the content is required to understand the representation type.

In electronics education and drawing on the use of symbol systems, using a particular strategy has been linked with the adoption of a preferred learning style (visualisation method preference) and memory (Pule and McCardle, 2010). Chen et al. (2011) believe conceptual learning is enhanced when reflective thinking is linked with visualisation based learning, and ICT-based graphics, to model circuit behaviour. Together these studies support the view that visualisation skills are not ‘fixed or culturally exclusive abilities, but respond to instruction and mediation’ (Potter et al., 2009: 109) and that there is a high degree of individuality attached to the use of visual representation in concept formation.

2.6.4 Computer programming as an electronics model

Drawing on the work of Larkin and Simon (1987), I consider in this study the possible merits attached to computer program code (referred to as computer programming), as a supporting sequentially presented representation for electronics concepts. There is little research linking electronics, programming and learning, however. Research into text-based programming has revealed its advantages for beginners, when compared with their use of graphical means, such as flow-charting based programming (Petre, 1995). Whilst not the main focus of the current study, this phenomenon is a useful starting point for considering text as a supporting representation for electronics concept development, because students beginning a GCSE course in electronics are usually limited in their knowledge of programming and therefore considered beginners in the field. Paivio (1986, 53) captures the notion that computer coding may provide a supporting representational referent by explaining that ‘the language system … [serves] a symbolic function with respect to nonverbal objects, events, and behaviours’. Therefore computer coding may present the possibility that concepts can be understood in terms of the descriptive means provided by the written code, as a support for representations such as circuit diagrams, graphs and truth tables.

Research with secondary school age children has shown that the use of programming syntax (rule based language structure) which replicates natural language, in combination with a practical approach to simulating the effects of the program in operation are beneficial to learning about computer programming (Lauria, 2015). Using simple on-screen graphics and visual feedback from a physical robot, Lauria’s (2015) research also suggests that cognitive load can be reduced leading to enhanced engagement with the concepts of programming. This approach may have some potential to support the teaching of electronics, where programming is used to represent the complexities of circuit function through the application of language and active simulation-based learning. Further inquiry may reveal how the research from computer science can be applied to the teaching of electronics and learners' development of understanding.

2.6.5 Conceptual thinking as an electronics model

Some conceptual knowledge in electronics education has developed from common practice, such as the concept of conventional current (current flows from positive to negative, rather than negative to positive) which is opposed to that grounded in scientific fact (Fischer-Cripps, 2005), but enables its effective communication. Other electronics concepts are commonly explained by 'limited' analogies, such as the 'water-in-a-pipe' comparison to aid learning (Pitcher, 2014: 398).

A significant amount of research has been generated in relation to concepts surrounding voltage, current and resistance in science education. This is summarised by Engelhardt and Beichner (2004) in a detailed review which focuses on student misconceptions in relation to voltage behaviour, often revealed through testing and interviews. Others have claimed that 'all [electric circuit] phenomena' are interpreted using the principles of voltage and current (Metioui and Trudel, 2012: 24). However these conceptions have been developed relative to research largely in science education, which tends to focus on the theoretical aspects of electronics, rather than on the system's design (Hiley et al., 2008), as I outlined in the Introduction (Chapter 1). And as Ben-Ari (2001) points out, only highlighting the misconception is not useful in terms of identifying the learner's actual knowledge model, or instructive as to how the existing knowledge (represented as misconception) can be used to build new knowledge.

Although electronics principles are clearly at the root of knowledge about circuit behaviour, I will explore below alternative means with which to conceive of electronic systems within product design which can evolve through students' application of systems design approaches, often described as 'procedural' (McCormick, 1997: 142). The reason for these perceived differences is that this study is concerned with the technological context, rather than the scientific context, and it is the context itself which differentiates electronics thinking in technology from that in science (McCormick, 2004; France et al., 2011). As McCormick (2004) suggests, viewing learning as situated leads to a concern for context and the nature of the task. Research suggests that targeting and scaffolding the appropriate 'knowledge-component model' during learning leads to improved learning, in relation to conceptual, contextual and procedural knowledge types (Rittle-Johnson and Koedinger, 2005: 343). In addition research has shown that identifying and focusing on appropriate knowledge types, such as declarative, procedural, contextual and qualitative in technology education improves learning with appropriate scaffolds (Barak, 2012). I develop points surrounding conceptual understanding and knowledge types in the Discussion Chapter (Section 5.3).

As noted above in relation to the nature of representations, a very relevant and influential area of literature for this study is the work on conceptual knowledge by Wu et al. (2001) focusing on chemical representations. The approach to conceptions of chemical structures are here considered interchangeable with those in electronics, through the application of representations in relation to three areas of conceptual understanding, which also lead to thinking about representations is three different ways, as follows:

- Macroscopic (observable phenomena)
- Microscopic (atoms and particles-abstract/invisible)
- Symbolic (symbols, numbers, formulas and equations)

Wu et al. (2001) suggest that when these levels are satisfied through instruction, an increase in understanding is achieved. Mathewson (1999, 38) believes understanding of this type leads to a 'higher-order' visual metaphor. Underlying these representation types are the three concept understanding types: domain specific representations (e.g., circuit diagrams), domain specific concepts underlying representations (e.g., logic gate function) and connections between domain specific properties and structures (e.g., electronic components and circuit diagrams).

Adapting Dual Coding Theory as a theoretical framework, Wu et al. (2001) explore students' development and understanding in the three areas of representation and use the framework as a method with which to explore transitions between representations. The framework also provides a basis for exploring transition, representational connection and concept development in electronics education, especially as research indicates that multiple representation use is beneficial to students' concept understanding development (Ainsworth, 2006). Finally Wu et al. (2001) suggest that conceptual understanding (metaphorical, mental constructs) and visual-spatial skills are required to translate between representations, a position others have supported with some enthusiasm (Mathewson, 1999; Pule and McCardle, 2010). For these reasons Wu et al.'s (2001) framework provides a significant point of departure for this study and is discussed further in Methodology (Chapter 3) in support of an analytical framework.

In common with the large body of work reviewed by Engelhardt and Beichner (2004), Streveler's et al. (2008) research focuses on students' theoretical misconceptions and questions why reversing such thinking can be difficult to achieve. The answer proposed relates to the difficulty in altering the learner's perspective when the nature of the phenomena, particularly in science and related fields, is abstract and invisible and therefore the learner 'holds on to' existing conceptions. Streveler's et al. (2008) discussion highlights the emergent and time bound nature of conceptions in science. Emergent as opposed to direct phenomena (Chi, 2005) describes the difference between phenomena that can be observed as a direct result of an event (e.g., light on following a switch push-direct), and that which emerges but is not directly observable (e.g., voltage amplification-emergent). Consequently there is a suggestion that some conceptual learning problems may have age related developmental causes, indicating that learners cannot yet make use of the required logical arguments (Perkins, 2007 as cited by Streveler et al., 2008). This notion is explored further in the study and included within the research questions below.

Chen et al. (2013), focusing specifically on electronics-based misconceptions, promotes a prediction-observation-explanation strategy (POE) as a means to engage students in the use of ICT-based visual imagery and the more meaningful development of knowledge and its transformation, from misconception to understanding. The technique promotes students' engagement in self-explanation following a knowledge transformation event as a strategy for overcoming misconceptions. Chen et al. (2013) points out, however, that successful use of visual simulations is linked with learners' opportunities for autonomy and task manipulation within the learning system. Therefore adopting these principles, the current study incorporates this approach into the lesson design used during data collection (see Methodology, Section 3.6.2).

Conceptual understanding has thus been modelled as a developmental process, particularly in the field of science (NSRC, 2002; Ben-Ari, 2001; Treagust and Duit, 2008). Chen et al. (2013), promoting a conceptual change model, suggests that students must construct their understanding by gradually integrating new conceptual knowledge into existing understandings. In doing so, learners undertake a conceptual change which parallels Bruner's (1977) learning processes. Thus four conditions are said to operate when learners undergo a conceptual change: 1) learning material triggers dissatisfaction with existing understandings, 2) new concept visualisations provide intelligibility, 3) plausibility of concept is achieved when visualisation can be matched with theoretical understanding and 4) to overcome long standing misconceptions, visualisation needs to be linked with manipulation and exploration opportunities (Chen et al., 2013). This developmental model therefore represents the combination of imagery and experience in the modification and improvement of learners' understanding.

Research supporting this phenomenon has suggested that this type of conceptual change occurs more readily in the later years of education and is 'gradual', 'piecemeal', supportive of 'contradictory ideas' and 'elemental knowledge pieces' (Ozdemir and Clark, 2007), in support of Chi's (2005) emergent phenomenon concept. Caution though is warranted when considering research in relation to learners' development and conceptual change, as researchers have found that participants may describe understanding differently dependent on context; therefore perceived conceptual change may actually represent a contextualised response from a participant (Treagust and Duit, 2008). Nonetheless Treagust and Duit's (2008) discussion emphasises the benefits to learning of adopting a conceptual change approach, particularly where sufficient account is taken of learners' multiple perspectives (the topics identified below incorporate the notion of fragmented and emergent knowledge as a focus for further exploration through research questions).

Adopting a multi-perspective view is key to defining the conceptual profiles in Solsona et al.'s , (2003) research on chemical concepts. The profiles are developed from participants' essays about chemical change and highlight the different ways concepts can be held by individuals, including the recognition of different levels of understanding which are considered to 'give coherence and meaning to the diversity of facts that they encounter' (Solsona et al., 2003). The use of conceptual profiles therefore represents a useful tool with which to present individuals' personalised, multiple perspective conceptions. Solsona et al.'s (2003) conceptual profiles and Gentner and Gentner's (1983) conceptual analogies represent the few examples of learners' actual representations of knowledge in relation to the type of conceptual understanding discussed in this study. In the current study the different levels of understanding are drawn from Wu et al.'s (2001) framework which includes microscopic, macroscopic and symbolic levels of understanding; these ultimately represent learners' multi-perspective views.

2.6.6 Analogy and metaphorical modelling

The formation of mental analogies (comparisons) using specific metaphors (representative models) draws upon imagery and words in their creation. Metaphor has been defined as 'seeing, experiencing, or talking about something in terms of something else' (Ritchie, 2013: 8). Paivio and Begg (1981) suggest metaphors are compact representations, which allow information conversion and transfer, enable communication and personify imagery related to experience. Complex metaphor has been suggested as an important learning tool within the sciences generally (Wu et al., 2001) and electronics education specifically (Pule and McCardle, 2010), as abstract concepts cannot be observed or easily related to everyday experience. It has been suggested that a metaphorical model can support both the development of understanding and enable its communication (*ibid*). It has been considered key to creative scientific thinking and problem solving (Gentner and Grudin, 1985). Common electronics analogies, used to explain voltage behaviour, are the flowing water and moving crowd analogies (Gentner and Gentner, 1983). These are likely to be modelled, as indicated in the previous sections, differently by different individuals.

Mathewson (1999, 38) suggests (in science education) 'higher-order visual spatial thinking is inherently analogic', and that this is achieved through visualisation and metaphor development. It links external representation with stored knowledge and new stimuli in a variety of forms, providing a visual likeness combined with verbalisation to support explanations of concepts (Petrucci, 2011). Using verbal-only means, it has been suggested, does not allow engagement in a successful way or support the correction of misunderstanding (*ibid*).

Previous experience plays an important part in the development of a metaphorical model, in the form of foundation metaphor (Sibbet, 2008). A relevant example of a foundation metaphor is the relationship between the behaviour of water (the foundation) and the metaphorical 'water-in-a-pipe' comparison often used in electronics education. The analogy uses the visual water-in-a-pipe representation to represent the 'flow' (itself a metaphor since current does not actually flow in a scientific sense) of current along a conductor. Comparisons of this kind (Figure 4) also draw upon visualisation skills in the construction of the metaphor, through mental manipulation of representations and stored experiences (Paivio, 1986); in this case the experience of water behaviour.

Figure 4: Analogy of electronic circuit (right) with hydraulics (left) (after Hughes and Smith, 1995: 90)

However Pitcher (2014) notes, in relation to electronics education, that metaphor is useful only to a point, suggesting that commonly used metaphors such as 'water-in-a-pipe' break down once the learner has reached an understanding based on the theory or principle itself and are thus discarded. Resonating with the discussion on conceptual change above, the use of a metaphor in this view has developmental implications because the nature of the metaphorical model may be linked with the learners' stage of development and understanding. Matching model and learning stage is therefore crucial to the learner's progress.

Nonetheless there are a number of metaphorical types relevant to electronics which Ritchie (2013) discusses in relation to conceptual metaphor theory (CMT). These include metaphors 'ground[ed]' (Ritchie, 2013: 69) on conceptions of height, direction, dimension, physical orientation/proximity and object manipulation. According to Ritchie (2013), who draws on the seminal work by Lakoff and Johnson (1980), grounding occurs early in childhood through the process of embodiment (e.g., physical proximity and physical warmth are relative to experiences of affection and lead to *hot*/*cold* metaphors). Later, the child's physical interaction with the world leads to the formation of concepts related, for example, to object manipulation, direction and dimension. This extends further support for the importance of sensori-motor engagement during learning. In the study I refer to these grounded metaphors as foundation metaphors.

Metaphor relates to the more general cognitive process of analogy generation. Geake (2008, 187) has considered the benefits of 'fluid analogising' which describes the ability to draw upon several areas of the brain in response to visual stimuli and use working memory as a 'dynamic workspace' (*ibid,* 191), where divergent thinking allows problem solving beyond concrete solutions. This may impact on electronics learning through the ability to operationalise multiple representations, metaphor and personal experience seamlessly, discussed above in Conceptual Thinking as an Electronics Model (Section 2.6.5).

2.6.7 Language as a representational model

So far learning has been discussed largely in terms of a general process used to develop understanding (Piaget, 1955; Bruner, 1977; Kolb and Fry, 1974). Halliday (1993) provides a useful elaboration in the form of a language-based theory of learning. In this model all learning is considered to emerge from the use of language. Whilst this is not a main focus of this study, it is useful to consider that learning can be represented by the interplay of 'common' grammar and the more developed written form which is referred to as the 'synoptic mode' (Halliday, 1993: 112). Learners are said to develop meaning through language, and progressively through formal written means.

Swain (2006, 96) refers to language as the 'agent in the making of meaning' which represents a cognitive tool for what she calls 'languaging', meaning the production of language to aid understanding, problem solving and meaning making. Swain's (2006, 97) learning example, taken from the biological sciences, provides an insight into how language might support learning in electronics education, essentially through the production of 'a visible or audible product'. Ideas are thus modelled objectively in language, which can be used to explore, discuss and explain.

Halliday's (1993, 112) model suggests that this process involves understanding from the viewpoints of both the 'everyday commonsense grammar' [*sic*] (dynamic mode) and the 'synoptic mode' of the written grammar; the two modes forming a requirement for learning. Ausubel's (1963) meaningful learning theory explains this as the gradual assimilation of simple terms, progressing towards more developed vocabulary. For learning to be effective and 'meaningful', this assimilation process requires that the learner actively integrates new knowledge with that already known (Novak, 2011). In the context of electronics learning, the learning through language perspective indicates two considerations; firstly that discussion between learners about electronics topics should enhance learning through the development of a deeper understanding (Swain, 2006) and secondly that the gradual introduction of electronics terms should support the development of meaning through learners' mapping of new knowledge with formal grammatical descriptors (Ausubel, 1963; Halliday, 1993).

2.7 Discussion of the literature

The review identifies visualisation as both an artefact and a process. As artefacts, visualisations have been discussed as different representations, each suited to the representation of different phenomena. Different cognitive mechanisms have been discussed which support the process of visualisation, or thinking with a model of representation characteristic of the phenomena of interest. The cognitive mechanisms are themselves supported by a number of more general learning processes which describe the procedure used to apply visualisation skills. The interplay between cognitive mechanisms, learning processes and representations therefore emerges as the object of interest in this study, because they form the catalyst for development and learning. This learning is considered to manifest itself in the learner's developed conceptual understanding.

The specific research exploring students' conceptual understanding of electronics is drawn mainly from the science and engineering fields, but also draws on psychology, education and neuroscience providing an holistic view. A central argument underpinning this study, is that conceptual development draws upon several areas of the learner's experience and to enable a description of these, an approach to their study is needed that captures the whole, rather than isolated aspects of it.

The overlapping nature of the theories reflects the different approaches adopted by researchers who have explored visualisation skills in different contexts. These researchers represent visualisation as a supporting developmental learning process. The learning context is therefore important to both understanding the wide range of theories and their use of terminology. Students of mechanical engineering, for example, will clearly benefit from instruction in the application of spatial relation and spatial rotation skills. Whereas analogy, metaphor, the use of icons and symbols may support the development of electronics concepts. Many of the studies explore these variables in isolation (e.g., Shepard and Metzler, 1971). However in education research (and relative to the aims of this study), the isolation of a variable is less useful because as this review reveals, there are many factors involved in learning which taken as a whole, appear to effect students' learning and concept development. Indeed the literature on cognition suggests significant interconnectivity of cognitive mechanisms, including the prominent role of sensori-motor input leading to embodied cognitive processes.

Suh and Moyer-Packenham (2007) suggest that opportunities for reinterpretation reinforces conceptual connections when translating between (visual and verbal) modes of representation leading to increased understanding. This is also in accordance with earlier theorising suggesting the need for a transformation as a part of the learning process (Bruner, 1977). Wide support is provided by many of the studies reviewed here, which point to some manipulation of the visualisation/learning material to reinforce learning. As the role of translation in practice remains uncertain (i.e., uncertain how individuals attach meaning in practice), on the basis of the literature reviewed here, further exploration may reveal how students develop this understanding in practice and how the manipulation of imagery, icon, verbalisation and symbols is used when translating within an electronics education context and how this may lead to conceptual change (Chen et al., 2013).

The development of understanding has been shown to involve individual differences, which can be observed in the preferences for imagery type and constructions of personal knowledge systems on the basis of pictorial, animated and schematic representation types, when thinking about abstract concepts (van Garderen, 2006; Edens and Potter, 2008). Thus it appears individual differences and 'learning style' (Dunn et al., 2002; Kolb and Fry, 1974) are key to understanding how conceptual understanding is achieved, on the basis of this review.

Dual Coding Theory has provided a starting point for thinking about interactions between verbal and visual stimuli, the use of symbols and icons, development of personal analogies and specific metaphor and permeates many of the studies explored above as a 'foundation' theory. Further exploration may reveal how Clark and Paivio's (1991) concreteness, abstraction and imagery categories relate to conceptual understanding when considered within an electronics learning context. These categories, and the DCT theory, can be usefully combined with Wu et al.'s (2001) three levels of representation and the concepts proposed by Larkin and Simon (1987) outlining access to diagrammatic information, as a conceptual framework for exploring learning within electronics education. Indeed Wu et al.'s (2001) research seems to encapsulate much of the literature and theorising reviewed here, in their focus on the three levels: macroscopic (observable phenomena), microscopic (invisible phenomena), and symbolic (use of symbols/icons).

In connection with DCT, the notion that computer code forms a valid representation for conceptual electronics knowledge warrants further investigation, in relation to Paivio's (1986) and Arnheim's (1970) theorised advantages of explanatory verbal mediators. Petre's (1995) discussion focuses around the differences inherent in graphical (usually flow charting) and coding (written codes) approaches to programming computers. My interest, conversely, links with Larkin and Simon's (1987) position that diagrammatic information provides instant access to information, but also draws on notions of DCT theory which suggests that sequential verbal representations may provide an explanation absent from the diagrammatic representation. A significant gap in the literature exists in relation to whether written computer code can provide a supporting explanatory function, alongside the more 'traditional' circuit diagram representation and whether the act of translating between diagrams and computer code contributes to students' conceptual understanding.

While the review has highlighted a pattern of research focused on electronic circuit knowledge (mainly voltage behaviour) and particularly students' misconceptions in science and engineering, little research exists in relation to electronics concepts relative to technology, systems design and what has been termed procedural knowledge (McCormick, 1997) and situated knowledge (McCormick, 2004). Although the misconception approach, which has been shown to emerge largely from multiple choice testing is insightful, its limitations include the inability to reflect students' actual experiences within the learning context since multiple choice testing restricts students' responses to a narrow range of answers, out of context. Providing multiple choice questions also presents the possibility that students who do not have a good understanding guess the answers and therefore the data reveals a speculation, rather than a misconception *per se*. However the use of follow-up interviews is acknowledged in some of the studies reviewed in an attempt to overcome this.

Finally consideration of knowledge types is important to this study which focuses on applied skills learning in relation to technology education (see Introduction, Chapter 1). A common pattern recognises the role of practical experience in the use of visualisation and the development of conceptual understanding. Students' problem solving approaches, particularly those based on heuristic methods, link with and provide a necessary foundation for the applied nature of knowledge and practical experience.

The notion that technology learning is procedural and situated (McCormick, 1997; 2004), and that knowledge can be classified in particular ways, such as emergent (Chi, 2005), leads to alternative ways of designing learning opportunities to allow the procedures to be used and learning to be successful. This has been shown to be successful when a project-based-learning approach is adopted (Barak, 2012), as is typically the case in school-based Design and Technology education. Consequently the technological context leads to the design of research which allows the procedures and emergent nature of students' learning to be observed.

2.8 Research questions

I conclude the literature review by setting out the topics and revised research questions which emerge from the preceding discussion. The review justifies a focus on the following key topics as vehicles for exploring students' conceptual understanding:

- Individual differences in conceptions of electronics knowledge
- Individual differences in student approaches to representation use
- Embodied cognition/knowledge/influence on learning
- Conceptual change/emergent knowledge
- Computer coding as a representation for conceptual understanding
- Metaphor use

At the beginning of the literature review I broadly considered how students use visualisation skills to support their learning of electronics. The *prima facie* (Thomas, 2011a) question is here expanded on the basis of the preceding review of literature. A key question to be answered concerns the individual nature of concept development, and may lead to insights into the appropriate methods deployed in teaching concepts to students. The specific use of visualisation skills, such as ways of using and manipulating imagery is also of interest because these may impact upon learners' successful development. The practical engagement with electronics is of interest because, in line with notions of procedural knowledge, electronics education within the applied skills field (i.e., Design and Technology) has much in common with embodied knowledge conceptions. Metaphor use appears to link many of the concepts reviewed, in particular foundation metaphor and embodied cognition.

The revised questions, which focus on visualisation in terms of observable phenomena, are as follows:

1. How do students describe their use of electronics representations when translating and performing transitions between multiple representations?
2. How do students describe their conceptual understanding of electronics in relation to 'traditional' circuits and 'programmed circuits' and how do these differ?
3. What is the role of practical experience in translating and performing transitions between electronics representations?
4. How do students relate learning to their experiences of translating and performing transitions between electronics representations?

In the following Methodology chapter, I develop an analytical frame on the basis of the questions proposed above and outline the approach taken to data collection.

Chapter 3 Methodology

3.1 Introduction

The research study aims to describe the different ways students use external representations to construct abstract electronics concept understandings. The literature review revealed very little research linking conceptual understanding with external representation use and its operationalisation as a vehicle for learning about electronics. Therefore the study aims to make a contribution to new knowledge in this area through the in-depth study of a group of students following a GCSE Design and Technology Electronic Products course.

Because electronics knowledge is considered to be abstract, that is it cannot be easily related to the physical world (Pule and McCardle, 2010), both learning and teaching are considered to need to draw upon representations of concepts in at least three different ways, including: observable phenomena, symbolic representations and abstract concepts (Johnstone, 1993; Wu et al., 2001). Therefore one aim was to explore the extent to which each of these levels is utilised by students in the development of their conceptual understanding. It was envisaged that knowing more about how students conceive of electronics knowledge could lead to improvements in the way representations are used with students during learning activities. 'Using' a representation is defined as translating (attaching meaning to) and making transitions between (understanding how concepts can be represented differently and moving between these representations). In addition, the usefulness, or otherwise, of computer program code as a vehicle for electronics knowledge development was a key interest in the study, due to its perceived explanatory benefits.

3.2 Rationale and methodological approach

In the natural world, scientists seek to determine 'truth', 'fixed' propositions and explain cause and effect through 'universal empirical generalisations' (Bhaskar and Danermark, 2006: 283). As discussed in the literature review, research into electronics learning and conceptual development has often focused on this approach (Engelhardt and Beichner, 2004; Streveler et al., 2008) and does not account for the learner's individual differences. Conversely in educational research, strong links have been maintained with the traditions of the social sciences (Hitchcock and Hughes, 1995) and therefore has focused on the meaning that brings sense to the social world and individuals' understanding of it (Crotty, 1998). In practice this has created two main paradigms; positivism in the scientific world and interpretivism in the social world. This research study is therefore embedded in the interpretivist paradigm because it seeks to describe and explain meaning within an educational context; that of the students involved and the researcher's value system (Robson, 2011). Bryman (2012, 28) describes interpretivism's distinction as the 'empathetic understanding of human action', which contrasts with positivism's objective of explaining the 'forces [that] act on it'. I was interested to draw out the meaning that individuals attach to their experiences embedded in the learning activities they engage with.

Related to the two paradigms are two ways of representing knowledge. Positivism often involves a significant degree of quantitative data, whereas interpretivism usually involves qualitative data which is considered to 'facilitate reflection, criticism and a more informed view of the educational process' (Hitchcock and Hughes, 1995: 17). Because the study seeks to describe the experiences of students and present their descriptions of conceptual understanding, adopting a qualitative approach was considered to allow the reflection, interpretation and in-depth description necessary to make sense of this social situation. However as noted above, the researcher's position is highlighted during the process of sense making to emphasise credibility and account for researcher subjectivity (McMillan and Schumacher, 2010). I thus adopt a position in this study of pursuing reality and truth related to interpretation, consensus and approximation to experience (discussed more fully in Researcher Positionality, Section 3.4).

One way to conceive of consensus in matters of reality is in terms of 'default positions', that is those understandings held by individuals 'prereflectively' (Searle, 1999: 9) and often collectively (Black, 1973). I begin here with the 'background presupposition' that an external reality exists beyond the individual's representations of that reality which assumes '[that] there is a way that things are' (Searle, 1999: 10). For the purposes of this study, this allows for an assumption in relation to the knowledge underpinning the study, specifically the electronics knowledge at the heart of representations and students' learning. This leads to a categorisation which has been termed 'epistemic objectivity' (*ibid*, 44) and reflects the factual basis of this type of knowledge, in terms of a consensus of acceptance, which is positioned irrespectively of our opinions about it.

On the other hand 'epistemic subjectivity' describes the category of knowledge relative to individual experience, for example thought and feeling (*ibid*), and underpins the type of knowledge of particular interest to this study, namely students' different ways of *conceptualising* electronics knowledge. Subjective experience, however, has been criticised for reducing reality to that which is only in the minds of individuals (Meyer, 2009). Searle (1999, 132) and others (e.g., Fleer and Richardson, 2008) nevertheless overcome this dilemma by suggesting that a 'mechanism' of 'collective acceptance' operates to 'create and maintain a reality' (*ibid*, 131) among individuals and different knowledge frames and is referred to as constructivism (discussed in Section 2.4).

3.3 Developing conceptions of electronics understanding: A pilot study

As outlined in the literature review, a large body of research focuses on electronics knowledge within the scientific domain (Engelhardt and Beichner, 2004), often based on experimental methodology. The experimental approach overlooks the learner's development of meaning in context. These 'pencil and paper' type tests are often conducted in 'laboratories', and adopt the techniques of correlation and factor analysis treating cognitive ability as a 'domain' to be studied using such measurement techniques and represent a positivist stance (Carroll, 1993: 305). This reflects a reductionist, deductive approach which converts variables into measurable units which can be used for hypothesis testing and the confirmation of theory; for example in this context that learners tend to adopt specific electronics knowledge misconceptions (Chen et al., 2013; Chi, 2005). The literature review also reveals a reliance on methods such as pre and post-testing (particularly testing for electronics misconceptions), use of control/experimental groups, and the isolation of ability variables. These approaches attempt to generalise beyond the research situation (often laboratory) and may reveal something about cognitive behaviour, for example electronics misconceptions, under the controlled conditions employed, but lack the meaning attached to individuals' understandings in relation to their 'background knowledge, skills, and cognitive capacities' (Ainsworth, 2006: 193).

In order to explore Paivio's (1986) Dual Coding Theory in a structured and tightly time bound manner, I carried out a pilot study with students who had previously completed the GCSE Design and Technology: Electronics course with the researcher. As noted in the Literature Review (Section 2.5.4), DCT provided a useful starting point for considering learners' use of representations in making inferences and concept development. The pilot study consisted of a range of electronics-based questions (Appendix 1) which aimed to reveal the different ways students use representations within the framework of DCT. As discussed, DCT describes the use of links between and within the category of 'images' and between and within the category of 'words' to develop conceptual understandings. My concern was to reveal how these links were made in relation to electronics specific representations.

The pilot study revealed students' specific use of metaphor and their application of practical experience as strong referents when engaging with the questions. The notion that foundation metaphor (see Section 2.6.1) plays an important role in electronics conceptual understanding was also revealed in the research. However it became apparent that the results did not account for the way metaphor had developed, or how practical experience had supported the learning within an educational setting. Consideration of the educational setting has been noted as important to research concerned with explaining the learning process (Fleer and Richardson, 2008). The exercise therefore raised questions about whether all students would conceptualise their electronics knowledge in this way and how this type of knowledge developed within the specific learning context. Consequently an approach based around testing is not considered to attend to this study's concern to reveal something about the process of learning and how this may be different for different individuals in specific settings.

Consequently, to allow sufficient scope for elaboration and the ability to account for the perceived diversity among participants in the educational setting, an inductive approach was used in the study which aimed to develop explanations of phenomena, and notions of theory, on the basis of rich data in context (Bryman, 2008). Ideas about the design of the research study therefore developed following the pilot study, and a methodological approach was adopted which takes account of the variance in learner ability and learning approach (Dunn, Beaudry and Klavas, 2002). This was considered to avoid any mis-representation of relationships between variables (Thomas, 2009) which may arise from a test-based methodology. In sum the aim was to take account of student diversity, unpredictability and the multivariate nature of interaction and knowledge generation

(Guba and Lincoln, 1989), the meaning of which allows us to make sense of the social world (Crotty, 1998).

Finally it is acknowledged that a significant influence on the development of the methodological approach has been a) the researchers' personal interests, b) what is perceived as possible within the timeframe, research location and alongside a full time occupation and c) what is perceived as useful as a contribution to new knowledge. This represents an approach known philosophically as pragmatism and suggests the research focuses on 'what works', problem solving and using theory where it works (Robson, 2011: 28). The primary concern, alongside the possibility of 'methodological pluralism' (Cameron, 2009: 141), is the collection of evidence to support the research questions posed rather than holding to the doctrines of philosophical paradigms (McMillan and Schumacher, 2010; Morrison, 2007). The following sections therefore document, for transparency purposes, the decision making process which aims to explicate any influence of value system or personal interest (Robson, 2011).

3.4 Researcher positionality

So that my reasoning can be located within the context of the research, I provide a lens in the form of a research stance to explain my positioning (McMillan and Schumacher, 2010). My background in industrial illustration led to teacher training and a degree in Design and Technology. Basic electronics was an integral part of the degree and stimulated an interest in the topic. However the need to teach electronics as a GCSE subject led to the development of a significantly greater depth of knowledge and this was largely self-taught, fuelled by the need to teach the course. On reflection two observations emerge which link with a personal standpoint in relation knowledge and knowing.

Firstly I believe I have adopted a pragmatic approach to knowledge and its development based on the realities of practical needs and outcomes (Johnson and Onwuegbuzie, 2004). My knowledge therefore has developed as a result of different approaches adapted to the needs of the learning task and immediate problem. Secondly my approach to learning about electronics has reinforced a perspective on reality, which I also believe is philosophically grounded in pragmatism as it offers what has been described as a 'useful middle position' (*ibid*, 17). Thus I accept that within certain boundaries (e.g., extremes of temperature) electronics theory is a largely fixed and 'scientific[ally] truth[ful]' phenomenon, as Russell (1961: 789) termed this type of knowledge. Whereas students' learning about this and their subsequent understanding is liable to the 'successive approximations to the truth' which more closely reflect the 'questions of value [and] matters of feeling' associated with learning (*ibid,* 788). This position supports the earlier discussion (Section 3.2) on default positions and an acceptance that there is a way that things are (Searle, 1999).

Pragmatism therefore foregrounds my approach to reasoning about the collected data in the study. My view that multiple perspectives on knowledge are possible is paralleled by a belief that multiple perspectives are also desirable, because in my personal experience of learning, different problems have required different ways of overcoming them (e.g., trial and error, application of theory, testing). My approach to research is therefore framed within a need to conduct the research in practice, and a need to develop, or elaborate on, the perspectives gained from the analysis of data. Ultimately this has a philosophical impact, because the process of judgement making should consider the 'empirical and practical consequences', in this case of the reasoning and outcomes generated from data analysis (Johnson and Onwuegbuzie, 2004: 17). Furthermore this will be highly situated (Lave and Wenger, 1991). The generation of new and situated knowledge is discussed in the Conclusion (Chapter 6) in relation to recommended adjustments to teaching and learning and further research.

3.5 The case study approach to research design

The key aim of the study is to explore the nature of, and variance in, conceptual understanding among students within the context of their learning environment. Case study was chosen as an approach because it allows the in-depth focus on the students and the learning environment. The study adopts a cross-comparative case study approach (Bryman, 2008) and follows a sequential multi-strategy design (Robson, 2011) which mixes methods (Teddlie and Tashakkori, 2009). This design is considered to provide the opportunity to compare data across participants, while drawing on a sequence of data collection points, which it was hoped would reveal a picture of the learning within the educational context. Thus the study is interpretivist in nature and aims to remain close to the research setting and explore meaning using largely qualitative techniques.

The choice of case study as an approach to researching conceptual understanding was made on the basis of the 'exemplary knowledge' which may be obtained from this method (Thomas, 2011a: 211). Case study has been described as 'the study of the particular' (Robson, 2011: 137) or 'the phenomenon for which evidence is collected' (VanWynsberghe et al., 2007: 81). Here, this is described as the study of specific ways of translating and making transitions between multiple representations. However case study has been criticised on the basis that either the phenomenon under study or focus of study is often vague (Bryman, 2008). Criticisms also question the scientific basis of case study and, as Yin (1981, 58) points out, often conflate the 'strategy' with qualitative research *per se*. In this study it is hoped pitfalls of this kind are avoided by adopting a systematic approach, clearly presenting the research and adopting a clear conceptual framework (Yin, 1981), from which context specific knowledge can be generated from the unit of analysis.

To support the claim to case study, Bryman (2008, 54) asserts that the 'object of interest' or 'unit of analysis' be distinguished through a 'concern to elucidate the unique features of the case' and 'exemplify' the broader category of, in this instance, differentiated cognition and offer the suitable context of electronics knowledge to support research questions. In addition exemplification may also be strengthened by connecting the research with its spatial and temporal 'boundness' (VanWynsberghe et al., 2007: 84) and identifying how the unit of analysis is distinct from those that fall outside of the bounds (Yin, 2014). Identifying clearly what is and is not temporally and spatially in-bounds therefore allows for the comparison with other distinct cases (Yin, 2014), such as those students who participated in the Pilot Study and those highlighted during the literature review. Thus in this instance the spatial bounds are characterised by the types of representations used by students in the context (i.e., circuit diagrams, symbols, the department and teaching rooms) and the temporal bounds are characterised by the GCSE course start/end dates which reflect the period of learning of interest to this study (i.e., September 2013-April 2015).

A particularly useful conception of case study is described by Thomas (2011a: 14) as the combination of a ‘subject’ (in this case Y10 Design and Technology students’ conceptual understanding) and an ‘analytical frame’ or ‘object’ (here the use of representations by Y10 Design and Technology students to support conceptual understanding). As Thomas (2011a) suggests, a case study, by definition, has to be a case *of* something. This study therefore is a case of a class of GCSE students’ use of representations to support conceptual understanding in GCSE electronics education. This contrasts with other cases of representation use, highlighted in the literature review, that for example relate visualisation to manipulating spatial forms in engineering (Akasah and Alias, 2010), or exploring spatial grouping in mathematics (Bobis, 2008).

The research study emerged from my observations of and interactions with students in my lessons and a curiosity about how the presentation of learning material might be adjusted to suit a variety of possible approaches to learning. It is therefore an instrumental study carried out with a specific intention in mind (Thomas, 2011a) and provides the key qualities of ‘substance’ (what it’s about) and appropriate how and why questions which can be shown to evolve from the literature (Yin, 2014: 11). The study aims to explore students’ conceptual understanding, partly (although see discussion on phronesis below) ‘testing a theory’ (or drawing on a number of theories explained below in the Analytic Frame and Unit of Analysis sections) and partly ‘building a theory’ (considering the extent to which the process of computer coding/sentential representation may support conceptual understanding of electronics) (Thomas, 2011a: 111). Inherent is the interpretative nature of the study which will draw upon a conceptual framework which may be ‘held, tested and then discarded or retained’ as appropriate (Thomas, 2011a: 126). The intention therefore is to explore and explain using the predominantly how and why questions emergent from the literature review.

The process and structure of the study focuses on multiple cases (also called comparative case or cross-case analysis), and adopts a sequential design for data collection. Therefore the comparison of cases forms the emphasis of the analysis which seeks to highlight the similarities and differences between participants (Thomas, 2011a). Bryman (2008, 58) suggests this allows us to ‘understand social phenomenon better’ through ‘more meaningfully contrasting cases or situations’. In this study, therefore, a comparison between students’ different approaches to knowledge construction.

As Thomas (2011a) points out, case studies do not allow for generalisation. The alternative is to conceive of case study outcomes in terms of the 'exemplary knowledge' they provide (Thomas, 2011a: 211) and '[the] fluid understanding explicitly or tacitly recognising the complexity and frailty of the generalisations we can make about human interrelationships', sometimes referred to as 'abduction' (*ibid,* 212). Therefore rather than attempt to emerge with a 'theory', Thomas (2011b, 30) describes 'phronesis', the knowledge that can be gained from practical, personal experience in context. Validation therefore comes from a connection between the subject and context and the researcher's experience, supporting an approach which embraces 'wholeness' in case study research (Thomas, 2011a: 50). Yin (2014) provides a taxonomy consisting of the five components: case study questions, propositions, units of analysis, logic linking data to propositions and criteria for interpreting the findings which supports the approach emphasising wholeness, the application of which are in this study explained in Quality and Trustworthiness (Section 3.6.7) and Discussion chapter.

Revealing exemplary knowledge in this study has drawn upon the researchers own class of students. It is accepted that this presents the potential for bias and raises the question of trustworthiness of the research. However adopting an insider researcher approach has enabled the study of a group of students in a way which would otherwise be difficult to achieve, since a) the study evolved from issues presented to the researcher during his teaching (see Introduction, Chapter 1), b) the study took place as a part of, and integral to, the students' curriculum therefore linked to context and c) interview discussions could be developed on the basis of the researchers' knowledge of the students' experiences on the course. In addition the students involved were well informed 15-16 year olds (also see Ethics, Section 3.9), who were very able to understand the research information presented to them and it was considered (and thoroughly explained to participants) that participation in the study would have no effect on the performance of participants or the outcome of their GCSE qualification.

The outcomes from the approach are therefore considered to provide unique insights which may subsequently benefit and improve the researcher's teaching of electronics concepts and through others' acts of relatability (Lincoln and Guba, 1985), transfer to a wider audience. Nevertheless to overcome the issues associated with bias and trustworthiness, the study outlines in Quality and Trustworthiness below (Section 3.6.7) the steps taken to minimise bias using quality criteria and the Ethics Section (3.9) details the approach taken to fully informing participants and their parents of the research intentions.

3.5.1 Analytic frame and the unit of analysis

The unit of analysis (Bryman, 2008; VanWynsberghe 2007) or object (Thomas, 2011a) has been emphasised as a necessary feature of case study research, providing 'the in-depth analysis of a single entity' (McMillan and Schumacher, 2010: 344). VanWynsberghe (2007, 83) suggest a 'prototype view' of case study which provides seven common features that support the description of and relationship between the unit of analysis and case. These are detailed in Table 1 below, with their application in this study explained.

Common Feature	**Application**
Small sample size	▪ One class (n=17), reduced to a focus group (n=10)
Contextual detail	▪ Case embedded in the relevant subject, teaching scheme and teaching time frame
Natural settings	▪ Case focuses on normal lessons, at their normal time, within the scheme of work
Boundedness	▪ Case focuses on the use of representations related to GCSE electronics course and one class of students only ▪ Case focuses on translation and transition between representation types
Generation of working (surfacing) hypotheses	▪ Working hypothesis that learners engage with phenomena at three levels: observable, symbolic and abstract ▪ Emergence of focus on learners' conceptual change
Multiple data sources	▪ Observation, dialogue, documents, interview transcripts
Extendability (particularly of readers' experience)	▪ Insight beyond that normally experienced during teaching

Table 1: Application of common features found in case study research adapted from VanWynsberghe (2007, 83)

Thus attending to these features is recommended to overcome the difficulty of linking the unit of analysis and case and helps to highlight their specific relationship, supporting validity in case study research. Here the focus is on the relationship between conceptions of electronics knowledge (the case) and the different methods applied to translate and perform transitions between representations (the unit of analysis). VanWynsberghe (2007, 88) suggest that in addition any domain assumptions are explained to support the 'unique understanding' gained from these relationships (see Domain Assumptions below). Similarly Yin (2014, 30) notes the importance of highlighting 'directional propositions'. In this case the application of supporting theories, the focus on any qualitative differences in thinking about analogue and digital circuit types, and computer programming as analytical starting points and foci. These considerations are fully explained in Analytical Procedure (Section 3.7).

3.5.2 Participants

The research was conducted at a Boy's selective 11-18 Grammar School in the south of England, as described in the Introduction. Participants were drawn from the researcher's GCSE Design and Technology: Electronic Products class. Seventeen students participated in the lesson tasks and on the basis of consents received, ten students participated in the interviews. Overall, across the electronics group, participants' YELLIS (Year Eleven Information System) scores were in the range 91-134 (16 of 17 students were in the range 114-134) with 100 representing the national average. Those participating in the interviews were in the range 114-134, although 80% of these (n=8) were in the range 126-134. Therefore a majority of those participating in the interviews would be considered to be the higher performing students (in relation to the type of tasks performed on a cognitive ability test). Participants had all received the course of study outlined below in Table 2, prior to engaging with this research study.

Date	Topic	Outline
September 2013	▪ Electronics basics (mainly analogue, varying voltages, timing, RC Networks) ▪ Voltage/current behaviour ▪ Prototype board use ▪ Components	Introduction to electronics basics and analogue circuit behaviour Introduce prototyping method

	▪ RC Networks (timing theory)	
October 2013	▪ Timing with electronics (555 timer-astable/monostable) ▪ Joining components (e.g., LEDs to wires, PCB population & assembly)	Begin a 'mainly make' project based on timing theory and basics
November 2013	▪ FETs, diodes, relays ▪ Practical manufacture of timer ▪ Materials (timbers, metals, polymers)	Continue theoretical coverage of GCSE specification alongside manufacture of timer
December 2013	▪ CAD/CAM (vinyl embellishments) ▪ Sequential counting (4017b) intro	Complete timer manufacture Introduce new component (4017b) and electronics for counting purposes
January 2014	▪ Sequential counting (4017b) prototyping ▪ Analogue digital dice (4017b) ▪ Sequential counting (4026b) ▪ Binary coded decimal (BCD) ▪ BCD prototype & test ▪ Writing up counting module	Electronics for counting using various electronics systems Introduction to digital electronics including binary/binary coded decimal theory Produce a mini folio of work for this section
February 2014	▪ Programming using flow charts (traffic lights) ▪ Programming exercises (project boards) ▪ Intro to digital dice manufacture ▪ Manufacturing digital dice	Introduction to programming using flow charts Introduction to BASIC programming language and programming project boards Begin 'Digital Dice' project
March 2014	▪ Design question (input) ▪ Design question (peer assessment exercise) ▪ Flow diagram to code ▪ Operational Amplifiers (Op Amps)	Focus on a significant section of the GCSE written paper-'design question' (20% of paper) Cover Op Amps theory
April 2014	▪ Op Amps (continued) ▪ Digital dice manufacture ▪ Programming folio	Manufacture of digital dice Continue folio

	▪ Folio completion	
May 2014	▪ Exam question work (ICT in manufacture booklet) ▪ Multimeters	Theoretical coverage of GCSE specification Multimeters exercise
June 2014	▪ Past paper (Year 10 exam) ▪ Feedback on exam ▪ Participant information sheet (17th June) ▪ Logic gates (types, combining) ▪ Moral & social issues ▪ GCSE Coursework (project outlines)	Year 10 exam Introduction to research study and discussion of participant info sheet Theoretical coverage of logic gates and social/moral section of GCSE specification
July 2014	▪ Data collection 1 (1st July) ▪ Data collection 2 (2nd July) ▪ GCSE Coursework (until end of term)	Study data collection alongside GCSE coursework introduction

Table 2: Outline of participants' actual learning experience during Year 10 (from teacher/researcher's lesson planner)

3.6 Research methods

3.6.1 Outline

The case study was organised around two main phases so that data could be obtained in relation to students' key learning experiences and the application of methods which were designed to explore learning at key points in the process. The methods adapt from science those used by Wu et al. (2001), who explored the understanding of chemical representations in a classroom setting. Wu et al.'s (2001) approach was influential because it included the combination of observation of students' task completion, analysis of artefacts produced and subsequent individual interviews. In particular, Wu et al.'s (2001) use of video to record on-screen computer simulations influenced my decision to use CamStudio (2013) to record participants' on-screen activity during the lessons (explained below). This allowed subsequent in-depth analysis of participants' application during the tasks.

Students engaged in key learning activities which were tied to previous learning about logic gates and computer programming (February/June 2014, Table 2) and which formed a part of the GCSE Electronics (Edexcel, 2009) Specification requirements. The learning activities were designed to occur over a two consecutive-lesson period which provided an initial focus for data collection. Activities were designed to allow students to apply their previous learning during the creation of electronic circuits (task 2) and computer programs (task 3) using visualisation skills such as the translation of and transition between electronics representations. The lessons also foregrounded the interview phase, providing a focus for the questions and discussion with students.

In phase one students engaged with three problem solving tasks, the purpose of which was to observe, discuss with students and collate documentary evidence about, their different methods of using representations to 1) construct an electronic circuit and 2) create a computer program to represent an electronic circuit. Students were randomly divided into 'analogue' (Group A) and 'digital' (Group B) groups, using a random number table (McMillan and Schumacher, 2010: 482). This provided the opportunity to explore the directional proposition (Yin, 2014) that thinking about electronics in terms of analogue and digital circuit types would reveal qualitative differences in understanding. Therefore this approach provided a starting point and added dimension to the analysis of findings (see previous discussion on analogue/digital conceptions, Section 2.2.2). As individual problem solving was carried out using a networked computer in close physical proximity to other students, this designation carried the additional advantage that students could not simply copy the work of their neighbour. Therefore future interview discussions were considered to be based upon a genuine engagement with the lesson material.

In phase two semi-structured interviews were carried out following the lessons with ten students who consented to participation. The purpose of the interviews was to explore in-depth students' experiences of the problem solving lessons and through their descriptions of electronics application the nature of their conceptual understandings. It was envisaged that a descriptive approach would reveal students' individual differences and the basis of concepts (e.g., metaphorical, embodied) more fully than an alternative experimental approach. Following Wu et al.'s (2001) approach the interview strategy 1) avoided mentioning electronics concepts unless raised by the student, 2) any responses deemed to be unclear were questioned further and 3) emerging ideas, meanings or explanations were explored further to encourage student discussion.

3.6.2 Lesson design

Data collection began with two lessons which engaged students in electronics-based problem solving activities (Appendix 3). The activities drew on three key conceptions emergent from the literature as follows: that translating and making transitions between representations can enhance learning (Ainsworth, 2008), that the act of creating a representation enhances the learning process by combining the generated with the given representations (van Meter and Garner, 2005) and that a qualitative difference exists between engagement with diagrammatic representations and sentential representations (Larkin and Simon, 1987).

Because specialised knowledge is needed to engage with electronics problems, the study focuses on the researcher's own class of GCSE Design and Technology: Electronic Products students who were considered able to meet this requirement. Engagement required the use of worksheets to guide each activity, which included instructions, diagrams and opportunities to record outcomes (Appendix 3). Activities were grounded in the Edexcel (2009) GCSE Design and Technology: Electronics Specification. This brought the additional benefit of linking the activities to students' normal curriculum, thus strengthening the case in context.

Students began lesson one working in pairs on an image/word matching task developed from Paivio's (1986) Dual Coding Theory (explained in Section 2.5.4). This enabled data collection in relation to both student dialogue and the use of electronics based images and words to aid concept forming. The images and words were each printed on a self-adhesive address label which allowed them to be moved around and eventually stuck to the worksheet when positions were established. The aim was to explore students' referential connections between verbal and nonverbal stimuli following Paivio's (1986) dual coding theory. The activity also considers Wu et al.'s (2001) symbolic level of representation and through analysis how this might be different to micro or macroscopic dimensions, in relation to the other tasks.

Lesson	Task	Theoretical Link
Lesson 1: Task 1	Paired image/word task Identification of themes Identification of underlying concepts	Dual coding theory (Paivio, 1986)-explores image/word relationships Levels of representation (Wu et al., 2001)-explores symbolic level of representation
Task 2	Circuit construction from representations provided	Translation/transition (Ainsworth, 2006)-explores approaches to translation/transition Levels of representation/transition (Johnstone, 1993; Wu et al., 2001)-explores how levels of representation support conceptual understanding
Lesson 2: Task 1	Program construction from diagram/representations provided	Diagrammatic/sentential representation (Larkin and Simon, 1987)-explores the relative merits of employing graphical/written methods to represent electronics knowledge/concepts

Table 3: Overview of lessons, tasks and theoretical links

Phase two of lesson one then presented students individually with a variety of representations and required the construction of a circuit diagram using the software Circuit Wizard (New Wave Concepts, 2012). To prevent students simply copying one another (as the ICT equipment is physically closely located) students were randomly assigned, alphabetically by name, to one of two tasks called ‘Circuit A’ and ‘Circuit B’, using a random number table (McMillan and Schumacher, 2010: 482). Each student therefore viewed a different task to theirs. In addition, insight from the feasibility study led to the application of the further categorisation of analogue and digital circuit types. This approach is supported by the ‘logic of comparison’ when applied to social phenomena through ‘two or more meaningfully contrasting cases or situations’ (Bryman, 2008: 72).

Consequently this activity explored approaches to representation combination and transitions between them. The activity encouraged engagement with the symbolic level as a starting point for evidencing conceptual understandings. This provided a basis from which to design interview questions (discussed below) and explore students’ conceptual (microscopic) level of understanding at interview. Building and virtually testing the circuits also drew on the outcome of the feasibility study which suggested a strong cognitive dependence on practical engagement. An assumption is made here that circuit construction on-screen is representative of practical engagement, although acknowledged as lacking in some areas of sensory feedback (e.g., tactile).

Developing lesson 1 activities, and again exploiting the more meaningful comparative case (Bryman, 2008), lesson 2 also drew on transition ability requiring students to use circuit diagrams to build computer programs. Students used a variety of representations to build the program which was required to perform the same function as the circuit provided using the software 'PICAXE Programming Editor 5' (Revolution Education, 1996-2013). This transition activity explored an insight gained during the Pilot Study which revealed that some students draw on specific knowledge from other subject areas (computing and program coding) to support their conceptual understanding of electronics.

3.6.3 Observation of lessons

Lesson observation was designed with a formal approach to the dimensions of structure and the role of participation in the observations, as described by Robson (2011). A structured approach was chosen to a) provide a guide for both observers that allowed the subsequent triangulation of specific responses to questions, or 'low-inference' recordings (McMillan and Schumacher, 2010: 209), b) to explore specific theoretical aspects relating to representation use and c) to support and guide the researcher who was also teaching the lesson. The structure involved a set of questions to ask students (Appendix 4) and a plan detailing which observer would speak with each pair of students (Task 1, Lesson 1) or individual student (Task 2, Lesson 1; Task 1, Lesson 2).

The role of 'participant-as-observer' (Robson, 2011: 322) was adopted by both the researcher and an additional observer. This status, as described by Robson (2011), best describes the roles of the observers which were fully known to participants. However the second observer, due to the more detached nature of engagement, is more accurately represented by Robson's (2011, 323) 'marginal participant' who adopted a more 'passive' approach alongside the researcher who actively conducted the lessons.

In practice the role of observer, particularly for the teacher researcher who undertook to manage the 'considerable burden' (Robson, 2011: 320) presented by teaching and researching, fell somewhere on the 'continuum of observation and participation' described by Thomas (2009, 187) (The dual role was not an easy one and comment on the process was recorded in the Research Journal, Journal Summary, Appendix 5). This emphasises the link between approach and fitness for purpose, sometimes called 'salient observation' (McMillan and Schumacher, 2010: 352). Consequently the purpose of 'structure', mainly prepared questions, was a starting point which allowed for elaboration where necessary in the classroom. The questions used reflect a desire to explore students' engagement with transition tasks and were of the 'what is happening here?' and 'what behaviours are repetitive and irregular?' type (McMillan and Schumacher, 2010: 353).

To strengthen data triangulation opportunities, screen capture software was used to record students' work as it evolved on screen in one of the tasks (see Analysis of Results, Section 4.6). This utilised 'CamStudio' software (CamStudio, 2013) and was designed to support the capture of phenomena not apparent to observers in the lesson. Similarly audio recording was used to collect dialogue during the lesson activities using the Apple iPad version of 'My Memos' (MacyMind, 2013). The dialogue was then transcribed, uploaded to QSR International's 'NVivo 10' (QSRInternational, 2012) and analysed using this software (see Analytical Framework below). To highlight potential researcher bias, a research journal was kept to record the 'self in research' (Journal Summary, Appendix 5) and reflect on observations during the fieldwork stage (McMillan and Schumacher, 2010: 354).

3.6.4 Interview

A useful distinction has been made between 'semi-structured interview' and 'interview schedule' and recommendation for selection indicated on the basis of the overall study methodology (Thomas, 2009: 164). As detailed description is the aim of this study and this was most likely to evolve from students' talk about their lesson experiences, an interview schedule (Appendix 6) based on aide-memoires was used to encourage talk and avoid the 'dichotomous-response questions' often associated with structured interviewing approaches (McMillan and Schumacher, 2010: 357). Therefore the schedule permitted adjustments to individual interviews as a more valid approach to qualitative research (*ibid*). In addition, care was taken to avoid framing questions in direct reference to the main research question (Silverman, 2013).

Participants were purposively sampled from the electronics class (n=17), however selection was restricted to the students who consented to participation in the interview (n=10). Interviews were recorded using the Apple iPad version of 'My Memos' (MacyMind, 2013), then emailed from the device for backup and transcription. The benefits of digital recording have been noted as: excellent sound quality, transcription/playback ease and recording/data longevity (Bryman, 2008). Transcription utilised Windows Media Player (Microsoft, 2009) and Microsoft Word (Microsoft, 2013) as methods to play back recordings and transcribe dialogue.

3.6.5 Documentary evidence

Students' worksheets were collected from the lesson tasks to facilitate subsequent analysis. The paired matching task generated the image/word pairings, accompanied by written responses to the questions posed on the worksheet. The worksheets from transition tasks also provided responses to the questions posed during task 2, lesson 1 and task 1 lesson 2. It has been suggested that these artefacts provide a tangible example of, in this case, experiences, actions and values and offer opportunities to interpret, corroborate and triangulate with other data types, such as student dialogue and interviews (McMillan and Schumacher, 2010).

To support the aim to elaborate upon the contextual perspective and spatial and temporal bounds of the case, several other documents were collected which allowed an improved in-depth analysis. These included students' YELLIS (Year Eleven Information System) test scores, the teachers' (and therefore researcher's) assessment records and the overview of lessons for the year 2013-2014 (Table 2). However some caution has been advised when using documents not directly associated with the research context, as the degree of accuracy and potential for bias may present difficulties in their use (Robson, 2011). Table 4 shows the range of documents used and their link between context and inter-documentary significance. The use of the additional documents was considered justified in supporting inferences, where necessary, about students' responses on worksheets and in interviews. The documents were temporally bounded (taken from the GCSE course period) and allowed inferences to be checked for quality and triangulation purposes.

Document	Contextual Link	Inter-documentary Significance
Record of teaching & learning	Records temporal aspects of student engagement with learning	Allows cross-check with topics, when they were taught and their sequence of delivery
YELLIS test result	Provides an overview of cognitive ability related to verbal, maths and nonverbal reasoning	Assists in inferring students' learning approaches
Teacher's assessment record	Provides an overview of attainment during GCSE course	Assists in inferring students' learning approaches

Table 4: Contextualisation and significance of documentary evidence

Further discussion on validity and trustworthiness is provided where relevant in Analytical Procedure below.

3.6.6 Domain assumptions

Table 5 outlines the domain assumptions underpinning the research study. These include considerations of assumptions about interactions within the social context being explored and the nature of phenomena within the social context (Bryman, 2012).

Domain Assumption	Application in Research
Electronics knowledge can be conceived in terms of practical application, rather than 'scientific' theory (Hiley, et al., 2008)	▪ Contributes to underlying conceptual framework, methodology, method and analytical framework
Wu et al.'s (2001) levels of representation (from Chemistry) apply to electronics education	▪ Used as a basis for considering an analytical framework and lesson/task design
Ainsworth's (2006) representation principles (from ICT) apply to electronics education	▪ Used as a basis for considering an analytical framework and lesson/task design
Analogue/digital conceptions (Duncan, 1997) represent a distinct categorisation of electronics knowledge for students	▪ Lesson task design, interview questions and analytical framework
Participants would understand the term 'research'	▪ Clear verbal explanation and written explanation of project aims on participant information sheet ▪ Understanding supports ethical approach
Participants' would be able to recollect their electronics knowledge	▪ In planning, delivering lesson tasks and worksheets

Participants' would be able to do the tasks presented	▪ In planning, delivering lesson tasks and worksheets
Virtual (on-screen) circuit building *adequately* replicates circuit prototyping in the 'real world', for the purposes of this study	▪ Circuit Wizard software was used to replicate prototyping boards in the study
Participants give truthful accounts during interview	▪ Acceptance of students' answers and consideration
Sharing the 'right' answer has not occurred between interviews	▪ Heightened awareness of possible collaboration between interviews

Table 5: Domain assumptions supporting the research study

3.6.7 Quality and trustworthiness

The use of terms such as reliability, validity and truth have been linked with the world of natural science research, however their application in social research has been questioned, with a preference for credibility and plausibility instead advanced as the conditions for quality research (Corbin and Strauss, 2008). To achieve these aims, the purpose of the research has been clearly and consistently linked with the methodology and final analysis, and the research adopts an empathetic attitude towards the participants and their engagement with the study (*ibid*). Within the case study approach the quality of inferences has been maintained by continually relating the conceptual framework, the analytical framework, data analysis and researcher experiences as the research has developed (Teddlie and Tashakkori, 2009). The process of judgement making centred on a reflexive stance, taking into account researcher positionality (Smith and Deemer, 2000) and as suggested by Corbin and Strauss (2008), a particularly detailed reflexive journal (Journal Summary, Appendix 5) was kept during the data analysis stage of the research to note research conduct, support depth of thinking and decision making generated from the findings.

The credibility and plausibility of themes revealed by the constant comparison of interview transcripts (see Section 3.8) and the conclusions drawn from this process form one specific consideration in respect to trustworthiness, as they are largely researcher driven and the use of themes has a direct association with the eventual research claims. The research journal was used to make regular records of thoughts and decisions in relation to the analysis of data (see Journal Summary, Appendix 5). It was hoped therefore that the reflexive journal would demonstrate rigour and transparency during this process, explain inference processes during data analysis and ultimately improve quality and trustworthiness.

3.6.8 Quality criteria

Glaser and Strauss (1967, 7), within their grounded theory method, appeal against the ‘verification rhetoric’ when discussing what seems more recently to be an approach to qualitative research described as promoting quality criteria, rather than validatory and generalisable aims (Lincoln and Guba, 1985; McMillan and Schumacher, 2010). Discussions around trustworthiness highlight the tacit nature of knowledge (i.e., knowledge gained through the process of conducting research in the context) generation in the type of research reported here (Anderson, 2002; Thomas, 2011a) and this has itself been promoted as a legitimising goal alongside the researcher’s and organisation’s learning benefits (Anderson, 2002; Morrison, 2007) and improvements to theoretical understanding and the researcher’s practice (Zeichner, 2007), as contributors towards ‘validation’. Although the caveats warning against over-reliance on criteria use in social science research are noted (Thomas, 2011a; Hammersley, 2005), the application of clear quality criteria (Smith and Deemer, 2000), alongside triangulation procedures (Anderson, 2002) and reflexivity (Morrison, 2007) have been emphasised as significant contributors to knowledge generation. Drawing on similar suggestions for quality criteria provided by Hammersley (2005), Thomas (2011a) and Yin (2014), I adopt here the following taxonomy and outline how this has been applied to the study (Table 6).

Quality Criteria	Application	Phase of Research
The Clarity of writing	▪ Consistent use of electronics terms ▪ Terms cross referenced with authoritative electronics texts ▪ Glossary provided to support these ▪ Care taken to construct a coherent narrative	▪ Introduction ▪ Literature review ▪ Methodology ▪ Analysis ▪ Discussion ▪ Conclusion
The problem or question being addressed	▪ Introduction outlines problem/background ▪ Rationale links with external theory and problem/background	▪ Introduction ▪ Literature review/question generation
The methods used	▪ Methods (and rejected alternatives) evolved from consideration of problem, background, literature & context ▪ Methods link with expected effectiveness of case foci	▪ Planning ▪ Methodology
The account of the research process and researcher	▪ Reflexive considerations of process and researcher's position link with researcher's journal records (Appendix 5)	▪ Analysis, discussion, conclusion sections
The formulation of the main claims	▪ Main claims presented as clearly defined statements ▪ Consideration of rival explanations made clear ▪ Nature of claims linked with desire to describe and explain	▪ Analysis, discussion, conclusion sections

Table 6: Quality criteria applied in the study adapted from Thomas (2011a, 66-67) and Yin (2014, 45)

Yin (2014), adopting a more technical stance than Hammersley (2005) and Thomas (2011a), promotes the use of logical tests and design tests to judge the quality of research, through the use of construct, internal and external validity and reliability. This conception parallels the process presented in Table 6, but includes identification of the relevant phase of use of each 'tactic' (Yin, 2014: 45). Table 6 includes the addition of the identification of the phases of research where quality criterion has been applied, to enable their location and verification. Following Thomas (2011a, 67) however, I also evaluate the study in the Conclusion chapter using the three questions as follows:

1. How well has the case been chosen?
2. How well has the context for the study been explained and justified?
3. How well have arguments been made? Have rival explanations for the same kind of observation been explored?

3.6.9 Transferability

As it will not be possible to generalise from a study such as this (Thomas, 2011a), the quality criteria will form an invaluable part of the trustworthiness of the study (Anderson, Herr and Nihlen, 2007) and support its transferability. Lincoln and Guba (1985, 297) suggest that this is dependent on a correspondence between the 'sending and receiving contexts' and a responsibility on the receiving party for transfer, as applicable contexts cannot be known by the sender. In addition the provision of 'sufficient descriptive data' has been noted as important when applying research to new situations and assessing its credibility (*ibid,* 298). Therefore a concern within social research has focused on the extent to which research outcomes transfer to other situations and its relatability (Scott and Morrison, 2006). Rather than provide generalisable outcomes, particularly within mixed methods designs, 'inference transferability' has been used to describe the process of inference making between data types (Teddlie and Tashakkori, 2009). In this study the conclusion section links the main claims with their perceived ability to transfer to other situations.

3.6.10 Triangulation

Triangulation has been defined as 'the convergence of data collected from different sources, to determine the consistency of a finding' (Yin, 2014: 241). It has been described as 'an essential prerequisite for using a case study approach' (Thomas, 2011a: 68) and important 'for assessing and improving the quality of (data and) inferences' (Teddlie and Tashakkori, 2009: 297).

Sagor (2000) offers a useful triangulation matrix which has been adapted here (Table 7) to show how cross-referencing connects research questions with data sources. Data included researcher and observer field notes, lesson documents, computer screen recordings, interview transcripts, GCSE course year plan, participants' GCSE course assessments and participants' GCSE exam results. Triangulation was used to confirm or strengthen inferences during the analysis of findings and these connections are clearly explained in the discussion of findings (Chapter 4).

Study Qstn.	Research Focus	Data Source 1	Data Source 2	Data Source 3	Triangulation Focus
Q1	How do students describe their use of electronics representations when translating and performing transitions between multiple representation types?	Observation dialogue	Observation notes- participant/ non participant observer	Interview transcripts	Comparing/ contrasting responses to check consistency of descriptions
Q2	How do students describe their conceptual understanding (e.g., through metaphors) of electronics in relation to 'traditional' circuits and 'programmed circuits' and how do these differ?	Interview transcripts Participant observer	Lesson worksheets Non participant observer		Compare/ contrast students' perspectives Compare/ contrast level of conceptual understanding, in relation to traditional and computer programming representations, from the perspective of teacher, observer and students' outcomes
Q3	What is the role of practical experience in translating and performing transitions between electronics representations ?	Interview transcripts	Screen recordings showing practical application	Practical/ worksheet outcomes	Comparing/ contrasting descriptions of practical experiences

Q4	How do students relate learning to their experiences of translating and performing transitions between electronics representations?	Interview transcripts	Lesson outcomes/ worksheets/ on-screen evidence		How do descriptions of learning compare with their actual outcomes?

Table 7: Triangulation matrix adapted from Sagor (2000)

3.7 Analytical procedure: Theoretical considerations

Yin (2014: 38) suggests that theories should act as 'theoretical propositions' which provide links with the literature and starting points for explaining various propositions in relation to methodological approach and data collection and analysis. A number of theoretical models have been adopted as a basis for the analytical framework in this study, which emerged as a result of the foregoing literature review. These include theories surrounding Dual Coding Theory (Paivio, 1986), diagrammatic/sentential representation (Larkin and Simon, 1987) metaphor use (Lakoff and Johnson, 1980; Paivio and Begg, 1981), the componential levels of representation (from chemistry) microscopic, macroscopic and symbolic representational dimensions (Johnstone, 1993; Wu et al., 2001) and Bruner's (1977) taxonomy of learning. These have supported the development of the analytic frame and are discussed in more detail below.

3.7.1 Dual coding theory

Dual Coding Theory (see Literature Review, Section 2.5.4) provides a method to analyse representation use and explore how students access the verbal and nonverbal modes of information presented. The theory suggests that associative (within mode, i.e., within the word or image category) and referential (between mode, i.e., between word and image categories) connections support thinking and learning with words and images and mnemonic development. The pilot study explained earlier for example (Section 3.3), revealed a preference for the use of the verbal mode coupled with imagery based on sensori-motor experience, among the participants involved. Therefore exploration of word and image use provides a specific approach to analysing students' conceptual thinking through word/image combinations and descriptions, which may lead to an assessment of their efficacy to support electronics knowledge in the form of conceptual understanding. Dual coding theory also links with simultaneous/synchronous approaches (Larkin and Simon, 1987) to interpreting representations such as diagrams, words and descriptions, discussed below.

3.7.2 Diagrammatic/sentential representation

Larkin and Simon's (1987) contention that diagrams provide simultaneous and faster access to information through spatially located information and that words provide sequential access to information which may be slower, supports a theoretically grounded method with which to explore students' cognitive behaviour in this context. As an approach to analysis, it supports in part the aim of determining whether computer programming may be a beneficial process in assisting concept development, alongside circuit diagrams, since as noted earlier, circumstantial evidence (from conversations with students) suggested an explanatory role for the process. As an analytical framework, Larkin and Simon's (1987) theory supported the analysis of interview transcripts and the development of themes during the constant comparison exercise. Thus particular attention was directed towards students' responses with respect to how they described representation use in relation to simultaneous and sequential information types.

3.7.3 Metaphor

Specific metaphor provides a method to explore the ways abstract concepts are represented by images and words. The feasibility study was instrumental in highlighting the use of foundation metaphor (e.g., related to dimension such as 'high' voltage), which in turn links with the engagement and experiences developed through the senses (Lakoff and Johnson, 1980; Ritchie, 2013). Other specific metaphor may illuminate the nature of abstract concepts, such as the common hydraulic analogy which uses the metaphorical term 'flowing' to describe voltage behaviour. Exploring metaphor may reveal both their structure and origin and any individual differences in concepts held therein.

3.7.4 Levels of representation

The three levels of representation noted by Wu et al. (2001) are here considered to be encapsulated by the previous three approaches to analysis (i.e., Dual Coding Theory, diagrammatic/sentential representation, metaphor), in that to illuminate any one of the three levels (observable, abstract, symbolic), an exploration using one or more of the above approaches may be necessary. As Wu et al. (2001) note, attending to the three levels during learning and teaching may enhance conceptual understanding. Relating this to electronics, the study applies this principle to the present context using the taxonomy to categorise representations, analyse their use and enable discussion about students' conceptual thinking during data collection and analysis. The analytical procedure is discussed fully below.

3.7.5 Bruner's taxonomy

Bruner's (1977) learning taxonomy (discussed in Literature Review, Section 2.4) provides a practical foundation for considering how students may have approached their learning and the development of concepts. The three stage taxonomy (new knowledge, manipulation, verify with existing knowledge for plausibility) was used as a basis for analysing interview transcripts and subsequently considering the sequence of events leading to learning and concept forming. Particular attention was directed towards descriptions which revealed these stages and were recorded in the form of themes during the constant comparison of interview transcripts.

3.8 Analytical procedure

The analytical procedure is organised to follow the sequential order of data collection and subsequent recording of results (Findings and Analysis, Chapter 4). The analysis follows an approach originating in the work of Glaser and Strauss (1967), where the constant comparison of data draws out themes from recursive reading, which are then organised around a schemata of categories. The schemata of categories however both emerge from the data and relate to Wu et al.'s (2001) levels of representing phenomena (i.e., observable, symbolic and abstract). The constant comparison procedure described by Thomas (1992, 2009) was adopted as it provided a clear approach to the analysis and presentation of results. Once the categories had been established at each stage, concept maps, developed from Thomas (1992, 2009) were created to present the results and enable the classification of the themes and categories. The close involvement of the researcher was acknowledged and care taken to document the reasoning behind inferences drawn about participants' work and comments (see Journal Summary, Appendix 5).

Interview Question 1 related to the paired image/word matching task and was analysed separately to allow a full exploration of this task and to explore gaps in participants' worksheet responses. Analysis of the remaining interview questions led first to a general outline of participants' conceptual understanding. This was based on the emerging themes and categories and incorporated representative quotations to illuminate the results. Secondly, four of the participants' transcript analyses were used to generate cognitive maps and a detailed description of the participants' conceptual understanding. The use of cognitive maps follows that described by Jones (1985) and developed by Thomas (1992, 2009), where diagrammatic modelling represents, in this case, individuals' conceptual understanding on the basis of applicable categories emerging from the interviews and the perceived beliefs surrounding the connection between these. The four categories represented specific constructs, or ways of thinking about electronics knowledge as determined from the analysis, and represented each of the ten participants who agreed to an interview.

3.8.1 Lesson 1 task 1 paired image/word activity and task 2 circuit building

Worksheet documents were read and themes and categories recorded. These contributed to the overall summary of themes and categories for the lesson data. Recordings of dialogue from the lesson were listened to and a typed summary created (Appendix 11). This was coded using the qualitative data organisation software NVivo (QSRInternational, 2012). Similarly observers' record sheets from the lessons were reviewed and a typed summary created, then coded using NVivo (Table 12). All three summaries were used to triangulate between the data sources, which provided an opportunity to compare and verify the results emerging from different sources. The worksheets, recordings and observation results were then combined to create summary themes and categories representing data from the taught lesson phase of the study. The Findings and Analysis chapter records these as tables and summary concept maps.

3.8.2 Screen capture: Lesson 2

Screen capture video of participants creating a computer program from multiple representations was viewed using Windows Media Player (Microsoft, 2009). Each video lasted around 30 minutes. A hand written summary of key events was made while viewing the data, which was then presented as a summary table (Table 13, Findings and Analysis chapter, Section 4.6). A comparison between each participants' summary then led to a record of key themes representing participants' individual approaches to the task. The key themes also led to the development of interview questions and was used to triangulate with the interviews and lesson data.

3.8.3 Interviews: Paired activity, circuit building and programming

All interview recordings were first listened to and checked for value as data sources. It was decided that all of the interviews should be transcribed and this was achieved by listening to the recordings using Windows Media Player (Microsoft, 2009) a second time and typing the transcript using Microsoft Word (Microsoft, 2013). The interviews were initially coded during transcription, where key themes began to emerge, by annotating the text in a different colour. The first two interviews included all of the pauses, exclamations (e.g., 'um') and non-linguistic data. However it was felt that this approach was unnecessarily detailed, given that the focus of interest did not seem to be affected by these contextual data. Therefore the remaining eight interviews comprised a more streamlined transcription which accurately recorded participants' answers, but omitted less helpful utterances making them easier to read and analyse.

The analysis of interview data first focused on the paired image/word matching task and coded this separately to allow a comparison to be made with the lesson data from this task. The transcripts were read from a printed paper copy, comments of interest highlighted and themes marked up by hand. The transcripts were then uploaded to NVivo 10 (QSRInternational, 2012) and coded within the categories emerging from the analysis. This allowed straightforward access to the transcripts during the analysis stage. Following each phase of coding (the coding of lesson data and interviews) an analytic memo was created within NVivo to summarise results and add researcher observations about the data. NVivo proved to be an invaluable organisational tool, however the principles of the constant comparison method, as described by Thomas (2009), were observed and recognised as instrumental in revealing plausible and context specific findings.

Analysis of the remaining interview questions followed a similar pattern. A summary of participants' responses was produced using quotations from the interview, which led to the generation of an individual cognitive map and commentary representing the conceptual profile, or summary of understanding, of each participant. During the analysis, it was borne in mind that research has shown that participants may contextualise their answers during interview (Treagust and Duit, 2008), possibly responding to the effects of a particular interviewer or location. Particular caution is thus needed when analysing the possibility of conceptual change (*ibid*) and consequently participants' interview answers were triangulated with other data from the lesson observations to check their plausibility.

3.9 Ethics

The study has been designed within the frameworks of both the British Education Research Association (BERA) *Ethical Guidelines for Educational Research* and Oxford Brookes University (2000) *Ethical Standards for Research Involving Human Participants*. Full ethical approval was obtained from Oxford Brookes University Research Ethics Committee (UREC, 2014), on the basis of the approach detailed above and is outlined in Appendix 7.

3.9.1 Dependent relationships

A key ethical consideration concerns the insider researcher approach adopted in this study. Smetherham (1978) promotes this in terms of the benefits to knowledge generation, knowledge that would otherwise be difficult, or impossible to obtain. Indeed the topic and approach was considered to be worthwhile only on the basis of this approach, because the issues of interest evolved from close interaction with learners and therefore researching within the boundaries offered by the researcher's teaching environment and learners is considered to be of most benefit to implementing any modifications to current methods of teaching electronics concepts. Although insider research has been the focus of some concern, for example Drake and Heath's (2008) discussion surrounding potential discomfort among and between colleagues, issues raised by certain data types and its emergence and the problems of change implementation, in this study researching as an insider has not presented problems in these respects.

Floyd and Arthur (2012) on the other hand focus on internal ethical considerations, particularly those faced by insider researchers, highlighting those which are often complex and present particular dilemmas to researchers. Two of these which have been particularly relevant to this study are: 1) the 'ongoing professional relationships' with students and 2) protecting 'anonymity of respondents in the long-term future' (*ibid,* 6). No issues emerged in relation to consideration 1 and the anonymity of participants (consideration 2) was considered a high priority throughout the study. Anonymity and de-identification are discussed further below.

An important factor therefore, has been the concern for matters arising from the dependent relationship posed by the research, between teacher and researcher and student. The issue arises through student dependency on teacher guidance, assessments and ultimately their success with an externally verified qualification. The conditions under which they may or may not agree to participate in the teachers' research is thus distinct to that undertaken by an outsider researcher. Oxford Brookes (2000, 3) regard the 'quality' of students' consent as key to justifying the approach, which also permeates other ethical areas of the research endeavour (BERA, 2011). Quality of consent is here interpreted as full awareness by participants, parents and the school of the study aims, participants' role and willingness to participate on an opt-in basis.

The aims of the research were explained to students verbally as a class and a consent form (Appendix 9) used to record the nature of consent. Students' right to withdraw was also made clear and there were opportunities to ask questions (Oxford Brookes, 2000). In addition a participant information sheet (PIS) outlined the study aims, participatory information including the necessity of participation (BERA, 2011) and intended benefits (Oxford Brookes, 2000), one month in advance of the research events (Appendix 10). This provided time for participants to digest the information before completing the consent form, which reflected the following method related issues.

3.9.2 Observation, interviews and informed consent

Observation of participants during lessons is potentially intrusive and may 'provoke anxiety' (Oxford Brookes, 2000: 1). Clear explanation of aims and procedure was provided on the PIS to minimise this, focusing on the intention to capture, in all tasks, phenomena relative to task completion, rather than the specific performance of individuals. In addition it was clearly explained that the reporting of results would de-identify or anonymise where appropriate, students' contributions. The consent form sought consent to use quotations in this sensitised way. The use of audio, video and screen capture methods was also detailed on the consent form so that voluntary informed consent could be gained where participants 'agree to their participation without any duress' (BERA, 2011: 5).

Where consent to electronically record, in any form, was not received, those participants were the subject of observer's note making only. Similar conditions operated in relation to interviews, which were conducted following the lessons on an opt-in basis, during the school lunch hour. A key condition of participation was the assurance that any recording would be used for analysis only and their secure storage (Oxford Brookes, 2000). The UREC (2014) condition that students be provided with adequate lunching and rest time was met by restricting the interviews to a maximum of thirty minutes.

3.9.3 Documents

The creation and storage of documents containing personal information during research (e.g., worksheets or video files) and that specifically identify individuals (Oxford Brookes, 2000) are subject to the requirements of the Data Protection Act (1998), as outlined in the BERA (2011) guidelines. The PIS explained what information would be collected and that storage included the use of the researcher's school laptop, backed up using an external 'hard drive' and the school network, all password protected. As in all the research activities explained here, the key consideration was participants' protection and anonymity (BERA, 2011).

Chapter 4 Findings and Analysis

4.1 Introduction

The research study aims to describe the different ways students use external representations to construct abstract electronics concept understandings and reveal specific approaches to learning those concepts. The section presents the findings which emerged from my own records (participants' characteristics and GCSE results), the observation of two lessons, participants' outcomes from the lessons and subsequent semi-structured interviews. I present the findings in the following sections: participant characteristics data, participants' GCSE examination results, paired image/word matching activity from lesson 1: observations and documents, semi-structured interview data from Question 1, conceptual understanding: categories and themes from the interviews, and conceptual understanding: cognitive maps. Table 8 presents a summary of the data collected during each research phase.

Research Phase	**Data Item**	**Date Collected**
Pilot Study	Problem solving activity	October 2013
	Interview record	November 2013
Phase 1		
Lesson 1	Paired matching activity dialogue	1st July 2014
	Paired matching worksheet	1st July 2014
	Researcher lesson observation records	1st July 2014
	Non-participant lesson observation records	1st July 2014
	Completed circuit diagrams	1st July 2014
Lesson 2	Researcher/Non-participant lesson observation records	2nd July 2014
	Completed computer programs	2nd July 2014
Phase 2		
Interviews	Interview transcript	July-Sep 2014
Miscellaneous data	Participants' course assessment record	July 2015
	Analysis of technical term use	July 2015
	Participants' characteristics profile	July 2015
	Participants' GCSE outcomes	August 2015

Table 8: Summary of data collected at each research phase

The findings are explained in connection with the analysis used to generate representative themes as they emerged from the data. Themes are presented in tables. The total number of participants (n) contributing to the research phase is shown in each table heading. 'Frequency' represents the number of instances contributing to the theme. ‘No. of data sources’ represents the number of participants contributing to the theme, within the research-phase total (n).

Participants’ names have been replaced with pseudonyms to provide anonymity. The analysis is carried out within the framework of participants’ use of representations and their approach to the problem solving tasks (see Methodology, Section 3.7). The conceptual understanding of each participant is then presented using cognitive mapping drawing from Jones (1985) as a method to summarise data emerging from the key sources. Quotations are enclosed within double quotation marks and a notation format is adopted following Thomas (1992, 93) where:

- Italicised text represents the key point about which commentary is being made
- Three dots ‘…’ without spaces represent a pause or discontinuity in the participant’s account
- Dots with spaces ‘ . . . ‘ represent editing of irrelevant material

In the final section (4.11) a summary of categories is provided with the patterns or concepts emerging from analysis representing perceived relationships within the data. These are developed in the Discussion chapter. An overview of the research process is provided below (Figure 5).

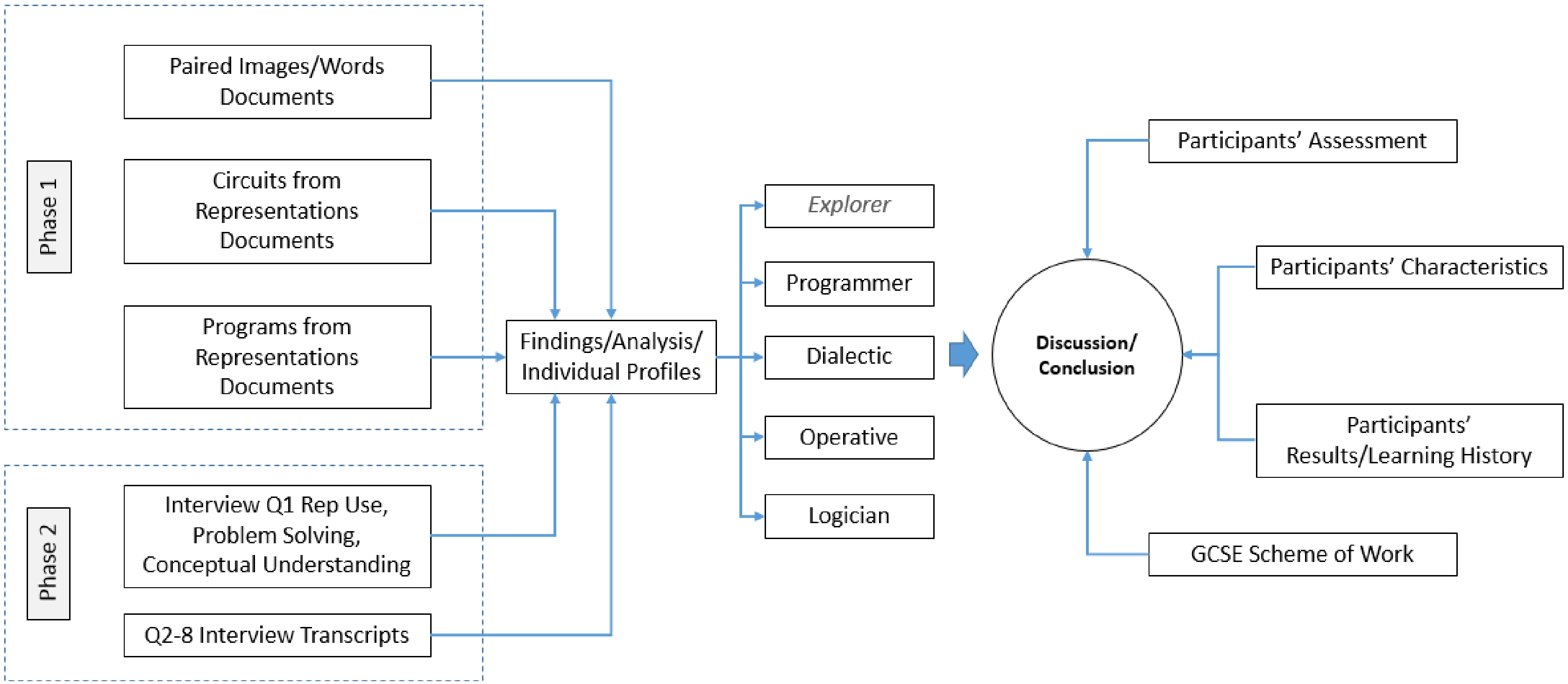


Figure 5: Overview of findings, analysis, discussion and conclusion process

4.2 Participants' characteristics data

Participants' characteristics data is presented to provide the context for the following findings and analysis, as a part of the case being explored. The data includes participants' date of birth, the results of the Year Eleven Information System (Yellis) test and the Learner Profile Type (discussed fully in Section 4.9). This cognitive ability test includes questions based around verbal, mathematical and spatial ability (patterns) skills and is used within the school as a baseline measure and as a target setting tool. In this study the data may be useful in contextualising discussion about participants, for example it might confirm on disconfirm a perspective generated by the main data gathering phases.

Participants	DoB	Verb	Maths	Patterns	Yellis	Learner Profile Type
Ben	26/08/1999	142	121	95	134	Operative
Connor	12/08/1999	119	132	114	129	Programmer
David	31/05/1999	124	137	137	134	Explorer
Ethan	26/07/1999	121	133	116	130	Logician
Feidhlim	15/06/1999	142	121	98	134	Programmer
Fergus	30/06/1999	124	123	119	126	Dialectic
Jacob	08/05/1999	111	145	122	132	Programmer
Luke	29/04/1999	118	114	109	117	Operative
Oliver	27/07/1999	109	116	116	114	Operative
Sam	21/12/1998	112	133	127	125	Logician

Table 9: Participants' characteristics data

The figures presented are standardised against the national population of students taking the Yellis test, therefore 100 represents the national average. It is important to note that the test results are of interest in support of the wider discussion surrounding conceptual understanding, the participants and the context and are not in themselves, for the purposes of this study, indicative of particular aptitudes. Further reference will be made to this data in Chapter 6.

4.3 Participants' GCSE course (Y10) assessment marks

Participants' GCSE course assessment marks are presented from Year 10, where most of the learning and data collection took place. The marks represent key assignments or homework which is drawn on during the Discussion chapter. The marks have been converted to percentages to allow a convenient overall average for each participant.

	Dual Trans Prototype Plan	Resistors. Ohm's Law	Mono/Astable Comparison	Switches	Diodes	FETs	555/4017b Prototype	Flowchart Conversion to Code	Op Amps	**Average %**	**Learner Profile Type**
Ben	40	41	25	100	60	53	40	60	75	**55**	Operative
Connor	0	62	67	88	70	53	40	60	0	**49**	Programmer
David	100	97	92	100	90	88	60	80	88	**88**	Explorer
Ethan	100	59	17	100	100	71	40	40	63	**65**	Logician
Feidhlim	100	76	50	100	0	100	0	40	81	**61**	Programmer
Fergus	60	86	58	94	0	76	80	80	100	**71**	Dialectic
Jacob	100	83	50	100	100	71	60	80	63	**78**	Programmer
Luke	60	55	25	88	40	41	0	20	0	**37**	Operative
Oliver	100	90	92	88	100	94	100	100	100	**96**	Operative
Sam	20	93	33	94	90	24	20	80	94	**61**	Logician

Table 10: Participants' GCSE course (y10) assessment marks and profile types

4.4 Participants' GCSE coursework and examination assessment data 2015

Participants' GCSE outcomes are presented to provide a context for the data analysis. This data includes participants' coursework and examination marks (Table 11). The GCSE Electronic Products coursework represents 60% of the assessment and the examination paper 40%. Coursework is submitted at the end of March and the examination paper is taken in June. An aggregate grade is shown for each participant.

GCSE Design & Technology: Electronic Products				
	Coursework Result	Examination Result		
	UMS Max 120	**UMS Max 80**	**Grade**	**Project Focus**
Ben	61	63	C	Sports Score Counter: Logic & Counting
Connor	76	80	B	MP3 Amplifier: Audio Amplification
David	108	79	A*	Sports Scorer: Programming, Logic & Counting
Ethan	96	69	A	Weather Station: Op Amp, logic & Counting
Feidhlim	111	73	A*	Sports Scorer: Programmed, Logic & Counting
Fergus	101	72	A	Electronic Game: Programming, Logic & Counting
Jacob	99	66	A	Electronic Game: Op Amp, Programming
Luke	68	65	C	Pet Door Lock: Timing, FET-based Solenoid
Oliver	107	73	A*	Infra-Red Object Counter: Programming, Logic & Counting
Sam	79	67	B	Chess Game Timer: Programming, Logic & Counting

Table 11: Participants' GCSE course based assessment data from researcher's records

The grade shown is the final achievement grade, post moderation, as released by the awarding body in August 2015. The relationship between coursework and examination marks and the final GCSE outcome may be of interest when discussing participants in context in Chapter 5. Overall use of the contextualising data in Sections 4.2-4.4 links with the ultimate purpose of the study, which is to illuminate the conceptual understanding of participants within context; consideration of the factors in Sections 4.2-4.4 is therefore necessary to achieve this aim.

4.5 Paired image/word matching activity: Data from lesson 1 observations and documents

The findings are drawn from the following data:

- researcher and non-participant observer notes on lesson activities

- audio recordings of conversations during the lessons
- participants' lesson worksheets
- CamStudio (2013) screen capture recordings (Lesson 2)
- interview transcripts

The emergent themes are illustrated with conceptual diagrams which were developed from Thomas's (2009) network maps, and quotations from the interviews. These summarise the themes generated from the data sources during commentary on each of the categories. The key point about which discussion is made is italicised in each quotation. Each quotation is referenced to its key interview question, or to the specific question eliciting the quotation. The concept maps include a key pattern or concept emerging from the analysis where appropriate. Key terms and phrases are explained in the Glossary of Terms (Page 9).

The paired image/word matching activity (Appendix 2) was completed by the whole class of seventeen students. The exercise, drawing on Paivio's (1986) Dual Coding Theory (discussed in the Literature Review, Section 2.5.4), was designed to reveal students' starting points when using electronics based representations (word or image) and the methods used to link words and images. Notes made by the researcher and non-participant observer, audio recordings of conversations with participants in the lesson and participants' worksheets contributed to the data which was summarised after the lesson and coded using QSR NVivo software (Table 12). Table 12 therefore represents two data sources (observer/non-participant observer), although the data is representative of the full class of 17 students. Where a participant provided verbal and written responses in relation to the same phenomena, only one record was made on the summary sheet. The data is presented in tables as frequency of coding and number of data sources (i.e., researcher and non-participant observer notes).

Findings reveal words as slightly more frequent starting points than images for participants when matching electronics specific representations (Table 12). This was the case despite the layout of the worksheet which presented an 'image column' before a 'word column' for participants to place their matches (Appendix 2). The finding concurs with the pilot study which also revealed an orientation to verbal representation as a starting point (see Section 3.3). It is interesting to note that the interviews revealed that those beginning with images often focused on an embedded word or term within the representation; for example a match was made "[By] taking the representation *at face value* e.g., it says 'full charge'" (Observer record, Lesson 1, Task 1). Where program code was featured this became a more prominent referent, possibly as the use of multiple words ('if…then…else') provided a strong association, for example:

> "*We translated it into a sentence*, so 'if the switch is closed, then the voltage passes through the transistor and the LED will be on' *then related it to the diagram*" and "*Try in sentence* then relate to diagram" (Observer record, Lesson 1, Task 1).

Participants beginning with images, on the other hand, alluded to the need for understanding, in that "[You] understand image then look for word" (Non-participant observer, Lesson 1, Task 1), which may reveal a preference for synchronously rather than sequentially focused referents, as noted by Larkin and Simon (1987). However when considering those participants that began with words, it is useful to reflect that the task presented a number of images that could be interpreted in a number of ways. It is possible that it is not until the participant considers the words that a successful match can be made due to the explanatory nature of words. This may lead initially therefore to a focus on the words, or at least this may have been the case once the participant had reflected on the activity and responded to questioning during the lesson.

An alternative perspective is offered in relation to Larkin and Simon's (1987) contention that the efficiency of recognising any given representation is linked with how explicit or implicit the information is. Thus when presented with words and images in the problem solving task, the words may have provided a strong focus since they represent explicit information, as opposed to the images which might be considered reasonably open to interpretation. The provision of additional mathematical representations, however may have provided the necessary support for participants and led to a different outcome. I expand on this suggestion and synchronous/sequential approaches in the Discussion Chapter.

Paired Matching Task Coding: Approach to matching (n=17)		
Theme	**Frequency**	**No. of data Sources**
Process of elimination	7	2
Existing knowledge	5	2
Word as starting point	4	2
Image as starting point	2	1
Infer 'states' from program code	2	1
Link using binary terms	2	1
Match image to word	2	1
Programming code expanded	2	1
Graphical or surface level info	1	1
Match word to image	1	1

Table 12: Code frequency for paired matching activity from observers' notes and discussion during lesson 1

The process of elimination was the most frequently cited method of matching the images and words (Table 12). For example "[You] do [the] obvious then *process of elimination*" (Observer, Lesson 1, Task 1). This could reflect a limited knowledge of the representations provided, however this is unlikely given the experience of the participants. It is more likely that participants chose to approach the task in a heuristic way (see discussion in Literature Review, Section 2.6.2), as this was revealed as an important approach to problem solving in other areas of the data, such as Section 4.8.8 (Learning with representations, Table 25) and 4.9.2 (David's Cognitive Construct).

Existing knowledge was also cited by participants as a prominent starting point for problem solving (Table 12). For example in response to observation record Question 1, exploring how image/word pairings had been achieved, a participant noted their starting point as "Previous knowledge of how the circuits work and how the components work" (Observer record, Lesson 1, Task 1). Interview responses also support this prominence (see Representation Use and Problem Solving Method, Tables 14 and 15). The link with existing knowledge can also be inferred from the coding, such as 'infer '*states'* from program code' and 'link with *binary* terms' (Observer, Lesson 1, Task 1), which suggests the use of programming knowledge in helping to match the words and images; the following is a representative comment from the worksheets, which also reflects a particular type of knowledge, namely the logic circuit type that is represented by terms such as *binary* and *states*:

> "'If-then' *suggests two different states*-matching two states inherent in circuit diagram with the two states contained within 'if-then'" (Participant worksheet comment, Lesson 1, Task 1).

In summary the paired image/word matching activity elicited a strong connection with existing knowledge and a logical approach, represented by a process of elimination, to matching the representations. The differences in starting points among participants for this matching task, who all received the same representations, demonstrates variation in the use of those representations to make links with existing knowledge, and suggests a personal approach to learning and problem solving, as discussed previously in relation to Bruner (1977) and Kolb and Fry (1974). I develop this point in the following sections and in the Discussion chapter.

As a part of the matching activity, the worksheets (Appendix 2) invited written responses to questions, which were not always fully completed. This provided an opportunity to explore the incomplete questions more fully during the interviews and pick up on gaps in worksheet answers. The findings from this interview focus are subsumed within Sections 4.7 and 4.8.

4.6 Screen capture: Lesson 2

Table 13 provides a summary of computer screen capture data which represents participants' construction of program code from the representations provided on lesson worksheets (see Appendix 3). Six students' screen captures were collected, from a possible ten; the remaining four were not captured to disk because unfortunately the student, or ICT support, did not save them. The capture of program construction on-screen proved a useful exercise in triangulating the data collected during interview. Therefore the data is included at this point, as it informed the interviews which are discussed in the following sections. Event numbers (column 1) represent the chronological order in which events were completed, as determined from watching the recordings. Colour coding is used to identify similar events and enhance readability of the table and is referred to below.

Summary Screen Recording Events (n=6)						
Event No.	***Ben (Analogue Task)*** *(Computing)*	***David (Digital Task)***	***Fergus (Analogue Task)*** *(Computing)*	***Jacob (Analogue Task)*** *(Computing)*	***Luke (Analogue Task)***	***Sam (Digital Task)*** *(Computing)*
1	If-then statement added	If-then statement added	If-then statement added	If-then statement added	Opens Circuit Wizard software	Adds 'if pin'
2	'Main program' header	'Digital Dice' file opened	Adds variable	Re-starts & adds output code	Begins building circuit shown in represent-ation	If-then statement added
3	Adds output command	Returns to program software	Adds sub-program name	If-then statement added	Returns to program software	Adds '3=1 then'
4	Saves file	Returns to 'Digital Dice' file	Adds loop command	Adds sub-program name	Types 'Main'	Adds sub-program
5	Errors on syntax check	Returns to program software	Re-arranges tabs/ creates indents	Adds variable	Adds colon	Opens Circuit Wizard software
6	Runs simulator	Coding annotate-ion	Syntax error message	Runs simulator	Adds 'Wait' command	Saves file
7	Saves file	Begins sub-program 'LEDON'	Changes PIC type	Adjusts simulation speed	Adds '3'	Runs simulator
8	Coding annotation	Adds annotate-ion	Moves all codes left	Runs simulator	Adds 'high'	Coding annotation
9	Runs simulator	Saves file	Corrects syntax error	Runs simulator	Deletes 'High', replaces with 'if pin'	Completes annotation
10	Coding annotation	Writes output code	New file-trials loop code	Coding annotation	Adds '3=1 then goto on1'	Continues subprogram
11	Saves file	Syntax check	Runs simulator	Saves file	Adds if 'pin3=1 and pin4=1 on2'	Runs simulator
12	Prints	Runs simulator	Implements changes	Prints	Adds subprogram 'on1'	Uses Notepad to word process
13		Prints	Errors emerge	Opens Circuit Wizard	Adds subprogram 'on2'	Runs simulator

14		Runs simulator	Changes PIC type		Coding annotation	Coding annotation
15			Error checking		Prints	Prints
16			Runs simulator			
17			Coding annotation			
Frequency (f) of Simulator Use	**2**	**2**	**2**	**2 (events 8 & 9 counted together)**	**0**	**3**

Table 13: Summary of screen recordings made using CamStudio (2013)

My interpretation focuses on the participants' transition between traditional representations and computer coding. Table 13 appears linear and tightly organised. In practice there was a reasonable amount of inactivity and re-writing during the approximately 30 minute period. The screen recordings reveal that five out of the six participants (Blue) began the programming task by focusing on a concrete feature of the circuit diagram (the central process component-a transistor for analogue group, a logic gate for digital group). Participants identify the central process component in the circuit and convert this to an appropriate 'if-then' code in the program. The general pattern then shows participants constructing the individual codes to represent output behaviour, in some cases using more complex subprogram coding structures (e.g., David, Fergus and Sam). Most of the recordings reveal the use of the virtual simulator to check program operation (Green). These actions represent a typical approach, consisting of establishing a central process representation ('if-then' code), developing programming to control outputs in relation to different input states, simulating the program to check its operation and finally the program is annotated to explain operation (Purple). To highlight interesting individual nuances and support the discussion of findings in the following chapters, I provide discrete summaries for each participant in turn. Those students who follow the GCSE Computing course are indicated below, to acknowledge their potential wider experience with programming.

Ben (Computing)

Ben uses straightforward programming codes, beginning with the input/process representation, then adds the outputs which are linked with the input conditions that control them. This reflects the use of basic programming codes, rather than more advanced codes, for example relating to variables (use of memory to perform calculation).

David

David writes a slightly more complex program, which begins with the input/process representation, then proceeds to add a subprogram for the output stage. Of particular interest is David's use of an existing program (Digital Dice), completed as a part of the Year 10 GCSE course, to borrow some code for use in this exercise (Red). This might demonstrate his need to clarify the approach to take, but also links with and supports the identification of this student's approach to learning using what I have termed a 'discovery' method (see David's Cognitive Map and commentary, Section 4.9.2).

Fergus (Computing)

Fergus constructs a more advanced program using a subprogram and 'loop' command. This enables the program to represent the circuit function more realistically than some of the other programs, which would perform only one cycle. Fergus begins with the central input/process representation. It is interesting that a lot of time is spent correcting an error, but this student does not access the help files available. The syntax check and virtual simulator are used to check functioning.

Jacob (Computing)

Jacob writes a more advanced program which includes a variable. Jacob also uses advanced features of the software, such as the facility to adjust the simulator speed. The simulator is used often, possibly indicating uncertainty. Ultimately the program is not representative of the reference circuit.

Luke

Luke constructs the circuit diagram using the Circuit Wizard software, even though this is not a requirement of the exercise (Yellow). This practical approach links with the preferred approach described by Luke when problem solving in electronics (see Luke's Cognitive Map and commentary, Section 4.9.5). However the circuit is not completed fully, or trialled. The recording overall suggests Luke is not able to complete the programming exercise. The emergent program appears to be a copy of the digital task that his neighbours were producing either side of him at the computer terminals. Difficulties with programming are confirmed by Luke in the interview:

> "*I don't really understand* programming very well . . . *I always thought electronics was making*, rather than programming because *I always thought that was computing*" (Luke, Interview Q6/7).

Sam (Computing)

Sam produces a program which works, beginning with the central input/process representation. Some incorrect coding remains, however. A very particular, and detailed approach to annotation is adopted. This links with inferences drawn from Sam's interview which suggest an extremely logical approach to problem solving. The virtual simulator is used most often in comparison with the other participants (f=3, Table 13), possibly suggesting the need to clarify his approach and to check functioning.

Two interesting points emerged from the analysis of screen recordings which helped to shape the analysis of subsequent interview question answers. Firstly the significance of using the software Circuit Wizard during problem solving (Luke, Sam) led to thoughts surrounding the value of the on-screen procedure, which allowed participants to test and trial their ideas in a practical way (Yellow). Secondly the benefits to conceptual understanding of using advanced programming commands by some (David, Fergus), were revealed as providing a more realistic representation of the underlying concept being modelled. These points are developed further in the analysis of Interview Question 1 and the category Problem Solving Method (Section 4.7.3).

4.7 Semi-structured interviews – Question 1

4.7.1 Paired image/word matching activity: Data from interview question 1

Question 1 explored students' experience of the paired image/word matching activity and allowed both a triangulation opportunity with lesson data and further opportunity to explore participant experience. Three categories emerged from this question: representation use, problem solving method and conceptual understanding. In practice the literature review directed the initial focus around the two broad categories of representation use and problem solving method, with analysis of the transcripts revealing the range of specific themes, including those contributing to the category conceptual understanding. In this section I explore the three categories in turn.

4.7.2 Representation use

When matching images with words, participants' engagement with representations most frequently elicited existing knowledge (Table 14). Responses include the following as good examples:

> ". . . that's how I'd associate charge and pulses *I know* when there's a period of high and well when there is current and when there isn't at regular intervals so I was able to link those . . ." (Ben, Interview Q1) and ". . . I used my knowledge of logic and computing *to recognise* that as a logic if-then [statement] . . ." (Fergus, Interview Q1).

This supports similar observations of the use of existing knowledge in other areas of the data, such as the documents and observations collected from the two lessons (Section 4.5), and supports Piaget's (1955) assimilation stage during the learning process.

Also prominent was the link with something observable within the representations (Table 14); for example "with that one *you can see* [in the graph] the capacitor being charged" (Feidhlim, Interview Q1) is a good example of how the representation is translated into voltage behaviour. An alternative response included a comparison between the graph and circuit diagram, which show:

> ". . . for example [in the graph] *resistance times capacitance*, voltage" whereas "the other ones [circuit diagrams] are *what you can see* pretty much . . ." (Jacob, Interview Q1).

Here the comparison suggests a difference between representations which embody conceptual information and those that indicate function or circuit behaviour more explicitly, i.e., a concrete referent or starting point (Kolb and Fry 1974).

Representation Use (n=10)		
Theme	**Frequency**	**No. of data Sources**
Represents existing knowledge	10	5
Represents observable phenomena	9	6
Represents abstract information	5	4
Represents graphical or surface level information	4	3

Table 14: Code frequency for representation use category from interview Question 1

Some of the responses suggested more explicitly that abstract information could be gleaned from the representation, for example "I next went to high and low, I saw that *in a high state* because it's turned on and that it's marked off with the switch, so it was low and high" (Fergus, Interview Q1). Here Fergus both links with existing knowledge and characterises the circuit function through a conceptual understanding of logic circuits.

Finally there were instances of literal translation of representations, such as:

> ". . . *it had an arrow that was going clockwise*, which meant that it was going forward and *it's the only direction stated so* that led us to believe it was forward bias since the circuit was only going clockwise" (Sam, Interview Q1).

This suggests Sam focuses on the concrete elements of the representation, where elicitation goes only as far as the elements depicted.

4.7.3 Problem solving method

Problem solving method refers to the inferred mental process used to complete the paired image/word matching activity. Five methods emerged during the interviews (Table 15). The use of existing knowledge was a prominent approach to linking the images and words. This concurs with the worksheet and observation data collected during lessons. Similarly the process of elimination, as with the lesson documents and observations, emerged as an effective approach by participants.

Problem Solving Method (n=10)		
Theme	**Frequency**	**No. of data Sources**
Existing knowledge	5	4
Process of elimination	5	4
Practical application	3	2
Programming association	2	2
Foundation metaphor	1	1

Table 15: Code frequency for problem solving method category from interview Question 1

Practical application (Table 15) refers to the link between representation and the physical experience of using components or products, which may be an experience recalled from memory. This approach was adopted by two participants, for example "We just worked out what it is they do [the circuits/components], what it is that each thing does" (Feidhlim, Interview Q1), indicates that the process of matching images and words elicited the tacit experience (McCormick, 1997; 2004) of the components or circuits, beyond the technical knowledge held about them.

Associating elements with programming also provided a starting point for participants, for example:

> ". . . for the first one we just associated, because in programming when you want to switch something off *you can say LED low or input low . . .*" (Ethan, Interview Q1).

This concurs with findings from lesson observations and documents discussed above (Section 4.5), suggesting programming as a significant referent for some participants. The analysis of screen recordings in this respect (Section 4.6) suggested that those with a more advanced knowledge of programming were better able to engage with the problem solving task as their knowledge enabled them to both link programming code with circuit function (e.g., Fergus, Table 13) and draw on other sources of program coding in support of the task (e.g., David, Table 13).

Where programming is referred to, there is often the use of a foundation metaphor (foundation metaphor is fully explained in the Literature Review, Section 2.6.6). "It goes from zero volts to a *higher place*" (Sam, Interview Q1) is a typical example of a foundation metaphor grounded in a sense of dimension and location. *High* and *low* work in a similar way relative to switching on and off outputs and the link with representations can be made by observing the position of a voltage trace relative to a fixed position (i.e., 0 volts). I return to foundation metaphor in the following section.

4.7.4 Conceptual understanding

The research study aims to determine the nature of individuals' conceptual understanding and ultimately draws upon the emerging themes and categories collectively in achieving this key aim. Many of the themes discussed so far in this chapter link with conceptual understanding since, as discussed fully in the Literature Review (Chapter 2), conceptual understanding involves developing knowledge in the light of representation use and problem solving, amongst other activities. The nature of conceptual understanding is discussed and developed in the following Section (4.8). In this section conceptual understanding is related to the analysis of Question 1 and the paired image/word activity. Table 16 therefore shows the themes emerging for this category, representing only participants' discussion around problem solving in this activity.

The interviews revealed references to a logic type circuit concept (Table 16), such as "it's *binary ones and zeros*, so that's what we thought . . . *logic*" (Connor, Interview Q1). Generally the concept was accurately conveyed, however there was conflation with digital and programmed circuit types, for example:

> ". . . it's almost just on/off or high/low like . . . all the different words are said here *they just mean the same thing really*" (Ethan, Interview Q1).

This demonstrates how logic and digital circuitry can become interchanged, where in practice the terms refer to different principles. Programming was also slightly confused with logic, although it could be argued that the 'if-then' statement is inherently logical. The following comment, from the theme Programming as Logic (Table 16) illustrates this point well:

> ". . . I used my knowledge of logic and computing to recognise that [the representation] as an . . . *logic 'if then'* [statement] . . . if switch 1 is down then the LED is high else A is high" (Fergus, Interview Q1).

The use of technical terms in relation to logic circuit types and programming tends to be restricted to those participants who demonstrate an affinity with programmed approaches to electronics understanding. Connor, Ethan and Fergus for example each present a clear awareness and understanding through the responses to Interview Questions 2 to 8 (Section 4.8). The use of specific language, such as technical terms, does not seem to determine conceptual understanding, however. As I discuss in Section 5.5.3 and in several of the participants' cognitive profiles (Section 4.9), the use of general terms by participants normally provides an effective conceptual representation.

Some of these terms I have labelled foundation metaphors (see below), such as the use of *flowing* and *strong* in relation to analogue circuit types. Other examples include more general phrases such as not "turning on *suddenly"* (Feidhlim, Interview Q3), illustrating the difference between analogue and digital voltage behaviour. This approach is typical of Feidhlim, who tends to describe circuit types in terms of what he observes explicitly in the representation, circuit functionality and practical application, rather than using technical terms; and indeed this is very effective in conveying meaning.

The distinction between analogue circuit types (fluctuating voltage) and digital circuit types (voltage either on or off) was clearly revealed in the interviews (Table 16). For example the following comments refer clearly to analogue and digital conceptions respectively:

> "... we'd put these two together with these two because they're the same sort of thing, just *a matter of on/off ...*" (Digital conception, Ethan; Interview Q1) and "In comparison to all these [digital circuit types], they show some kind of *variation in voltage*, whereas these don't" (Analogue conception, Oliver; Interview Q1).

Of interest is the use of general terms, as mentioned above, to describe an obvious understanding rather than the use of technical terms. This may be a reflection of the interview situation, where technical terms may not be as readily recalled 'on the spot', or alternatives used *because* of the situation (Treagust and Duit, 2008).

Conceptual Understanding (n=10)		
Theme	**Frequency**	**No. of data Sources**
Logic conception	14	6
Foundation metaphor	8	5
Analogue conception	7	6
Digital conception	6	6
Practical application	5	3
'it' as subject of verb	3	2
Voltage behaviour (Question 2)	3	1
Analogue-digital conception	2	2
Existing knowledge	1	1
Programming as logic	1	1
Representation use: Problematic search-recognition-inference	1	1

Table 16: Code frequency for conceptual understanding category from interview Question 1

The practical application of the circuit contributed to participants' conceptual understanding, in that concepts were compared with or explained in the light of their practical application. This links with the discussion around embodied cognition (Davis and Markman, 2012) in the Literature Review (Section 2.6.1). Thus ". . . 'if-then-else', that is like *if this switch is flicked then it goes to here . . .*" (Connor, Interview Q1) describes a programming code which is interpreted using the physical action of switch operation. This concurs with the interpretation relative to representation use discussed above, suggesting the interconnection between use and concept development.

Foundation metaphor (see Lakoff and Johnson (1980) in Literature Review Section 2.6.1) provided a means to embody a concept, such as ". . . it's [the output] *dropped* low . . ." (Feidhlim, Interview Q1). Here language is used in general terms and relates to an embodied concept (i.e., dropping an object). Other similar expressions are encapsulated within the following comment:

> "I'd put . . . charging . . . say in a category of current and where that's *flowing* because they're all something to do with how long the current's *flowing* for, how *strong* the current is" (Ben, Interview Q1).

The concept embodied in this statement is the variable voltage attached to the charging behaviour of a capacitor, an analogue type circuit. *Flowing* and *strong* (*ibid*) tend to represent this variation, as opposed to terms such as *high, low* or *higher place* (Sam, Interview Q1) which tend to be used to describe digital type circuits.

The remaining themes reflected conceptual understanding mainly in ways specific to individuals. The existing knowledge attached to RC Networks (the term used to refer to a resistor and capacitor in combination to achieve a time delay) for example was important to Connor when viewing a transistor image, for example "it was the thing that was mentioned the most when we came to work on transistors, so it's kind of like *we just associate transistors with RC networks now*" (Interview Q1). This phenomenon is also discussed in Connor's cognitive profile (Section 4.9.1).

Ben, in a development to Question 1, generated the theme Voltage Behaviour (Table 16) through his specific use of references to voltage, which were unusual in comparison with other participants, for example:

> "I'd probably put the forward bias with the circuit and the if-then-else picture and words, because they're associated with what goes on in the components rather than *where there is current flowing and how long it's flowing for*" (Interview Q2).

Similarly (also used above in relation to foundation metaphor):

> "I'd put 0, 1 and high and low and pulses and charging say in a category of current and where that's flowing because they're all something to do with *how long the current's flowing for, how strong the current is*" (Ben, Interview Q2).

Ben's comments reflect a conceptual understanding of the difference between analogue and digital voltage types and in doing so makes a very clear reference to voltage behaviour as a part of his understanding. This understanding is more closely conveyed using technical terms, rather than the general language highlighted above. Thus some of the differences between participants' understandings appear to be relative to their language use.

Finally David highlights a perceived problem presented by representations such as the circuit diagram, which require the viewer to work hard to find the information needed, in comparison with, in this case a representation in the form of a graph (Representation use: Problematic search-recognition-inference strategy, Table 16). David suggests that:

> ". . . [the graph] *makes it a lot easier to see what's going on* . . . because it . . . *shows you the information that you need* whereas something like the circuit diagram *it may be more difficult because you might have to pick out a certain bit of the circuit diagram that's relevant*" (Interview Q1).

There appears to be an anomaly associated with this phenomenon, as representations such as the circuit diagram should, according to Larkin and Simon (1987), provide easier synchronous access to information in this form (see fuller discussion on synchronous/sequential processing in Literature Review, Section 2.1/2.6.3 and Discussion Chapter). However David's point is recognised in research on representation use, which suggests that to a large extent search efficiency is dependent on the explicitness of information and its location (Larkin and Simon, 1987). David on this occasion therefore clearly appreciates the immediacy of the graph, which provides him with a time delay value and presumably avoids the need to carry out a calculation using values obtained from the circuit diagram.

4.7.5 Summary of findings from interview question 1

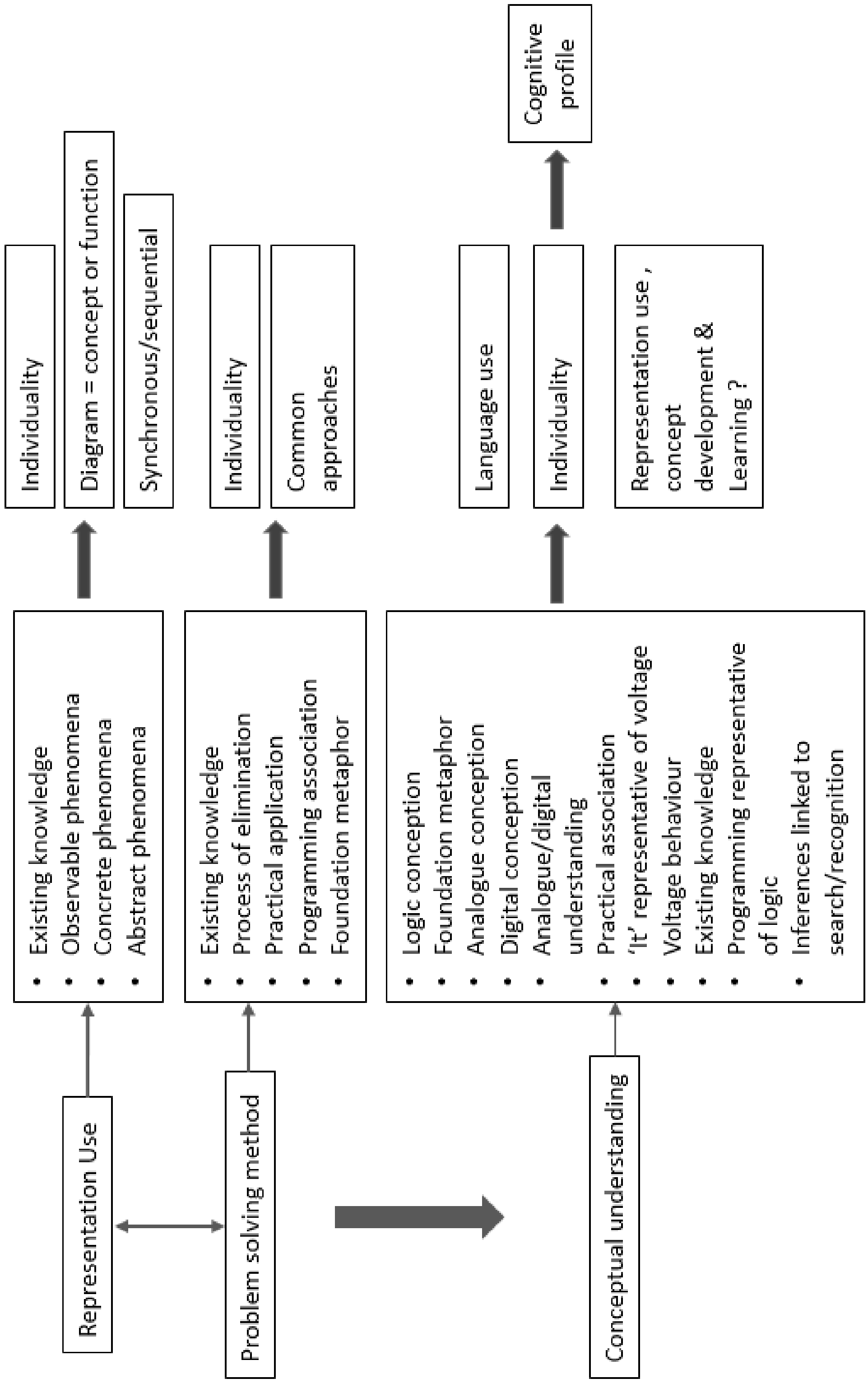


Figure 6: Summary concept diagram of responses to interview question 1 showing category, themes and key observations

Taken together the three categories discussed above represent the theme mapping for interview question 1 (Figure 6). They develop the initial analysis of the paired activity, which provided a starting point for considering how representation use may lead to conceptual understanding. An overview of the three categories and their themes is shown in Figure 6. The analysis reveals that participants use representations in specific ways to support subsequent problem solving. Evidence from the problem solving activity suggests that individuals have strong preferences in this respect, for example in their choice of word/image representation to enable problem solving (see Section 4.5). However there are patterns of common approaches to working with representations such as linking with existing knowledge and focusing on concrete or abstract information, as noted by others (Kolb and Fry, 1974). Some of the representations lead to conceptual thinking (a graph), others to functional understanding (a circuit diagram). The synchronous or sequential nature was also an important factor in determining the efficacy of a representation type.

Common patterns of problem solving included adopting a process of elimination, applying existing knowledge or relating representations to the practical application of the phenomena. Often, but not always, those adopting an approach to engaging with a representation also used this approach in problem solving. Further comment is made in this respect during each featured participant's cognitive profile commentary. Thus representation use and problem solving are shown as linked in Figure 6. The validity of these common patterns is considered to be strengthened by the fact that different data collection methods have highlighted similar themes and categories.

The third category Conceptual Understanding emerged where participants' elicitations were considered to reflect a way of understanding electronics more generally, rather than specific methods of engagement (such as representation use or problem solving). However the preceding discussion reflects the involvement of methods of engaging with representations and problem solving in the portrayal of conceptual understanding. For example the elicitation of existing knowledge surrounding logic type circuits during representation use or problem solving can often be linked with a participant's specific logical way of understanding electronics, consequently a link is made between conceptual understanding and patterns of individuality which are later developed in the conceptual profiles (Section 4.9). However it is difficult to determine from the data the sequential process of concept development. A reasonable inference might suggest that to develop a concept, some contact with a representation and/or problem solving experience would be necessary, i.e., phenomena are emergent (Chi, 2005). On the other hand it is possible that a concept can be developed through other means, such as a practical activity and drawn on in the interpretation of a representation or engagement with a problem solving task. Therefore a question mark is attached to learning using representations and conceptual understanding at this stage (Figure 6), although Chen's (2013) proposition that new knowledge is gradually integrated with existing knowledge in relation to conceptual understanding (conceptual change) appears to gain some support from the evidence presented so far. I return to this question in the Discussion chapter.

4.8 Conceptual understanding: Categories and themes from interview questions 2 to 8

This section documents the next phase of interview questions (after and including Question 2) and develops the themes and categories identified earlier from Question 1, and the analysis of the paired image/word matching activity, as discussed in Sections 5.1, 5.2 and 5.3. Each category is explained with themes that emerge from the interviews and example responses from the transcripts. Summary concept diagrams provide an overview of the key categories and indicate important considerations for the Discussion chapter at the end of the commentaries.

The interviews and subsequent analysis of transcripts first explore participants' engagement with the circuit building activity in Lesson 1 (Task 2), then move to an analysis of the programming activity in Lesson 2 (Task 3). Five of the ten participants who evidenced particular ways of conceptualising electronics knowledge are then presented. This includes a cognitive map representing each of the participants' conceptual constructs and a supporting commentary.

The presentation of findings that follow emerge from discussions in the interviews around both of these tasks. Where necessary, a comparison is made between the two task groups named 'analogue' and 'digital', which were used to a) explore the possible elicitation of alternative approaches to the two methods of conceiving of electronics, and b) ensure students could not simply duplicate the work of their neighbour while working at the computer screens. The interview findings are illustrated with quotations from the participants and organised within the following categories emergent from the coded transcripts:

- Circuit sequence and the use of representations
- Program sequence and the use of representations
- Use of representations
- Concrete to abstract thinking
- The role of memory
- The role of practical experience
- Conceptual understanding
- Learning with representations

4.8.1 Circuit sequence and the use of representations

Two groups were created, ‘analogue’ and ‘digital’, which provided the opportunity to explore any qualitative differences in thinking about electronic circuits (see Methodology, Sections 3.5.1; 3.6.1). Three representations were provided for each task group (Table 17). Participants were asked to use the representations (discussed further in Section 4.8.2) to construct a circuit which satisfied the conditions presented in the worksheet-based representations (Appendix 3).

Analogue Group	**Digital Group**
Component list	Component list
Time delay graph	Truth table
Time delay formula	Logic signal

Table 17: Representations provided for the circuit building task per task group

Table 18 shows that the analogue group all focused on the component list (Appendix 3) as their starting point when considering circuit construction. Jacob provided the most explanatory response stating that:

> “. . . *I used the component list* and saw that there was a capacitor so I knew it had to be some sort of timing device, timer and using my knowledge of electronics I could figure out where the different components went, apart from if the LED would be on or off after the time delay, which I used the graph for . . .” (Interview Q3).

Jacob uses the capacitor to determine circuit type and make a link with the graph. When asked to clarify his ‘knowledge of electronics’, Jacob comments:

> "Well the *RC network so that one resistor has to be above and one below*, the transistor has to be protected by *roughly a 1K resistor* and *the LED has to be protected by a 150 Ohm*" (Interview Q3).

Jacob's sequence of representation use thus focuses first on the concrete presentation of available components, then uses the graph to clarify an aspect of circuit function.

Circuit Construction (n=10)			
Task Group	**Approach**	**Frequency**	**No. of data sources**
Analogue (n=6)	Components List-Graph-Formula	3	3
	Components List -Formula-Graph	2	2
	Components List -Graph Only	1	1
Digital (n=4)	Components List -Truth table Only	2	2
	Truth table-Components Only	2	2

Table 18: Sequence of representation use on circuit construction task (lesson 1)

The digital group were evenly divided between beginning with the component list or the truth table. However it might be implied that even those, such as David, who claimed to begin with the truth table, actually looked at the component list first to recognise the existence of the logic gate, as this comment suggests:

> ". . . the first thing I did was I used the truth table to recognise … what kind of logic gate I needed, because in the components list it just says logic gate, so that could be anything" (Interview Q3).

Again the representation sequence suggests beginning with concrete phenomena, then using more abstract representations to clarify aspects of the phenomena. This is a commonality across the analogue and digital task groups.

4.8.2 Program sequence and the use of representations

Task 3 in lesson 2 followed a similar pattern to that in lesson 1. Participants in both the analogue and digital task groups were provided with three representations (Appendix 3), as follows: a pinout diagram, circuit diagram and programming commands list. The analogue group were additionally provided with what was termed an event schedule.

This described the specific events and actions expected during circuit function. Similarly the digital group were provided with a truth table to provide corresponding information about circuit function. It is important to note here that different skills are needed to interpret these two representations, since the event schedule constitutes a sequential and the truth table a synchronous representation. The responses during interview are discussed in light of this difference.

In common with the circuit construction task, the analogue task group focused mainly on the concrete circuit diagram representation as a starting point for program construction (Table 19). The use of the programming commands list, or the event schedule, was then a useful subsequent representation. Feidhlim summarises the interview responses well when commenting that:

> “. . . this [the circuit diagram] *told me exactly what the circuit had to do* and this [the programming commands] helped me with the programming because I didn’t know the commands so well and then this [pinout diagram] *helped me with which ones* [the outputs] *I had to do . . .*” (Interview Q5).

The phrase *told me exactly what the circuit had to do* seems to suggest an element of immediacy in the concrete symbol-based representation.

For Ethan, on the other hand, the event schedule was a useful starting point because it supported writing individual code lines, for example “writing the *different sequences*, for example if switch one’s closed then D1 would be zero” (Interview Q5). Ethan explains:

> “. . . I started off, I looked at the circuit diagram as usually that’s the most helpful, but it wasn’t for the programming I found, so I just had to keep relating back to it after I was going through this [the event schedule], like a check list . . .” (Interview Q5).

Ethan therefore begins with the event schedule working through it in a systematic manner, referring to the circuit diagram periodically. This approach concurs with Ethan’s perceived conceptual understanding (i.e., logical approach), as described below in his conceptual profile (Section 4.9.3).

Program Construction (n=10)			
Task Group	Approach	Frequency	No. of data sources
Analogue (n=6)	Circuit diagram-Commands-Pinout-Event schedule	6	2
	Circuit diagram-Commands-Pinout	1	1
	Circuit diagram-Event schedule Only	1	1
	Circuit diagram-Event schedule-Commands-Pinout	1	1
	Event schedule-Pinout-Circuit diagram	1	1
	Event schedule-Commands-Circuit diagram	1	1
Digital (n=4)	Circuit diagram-Pinout	2	1
	Circuit diagram-Commands	1	1
	Circuit diagram-Pinout-Truth table	1	1
	Truth table-Circuit diagram-Pinout-Commands	1	1

Table 19: Sequence of representation use on program construction task (lesson 2)

The group completing the digital task also focused on the concrete circuit diagram to begin programming (Table 19). David, for example, explains:

> "*. . . I used this . . . circuit diagram to show . . . how the circuit's meant to operate*, so then I knew that if the output would be high, to simulate that then one other of the . . . inputs . . . into the chip would have to be high too . . ." (Interview Q5).

David goes on to clarify that "I first used the logic gate *to show the basic function of how the circuit should work when you program it*" (Interview Q5). David indicates the value of the circuit diagram in representing the concrete features of *basic circuit functioning* in conjunction with the pinout diagram which "[was used] *to show what pins I needed to be high or low at a certain point* for the circuit to be on or off" (Interview Q5). The truth table seems to be a peripheral consideration as participants were able to recognise the OR gate from existing knowledge.

The exception to the pattern of themes is Sam's use of the truth table to be able to:

> ". . . say that that gate there is an OR gate . . .", although he admits that "*It wasn't as much help* to me this time as I knew that that gate in there was already an OR gate" (Interview Q5).

Some of the representations therefore appear to elicit existing knowledge and others the provision of a clarifying function, concurring with observations on circuit building and use of representations (previous Section). Consequently participants would appear to benefit from the use of multiple representations, concurring with Ainsworth (2006); in these examples two representations seem to provide most of the required understanding.

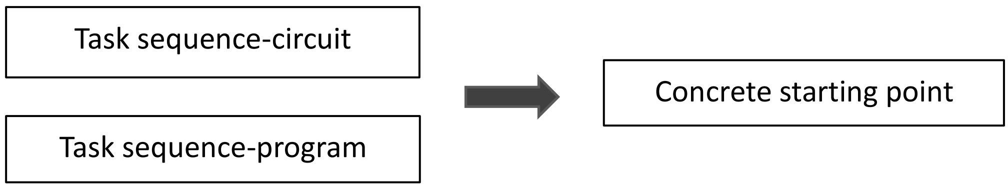


Figure 7: Task sequence concept diagram showing categories and key observation

4.8.3 Use of representations

The following section presents participants' specific approaches to representation use, as a part of developing conceptual understanding. The elicitation of existing knowledge emerged most frequently as participants' thought process when viewing the representations provided. Some explicitly cited their previous learning, for example "[I] *used prior knowledge* to recognise that and then . . . built a program around that" (Fergus, Interview Q5) and others implied their knowledge, for example "Has he made an *RC network* there, because I can see a resistor and capacitor?" (Connor, Interview Q4). The second quotation refers to knowledge (the RC network) not provided in the representation, therefore a clear reference to previous learning. The two approaches are considered to differ only in their linguistic choice. Findings in relation to existing knowledge concur with those from the paired image/word matching task, where the categories of representation use and problem solving also revealed significant elicitations of existing knowledge.

Building conceptual understanding therefore appears to involve, initially, a strong link with what is already known. However some of the comments relate to the subtly different *clarification* of existing knowledge, for example:

". . . you can see that *it's got to be the 20k* (20k resistor), that goes there because it's acting with the capacitor" (Feidhlim, Interview Q3).

In the next example Feidhlim recognises the combination of components and also uses the graph to clarify:

". . . *how long it took it* (the resistor/capacitor combination to create a time delay) to turn on and *it didn't turn on suddenly . . .*" (Interview Q3).

The latter comment "*it didn't turn on suddenly"* suggests Feidhlim's awareness of the gradual charging of the resistor/capacitor and therefore an awareness of the difference between analogue and digital type circuits, without mentioning these explicitly (see Section 5.5.3 and Discussion Chapter for reference to language use).

Use Of Representations (n=10)		
Use of Representation	**Frequency**	**No. of data sources**
Elicits existing knowledge	16	7
Focus on observable elements of representation	12	4
Clarification of knowledge	6	5
Support for multiple representations	7	4
Circuit is synchronous	3	2
Elicits link to programming	3	1
Program is sequential	3	2
Represents digital	1	1
Systematic approach	1	1

Table 20: Use of representations during circuit construction and program construction (Lesson 1 and 2)

Focusing on what can be observed directly in the representation was also prominent. Luke, for example, comments "most of them [output components] are *on the far right*" (Interview Q3), relating the representation to conventions for presenting electronics information where the output is normally on the right of the diagram. Fergus relates his understanding of the transistor to the diagram by observing the position of the input voltage:

". . . the circuit diagram visually helps you understand it [the transistor] as . . . it gives an idea of how a transistor works with the input voltage into it . . ." (Interview Q8).

The graphical layout, or spatial location (Larkin and Simon, 1987) and presentation of information is therefore an important consideration for some participants when using representations and forming electronics concepts in this case representing a synchronous preference in developing understanding.

For four of the ten participants, using multiple representations emerged as more useful to learning than singular representations (Table 20). Sam, for example, comments specifically:

> ". . . if a newcomer was to *see this diagram here* … they wouldn't know what the gate would be since there are different ones" (Interview Q8).

Sam implies that using a truth table in combination with a logic gate allows the learner to deduce the gate type where this is not recognised from the symbol. Conceptual understanding in this case therefore relies on the translation of two representations in its formation. This has been considered to increase some learners' 'cognitive load' (Ainsworth, 2006: 192), however in this study participants tend to report the benefits of using more than one representation type. This contradiction may relate to the nature of representations, with Ainsworth's (2006) discussion surrounding graphics with multiple elements, rather than multiple individual representations.

Recognising the synchronous and sequential nature of representations, concurring with the paired image/word matching activity findings, was noted as important for concept development. David commented that:

> "I think the circuit diagram *is easier to see*, because it's *represented graphically*" and "*Looking at the components* and *how the circuit's constructed* on a *basic level at first*, just seeing that . . . when one of the switches or both of them are depressed then the LED will light . . ." (Interview Q8).

David recognises that information presented graphically can be synchronously accessed *on a basic level*, which is here inferred to mean that the concept is quickly recognised through the circuit diagram. On the other hand Sam comments:

> "If they went to the program they would probably get more of a grip *since it explains it a bit more*, even when it's in the language [of computer coding] it's a bit understandable, since for example if pin 3 was 1, which is on, I'm pretty sure that someone would be able to figure that out" (Interview Q8).

In this section of the findings it is the same two participants comparing the synchronous and sequential approaches. Their comments however begin to explain the difference in approach more clearly than the inferences made in Section 4.5, in relation to image or word starting points, as they are able in the later questions to refer more widely to electronics and programming.

The remaining themes each relate to an individual approach to representation use. Connor for example elicits frequent links to programming when discussing representation use. Fergus makes a correct link between digital circuits and microprocessors and Sam's engagement with the representations revealed a markedly systematic approach to representation use. These individual approaches are discussed more fully within each respective participants' discussion of their cognitive profile (Section 4.9) and relate well to Kolb and Fry's (1974) perspective on individual differences during the learning cycle.

Figure 8 provides a summary of the category representation use when considered in relation to the overall aim of describing conceptual understanding. The common patterns and concepts are shown as emerging on the right hand side. When considering the phases of research and developing understanding about the data, Figure 8 shows Concrete to Abstract Thinking and the notion of Translation as additions to outcomes recorded in Section 4.7.5.

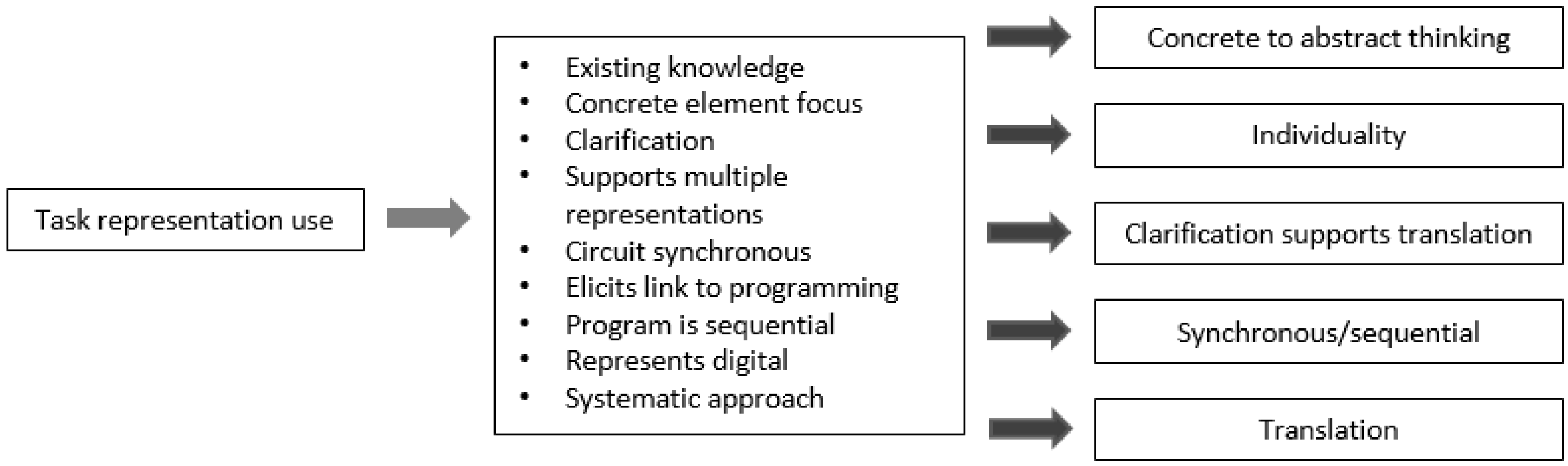


Figure 8: Task representation use concept diagram showing category, themes and key observations

4.8.4 Concrete to abstract transition

Engaging with an external representation signifies, at least initially, a concrete event in so far as the representation is a tangible object which is utilised by the user. Two participants (Table 21) evidenced solely concrete thinking. Luke for example refers to "the different *pins*" in answer to the exploratory question "what do these commands [output commands] represent?" (Interview Q6). In this case Luke relates the commands to tangible elements, the output pins of the microchip. The thinking is representative of Luke's cognitive approach (see Luke's Cognitive Map, Section 4.9.5) which remains close to those elements that can be observed within a representation or experienced as a practical activity.

Concrete to Abstract Transition (n=10)		
Theme	**Frequency**	**No. of data sources**
Concrete to abstract	10	5
Concrete only	4	2

Table 21: Transition between concrete and abstract thought (Lesson 1 and 2)

By contrast five participants evidenced clear incidents of a transition from concrete to abstract thought. Ethan, for example, stated that:

> ". . . I would sort of *visualise what the PIC chip would do* if it was trying to … complete the same function in this circuit" (Interview, Q8).

Ethan uses the concrete observation of a circuit diagram to produce a mental picture of the circuit's function when reproduced using a microcontroller. Ethan's thought moves beyond what can be observed in the circuit and creates the abstract representation of the microcontroller.

Similarly David comments ". . . the first thing I did was *I used the truth table to recognise* . . . what kind of logic gate I needed . . ." (Interview Q3). David uses the truth table, which provides the concrete representation of logic gate input/output conditions, to visualise the truth table's corresponding logic gate type. In addition to holding the abstract thoughts relating to logic gate function, David also evidences a transition from one representation type (truth table) to another (circuit symbol). Here the 'other' could have been a logic gate symbol, a logic gate within a circuit diagram or simply a verbal representation of the gate. David states:

> “. . . this [the truth table] *shows that the logic gate output is high when any or several of the inputs are high as well*, so that immediately *told me it’s an OR gate . . .*” (Interview Q3).

This demonstrates David’s knowledge, which is grounded in the binary notation of the truth table, rather than the form in which it is elicited in this example. I consider transition in detail in the forthcoming Discussion chapter.

It is interesting to note that the thinking emerging is either concrete, or concrete then a transition to abstract. In most of the cases recorded, participants began with a link to a concrete referent, then used this to generate an abstraction which enabled them to further their understanding of the problem and provide a solution. This concurs with Section 4.8.1 and 4.8.2 which discussed sequence of representation use. In the Discussion chapter, I consider the concrete to abstract transition in relation to Kolb and Fry’s (1974) experiential learning cycle and the notion that learners’ ability to make transitions between representations depends on their deep or surface level of representation use (Larkin and Simon, 1987; Seufert, 2003; Seufert and Brunken, 2006).

4.8.5 The role of memory

Ben, in contrast with the other participants, makes repeated references to memory and memorising information (Table 22). This is interesting as Ben appears to evidence and value memorising as a central element of his learning construct. Ben makes a valuable point about representation use and memory, suggesting that:

> “I think the program can help you to understand how the circuit will work, but I do think learning how to construct the circuit is better, because *once you memorise the circuit then you can remake it and adapt it*, whereas with the program you have to know what circuit you’re building a program for and exactly how that will behave” (Interview Q6).

Role of Memory (n=10)		
Theme	**Frequency**	**No. of data sources**
Role of memory	7	1

Table 22: The role of memory from circuit and programming construction (Lesson 1 and 2)

Ben’s comment emphasises the explanatory nature of the program on the one hand (sequential as opposed to synchronous) but infers that diagrammatic representation, through a circuit diagram, is more memorable and helpful to learning. Other participants support the explanatory nature of programming (see Section 4.8.8), but Ben's explicit mention of memory several times during the interview might suggest a closed approach to problem solving, rather than one based on discovery such as David's (see David's Cognitive Profile commentary, Section 4.9.2). Thus concept forming for Ben seems to be related to what can be held in mind about the visual nature of a diagram, which enables it to be made and adapted, but perhaps not fully understood; consequently memory may provide a pragmatic function, again a concrete referent, rather than an accurate representation of circuit function or theoretical perspective for Ben on this occasion.

4.8.6 The role of practical experience

Practical experience was important to developing understanding about electronics for six participants, who each evidenced specific comments to a hands-on approach through their use of the electronics simulation software Circuit Wizard. The simulation is here considered to adequately represent the 'real life' aspect of circuit function, as the animation provides real time representation of component function. Oliver explains:

> "I would first see *how the circuit would work in real life*, so taking that circuit and then putting it onto Circuit Wizard and seeing what happened when you put the two switches [together]" (Interview Q5).

In this case Oliver builds the circuit, even though the worksheets provided all the information needed to solve the problem. Feidhlim also relied on the circuit simulation to try out aspects of the problem, for example "I did the resistors *by trying them in different places* and seeing how long it [the time delay] took" (Interview Q3). Most of the comments relating to practical experience either suggested the opportunity to try out different approaches, or the opportunity to visualise aspects of the circuit.

In Luke's case, comments suggested a preference for physically working with the practical aspects of circuit building, for example:

> "*I prefer doing the more hands on thing*, like soldering and like getting the components and putting them in . . ." (Interview Q7).

When asked about learning preferences in relation to circuit building and program writing, Luke clearly prefers the practicalities of circuit building, rather than programming, for example:

> "I thought the first one [circuit building] because well *I always thought electronics was making*, rather than programming because *I always thought that was computing*" (Interview Q7).

The Role of Practical Experience (n=10)		
Theme	**Frequency**	**No. of data sources**
Reference to a practical approach	20	6

Table 23: The role of practical experience from circuit and programming construction (Lesson 1 and 2)

The role of practical experience in concept forming, for some of the participants, appears to make abstract information explicit and accessible. For Oliver circuit function is made explicit through switch activation and Feidhlim physically tries out the resistor options, rather than using the graph or formula. It provides a method with which to experience and visualise what is otherwise not easy to experience in real life, as Feidhlim comments:

> ". . . when you build the circuit *you realise the relationships* between the components" (Interview Q7).

In addition practical experience as a process enables some of the participants to try out alternative approaches to problem solving and arrive at a solution. This concurs with a similar process applied to problem solving in Task 1. It relates to McCormick's (1997) procedural knowledge approach to learning in Technology subjects. In the Discussion chapter I consider whether the role of practical experience is a replacement for references to existing knowledge or other approaches for some learners.

4.8.7 Conceptual understanding

The behaviour of voltage, as discussed previously (Section 2.2.2), either in its fluctuating form (Analogue), or in the form of a stable but polarised entity (Digital), represents a significant focus of the themes emerging within the category Conceptual Understanding. Because many of the concepts attached to component function are understood in relation to whether they are functionally analogue or digital, this understanding is considered key for concept forming and learning (see Literature Review for a discussion of this point, Section 2.2.2). The relative themes are represented by comments that reflect participants' understanding in terms of analogue, digital and logic circuits and are shown as linked with a highlighted cell in Table 24. Participant's overall understandings are commented on separately within each cognitive profile (Section 4.9).

Comments referring to analogue circuit types tended to focus on aspects of timing, possibly because the timing concept was used as a basis for some of the lesson materials, for example:

> ". . . [this is] a timing based circuit, because … *the capacitor is charging up* and then the LED comes on when it's charged" (David, Interview Q4).

David's comment reflects an understanding of analogue circuits through the concept of the time delay created using an RC Network (the combination of a resistor and capacitor). Other comments were not as technical, but nonetheless made a similar point, for example the comment ". . . it didn't turn on *suddenly . . .*" (Feidhlim, Interview Q3) in relation to the information shown on a charging graph (Circuit Construction Task A, Appendix 3) demonstrates an understanding of the analogue concept, as the alternative, turning on suddenly, would indicate a digital concept. The least technical comment, also from Feidhlim, stated "That's just *normal* electronics" when describing an analogue circuit in comparison to a logic circuit (Interview Q4). Judging from the comments, the variation in the use of technical terms does not appear to affect conceptual understanding, but may infer differences in the learning behaviour of these participants. This language link is explored in more detail in the Discussion Chapter (Section 5.5.3).

Conceptual Understanding (n=10)		
Theme	**Frequency**	**No. of data sources**
Analogue/digital distinction	11	5
Simple/complex construct	9	3
Analogue conception	8	3
Logic conception	7	5
Digital conception	3	2
Practical/cognitive distinction	2	1
Representation embodies concept	2	2
Foundation metaphor	1	1
Process component defines conception	1	1
Program representative of voltage	1	1

Table 24: Conceptual understanding from circuit and programming construction (Lesson 1 and 2)

Where a digital concept was explained, participants usually made a comparison with analogue circuit types, possibly because the interview question asked participants to describe differences or similarities between the types of circuit used in the lessons. For example:

> ". . . the other group they made a circuit *that either would or wouldn't turn on* when the switches were open or closed whereas the circuit that I made involved a time delay … the other one was simply a case of either on or off" (Ben, Interview Q4).

Ben indicates his understanding that voltage in digital circuits is bipolar. This understanding is reflected in a number of alternative terms, for example "multiple *states*" refers to the two possible states on and off (Fergus, Interview Q4). Ethan refers to a *pulse* in making the distinction, thus "this chip would generate more of a *pulse* I think so the LED would switch on off on off" (Interview Q4). Again use of the term *pulse* indicates an understanding of the digital concept, in that a pulse is either on or off. In one further example, Connor refers to ". . . [relating] logic gates more to *ones and zeros* than an RC network" (Interview Q4).

The term 'ones and zeros' is taken from logic gate terminology and is adopted by a number of the participants. Although participants use digital terminology correctly to describe differences in voltage behaviour, a number (n=5) use logic terms to make the distinction between analogue and digital voltage conceptions. This could be explained by the influence of engagement with the logic gate based task, however only two of the five participants (Connor and David) completed this task, the others (Feidhlim, Fergus and Jacob) completing the analogue version. Fergus refers to a distinction between the two circuit types used in the lessons by commenting "A logic circuit I would say involves some sort of … logic gate, *two or more states . . .*" (Interview Q4). 'Two or more states' indicates an understanding that the logic device operates using bipolar conditions as mentioned above. Concurring with earlier observations, participants therefore arrive at similar understandings using a number of approaches.

Other methods of describing differences in circuit concepts were used by a smaller number of participants. Simple/complex emerged as one method of describing voltage difference. David for example makes a distinction by considering that:

> ". . . they're both circuits that would light an LED, but they use different components and this [timing circuit] only has one input whereas this [logic

> gate circuit] has two inputs, then *if you had a different logic gate it could obviously be a more complex circuit* whereas this is more of a just a simple switch" (Interview Q4).

To clarify 'simple switch' David comments:

> ". . . this is just *basically a simple* [switch], but put into a circuit with a transistor, whereas *this could be made into a more complex circuit*" (Interview Q4).

David appears to relate simple/complex to the number of components used and to the nature of the central processes involved, thus one input to a transistor (simple) and two inputs to the logic gate (complex). Here there are similarities with the theme Representation Embodies Concept (Table 24), in that the imagery appears to elicit a conceptual perspective held in relation to its content.

David's conceptual understanding is revealed through language based in digital, logic and the more 'common usage' terminology discussed above. In contrast Oliver, who completed the digital task, used only common usage terms to describe his understanding of circuit concepts. Oliver refers to "a simple circuit" which involves "one process, an output and one input" (Interview Q3) when describing the digital circuit he completed. When describing the alternative analogue circuit, Oliver comments:

> "This one's [the digital circuit] *more straight forward than that one*" explaining "It's got a bit more background knowledge needed to do that one [the analogue circuit], than this one because this one's only got the one process *whereas you're combining transistors and an RC network here*, but you're not really doing anything on that one . . ." (Interview Q4).

Oliver arrives at the following position which suggests an understanding of different circuits, but eludes any distinction on the basis of voltage concepts:

> ". . . this one's [the analogue circuit] *more to do with timing than this one*, but the similar thing is they both have a input process and output, but the outputs are the same but the *processes are different* and the inputs are different" (Interview Q4).

In this comparison of two participants, one who demonstrates a clear understanding of voltage concepts (David) and one who demonstrates his understanding through functional differences (Oliver), a commonality can be found in the focus on component types and an understanding of the processes involved. Both participants demonstrate an understanding of the circuits, however their concept forming appears to be differentiated by a focus on terminology and voltage behaviour on the one hand (David) and a focus on circuit type and circuit function on the other (Oliver).

David's thinking may also relate to the synchronous/sequential method of presenting information, for example he suggests:

> "Looking at the components and how the circuit's constructed *on a basic level at first*, just seeing that … when one of the switches or both of them are depressed then the LED will light, whereas *in the program you have to sort of read it more* and then you also have to understand how it works . . ." (Interview Q8).

David clarifies further that ". . . you have to do the circuit [construction] first, then *writing the program helps you to sort of further your understanding of it*" (Interview Q8). 'Basic level' here appears to relate to the initial understanding of the circuit's basic function (LED turning on following a switch push), whereas writing the program could be inferred as a process which is helpful due to its sequential nature.

Other methods of demonstrating a conceptual understanding included Luke's circuit building/programming (Practical/Cognitive, Table 24) distinction ". . . one's more practical I guess and one's more *thinking about it*" (Interview Q7). As previously discussed, Luke tends to identify with a practical approach and prefers observable and tangible elements. The comment 'thinking about it' seems to suggest that Luke has formed an understanding of programming that is something other than electronics; electronics being understood by Luke in terms of something practical.

Referring to the comments of Connor and Fergus, the representations seemed to embody the voltage concept (Representation Embodies Concept, Table 24). For example the following from Fergus (Interview Q3) explains the relationship between a charging graph and conceptual understanding (ST-student, AT-researcher):

ST: Yes the component list that was obviously very helpful and the formulae was less helpful, *but the graph was quite helpful as well*, depending on what the actual task was.

AT: What's helpful about the graph, then, do you think?

ST: *I see it as a voltage charging*, so I saw that … *immediately as an RC network*.

AT: Right OK, and so how did you then relate that to the circuit that you built?

ST: Well I then looked at the component list and saw there was a 1000 microFarad capacitor and a 20K resistor and I had a quick glance at the formulae to make sure I was along the right lines and not using the wrong resistor and then went and built the circuit.

Fergus's comment 'I see it as voltage charging' in this context demonstrates the meaning he attaches to the charging graph and how he links this to his existing knowledge of RC Networks (the term RC Network was not introduced on the worksheets). The concept of a charging RC Network is therefore embodied within the graph.

Similarly Connor (Interview Q3) articulates a practical understanding of the truth table through his knowledge of binary, thus:

AT: When you talk about *gets a one*, what are you relating that to?

ST: *Binary, so on and off*.

AT: How does that work in practice, when let's say you've bread boarded this circuit, or indeed you created it on Circuit Wizard, how does one or binary relate to actually working with the circuit on screen in practice?

ST: Well *for this because* [the truth table] … *was in binary … I found it easier to relate this* circuit to binary.

Connor demonstrates his understanding in the binary notation used to represent voltage behaviour within a truth table. When he talks about 'gets a one', it suggests that the concept of voltage being received by a component is visualised in binary terms (zeros and ones), rather than for example as a voltage trace on a graph, as in the case of Fergus above. This relates to the common pattern of the personalisation of knowledge and approach to its construction.

A further conception is represented by Feidhlim (Interview Q8) who explains:

ST: It makes what the chip is doing clearer *because you can see what the chip is doing, turning on an LED because you programmed it to do that*.

AT: Ok so you're saying that the program makes that clearer?

ST: *When you can see the program and see what the chip is doing, you can see the relationship between the two*.

AT: And that is different than looking at the circuit you think?

ST: Yes because the circuit *you don't see what the capacitor is doing and what the resistor is doing*, you just don't see their effect. So you don't see what's happening inside the capacitor to make it charge up and you don't see what's happening inside a resistor that makes it have that resistance.

AT: Ok.

ST: And how an LED works, whilst *with the program you can see what the program does, so you can see that when you say high C.2 there it puts the second output high and that makes the LED or whatever's connected to the second output go high*.

AT: Ok.

ST: So *it just makes it clearer*, what's happening inside.

Here Feidhlim suggests that the concept of voltage is explained through the programming codes used to operate the microchip (Program Representative of Voltage, Table 24). The programming codes, in Feidhlim's terms, represent what's going on inside the microchip whereas when using discrete components (capacitors and resistors) you are unable to 'see' what's going on inside them.

A final conception is based in the Process Component that Defines Conception theme (Table 24). Ethan refers to the transistor as the 'main component' that defines the circuit type, thus this process component is identified as representing ". . . what the circuit does and what it is" (Interview Q3). In comparison Ethan comments ". . . this *chip* would generate more of a pulse I think so the LED would switch on off on off and this one is a … sort of time delay . . ." (Interview Q4). Ethan uses the central process components, the transistor and the 'chip', to distinguish between the two different voltage types and thus the analogue and digital circuits. He evidences another method with which to conceive of voltage types and communicate his understanding.

Figure 9 shows the emerging patterns and concepts for the category Conceptual Understanding. Some of the pattern and concept outcomes are shown in Figure 8 (Section 4.8.3), with the addition of language use as a highlighted outcome in this section. It is useful to reflect at this point, that Metioui and Trudel's (2012) claim that all electronics phenomena are interpreted in relation to the concepts of current and voltage, as proposed earlier, is a good starting point for considering learners' understanding, but can be clarified with the detail emerging from the evidence above (see Literature Review, Section 2.2.1).

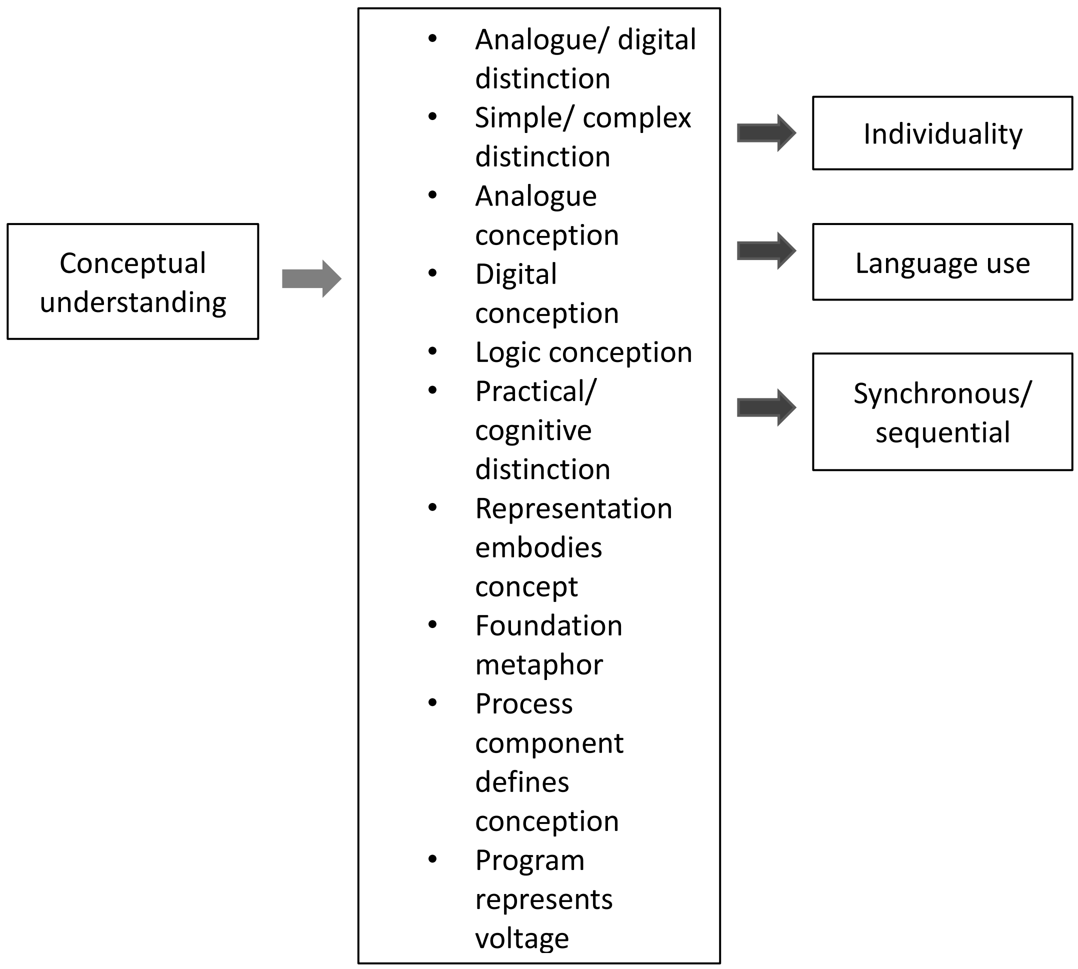


Figure 9: Conceptual understanding concept diagram showing category, themes and key observations

4.8.8 Learning with representations

In this final theme, consideration is given to the role of the representations in learning and developing electronics concepts. As previously the themes emerge from the second part of the individual interviews, which focused on the circuit building and program writing activities. Some of the responses emerge from asking participants to comment on their learning with representations in response to the question 'Having both built a circuit and written a program, which method of representing electronics is most useful to learning about electronics and why?' (Interview Q7). The themes are organised and discussed beginning with the most frequently occurring contributing utterance.

Eight out of ten participants made a specific comment in relation to the prominence of the circuit diagram for learning (Circuit Prominence, Table 25). Most of the comments compare the circuit diagram with writing a computer program, because Question 7 involved asking about both approaches. Responses demonstrate overwhelming support for the circuit diagram as a concrete starting point for understanding and for program writing. Oliver makes the point "you can't do the programming without understanding the circuit first" (Interview Q6). Fergus suggests this is:

> ". . . because *you can build a basic circuit without programming*, but you need to build a circuit to program in" (Interview Q7).

Feidhlim also supports the circuit as a starting point for understanding, suggesting:

> ". . . it's easier to *see how the circuit works* . . . and then use that to make a program . . ." (Interview Q8).

This preference may suggest, as discussed previously (Section 4.8.3) that viewing a circuit diagram provides synchronous access to information and a more immediate understanding, as opposed to reading a program which takes more effort and time (see Literature Review Section 2.1/2.6.3 for discussion on this point). Ben seems to imply this view commenting "I probably couldn't get a circuit to mind from the program, but I could probably think of the program from the circuit, I think the circuit's better for understanding" (Interview Q8).

Ben elaborates with a useful viewpoint:

> ". . . it [the circuit] *shows you the components*, whereas with the program *you just get the functions those components carry out* and there are quite a few components that could fulfil the same function" (Interview Q8).

Ben indicates that the circuit is specific in providing information about components, which would otherwise not be evident from a program, which as Ben suggests represents circuit function only. Therefore attempting to construct a circuit from a program would present a number of variables not present in the reverse sequence.

Learning with Representations (n=10)		
Theme	**Frequency**	**No. of data sources**
Circuit prominence	21	8
Programming explanatory	17	9
Role of trial and error	16	5
Practical approach-building the circuit	9	7
Programming develops understanding of electronics	9	4
Circuit represents functioning	6	4
Use of existing knowledge	5	3
Circuit accessed synchronously	3	1
Circuit embodies coding	2	2
Programming is not practical	2	2
Programming allows simulation & check of circuit design	1	1
Transition through Functional Elements	1	1

Table 25: Learning with representations from circuit and programming construction (Lesson 1 and 2)

This finding, that a consensus position exists supporting the circuit diagram as key representation, presents a contrast in relation to the next prevalent theme Programming Explanatory (Table 25). This theme suggests that the programming language helps to explain circuit function, as it provides a symbolic representation (Paivio, 1986) of the circuit, for example:

> "If they [a newcomer to electronics] went to the program they would probably get more of a grip [understanding] since it explains it [the circuit] a bit more . . ." (Sam, Interview Q8).

Similarly Ben suggests ". . . I think the program *can help you to understand* how the circuit will work . . ." (Interview Q6). This may be because:

> ". . . with the program you can *see what the program does*, so you can see that when you *say* high C.2 there, it puts the second output high and that makes the LED or whatever's connected to the second output go high [turn on]" (Feidhlim, Interview Q8).

Feidhlim suggests that the program explains the function of the circuit, which is considered to be helpful to learning. Fergus also clarifies with:

> ". . . if there was something on the circuit diagram that you didn't recognise then it would be easier to use the program, if you knew what you were doing, so then you can try and work out what that component is doing from reading the circuit diagram" (Interview Q8).

Here Fergus explains that the program provides the explanation about something incomprehensible (of course as long as an understanding of programming exists). The understanding, however, does involve the extra effort of reading the codes, as Fergus also explains:

> “. . . you can get that information [circuit functioning] from the program, yes, but sometimes particularly with long programs it might take . . . you a while to get your head around what’s being done in the program” (Interview Q8).

Overall the comments surround the effective use of the circuit diagram as a concrete referent whilst the program provides additional explanatory information, using codes which are sometimes in abstracted form. This emphasises earlier observations suggesting that a concrete to abstract direction is generally followed during representation use and problem solving.

These examples emphasise the differences between synchronous and sequential representations. The Synchronous access to information (Circuit Accessed Synchronously, Table 25) was a theme which emerged in its own right from Fergus’s interview. As he explains in relation to circuit diagrams:

> “. . . you can *see what’s going on very very easily without having to read through lines* of [code]” and clarifies in relation to sequential access “. . . well when I see a circuit diagram, maybe not immediately but it’s much much quicker to get your head around than a longer program” (Fergus, Interview Q8).

Although each participant seems to value both representation types, with the exception of Sam, the circuit seems to provide a specific point of reference for participants in identifying circuit type and components. The program then adds the explanatory information which clarifies circuit function if required. It is interesting that the first two themes largely represent the recognition of knowledge, whereas in subsequent themes the focus is mostly on the process undertaken by participants when learning about electronics (Table 25). This may be representative of earlier observations suggesting an initial focus on concrete features of representations.

The most prominent process related theme, in terms of number of data sources (n=7, Table 25), is related to the benefits of building the circuit in a practical way. Ethan for example suggests:

> “. . . I think they’re different [approaches to learning] because obviously this is programming and that’s building a circuit but *for the overall understanding I find that building the circuit is more helpful . . .*” (Interview Q7).

Feidhlim suggests that “. . . when you build the circuit you *realise the relationships* between the components” (Interview Q7). Both comments concur with the analysis above, revealing that a specific type of understanding and point of reference can be gained from the diagram, in this case relationships between components.

Sam explains that “*I experimented* with Circuit Wizard for a while, *trying different combinations*” (Interview Q3). The practical process emerged as a valuable approach, indicating that trial and error forms a useful approach by participants (see Literature Review, Section 2.6.1/2.6.2) and a prominent theme (Table 25). Feidhlim was a significant proponent of trial and error, whose comments are representative of the theme, as he comments:

> “. . . so I get it to work reasonably well but have the wrong time delay and then *I’ll move the resistors around until it has the right time delay*” (Interview Q8).

Oliver suggests that the process is representative of ‘real life’, as follows:

> “I would first see *how the circuit would work in real life* so taking that circuit and then *putting it onto Circuit Wizard and seeing what happened* when you put [closed] the two switches” (Interview Q5).

Building a circuit practically using Circuit Wizard simulation software (New Wace Concepts, 2012) is described as useful to understanding because the process allows participants to physically try different combinations and in addition this process has been considered to be representative of working with the real life components.

Extending the Programming Explanatory theme above, Programming Develops Understanding of Electronics (Table 25) emerged as a specific method of learning. In its most basic form, as discussed above in the Programming Explanatory theme, the program “… probably clarifies what you think that circuit is” (Jacob, Interview Q6). However in this new theme several participants eluded to program related learning, for example David (Interview Q7) explains:

> ST: I think that programming kind of *helps you to understand it more*, then I think that constructing the circuit’s good for, when you’re first getting used to how a component works.

AT: What is it about the program that helps you understand it more would you say?

ST: Because it's not just something that you construct and then know how it works, you have to understand how it works to then apply it to write a program, so *it's kind of the next level of understanding.*

Similarly (Q8):

ST: Well it's quite easy to construct a circuit from a circuit diagram.

AT: Right.

ST: That you have first, but then *you have to apply your knowledge as well when you're writing a program* because *it's not as easy as just putting a gate in there and then wiring it up.*

AT: Ok.

ST: *You have to think more about what you want the circuit to do* and then look further into that see how it would work.

David implies that programming supports learning, as to enable programming a good understanding is needed of the circuit, which is applied in the transition to program code. Connor also values the program as a learning tool, but applies his knowledge and enthusiasm of computing when making a transition between a circuit diagram and program, as follows:

> ". . . it's helped me [the program] understand . . . I do programming in my free time at home as well occasionally, so generally it's just an easy way *to relate something that sometimes I may find complicated to something that I find relatively easy . . .*" (Interview Q8).

The program therefore is considered to develop understanding by extending thinking about the circuit concepts and, in the case of Connor, enables understanding through a programming 'lens'. This is developed in Section 5.3.4.

There were some less prevalent themes related to learning and programming. For example Programming Allows Simulation and Check of Circuit Design (Table 25) emerged through David's concern to use the program as a method to check circuit function, thus:

> "I think it [programming] *helps you to understand* how the circuit works … if you're using a logic component as well *because you can simulate how it should work* by programming something [a microcontroller] . . . and [it] kind of shows you the basic of how this circuit should work, so if you're constructing a circuit and it was a more complex circuit with different logic

> gate or combination of gates I think that would make it more relevant to program something as well, just so you could show how the circuit should work . . .” (Interview Q6).

David here supports earlier analyses which highlighted the program as an explanatory representation. In addition David suggests that circuit functioning can be simulated by the program, alongside circuit construction, to help with the understanding of more complex circuits.

In the theme Programming Is Not Practical (Table 25) David and Ethan emphasise their understanding of programming as a non-practical approach to learning, thus:

> “. . . *you have to apply your knowledge as well* when you’re writing a program, because *it’s not as easy as just putting a gate in there* and then wiring it up” (David, Interview Q8).

David suggests both a distinction between circuit building and programming and increased difficulty attached to programming. The distinction between circuit and program is similarly emphasised by Ethan who comments:

> “. . . I think they’re different because obviously this is *programming* and that’s *building* a circuit, but for the overall understanding I find that building the circuit is more helpful . . .” (Interview Q7).

Ethan later suggests that “it [the program] helps you understand the *processes* in the circuit and what it’s actually *doing*” (Interview Q8). As discussed previously, these themes add further support for learning through programming as an explanatory representation. Ethan appears to value both circuit building and programming, but understanding processes in the circuit would seem to support the explanatory function of the program.

In the theme Circuit Represents Functioning (Table 25) the distinction between process and function is emphasised, for example:

> “. . . the circuit diagram *figures out where each connection is connected to*, *where everything is* in the circuit diagram, *where everything goes*” whereas “. . . you only see outputs like high one [in the program], *you don’t see what it actually turns on*” (Jacob, Interview Q7).

This seems to suggest that for concept development, both representations are useful as they adopt a different role in supplying information about the system in question; the circuit providing concrete information about component placement, the diagram providing an explanatory function.

In the theme Circuit Embodies Coding (Table 25), the diagram is perceived as an embodiment of the programming code. Ethan for example suggests:

> ". . . you can then *see what they're* doing [the codes] in the circuit and *this is a more visual way of seeing* what each of those . . . code lines actually is [as a function]" (Interview Q8).

This demonstrates Ethan's understanding of the relationship between code and circuit and represents support for learning through a transition between one representation type and another, based on functional elements of the phenomena. David also supports the notion of Transition through Functional Elements (Table 25), observing that:

> ". . . that line [if pin 3 is high or pin 4 is high then goto this subprogram] is acting like a logic gate would" (Interview Q8).

Here links can be made with earlier observations relating to synchronous and sequential representations and the ability to make transitions between one representation type and another. However the starting point is reversed possibly emphasising participants' preferences in approach.

Finally the Use of Existing Knowledge emerged as an important starting point for learning for three of the ten participants who evidenced this in a specific way (Table 25). Feidhlim for example stated that ". . . when I'm creating a circuit *I just use my knowledge* to try and get something that's quite close . . ." (Interview Q8) and similarly Fergus states ". . . I immediately started by seeing that the LED and resistor *should be* at the output . . ." (Interview Q3).

The use of existing knowledge links with the discussion relating to problem solving above. Participants appear to draw on their prior learning when problem solving and therefore during learning. This is not always explicitly stated, as noted earlier. Those who explicitly state the link may be more aware of their use of existing knowledge and this is considered in more detail in the Discussion chapter. Overall the approaches to learning with representations reflect parallels with Kolb and Fry's (1974) experiential learning cycle, particularly the processes in which learners actively experiment and clarify knowledge; this is also developed in the Discussion chapter.

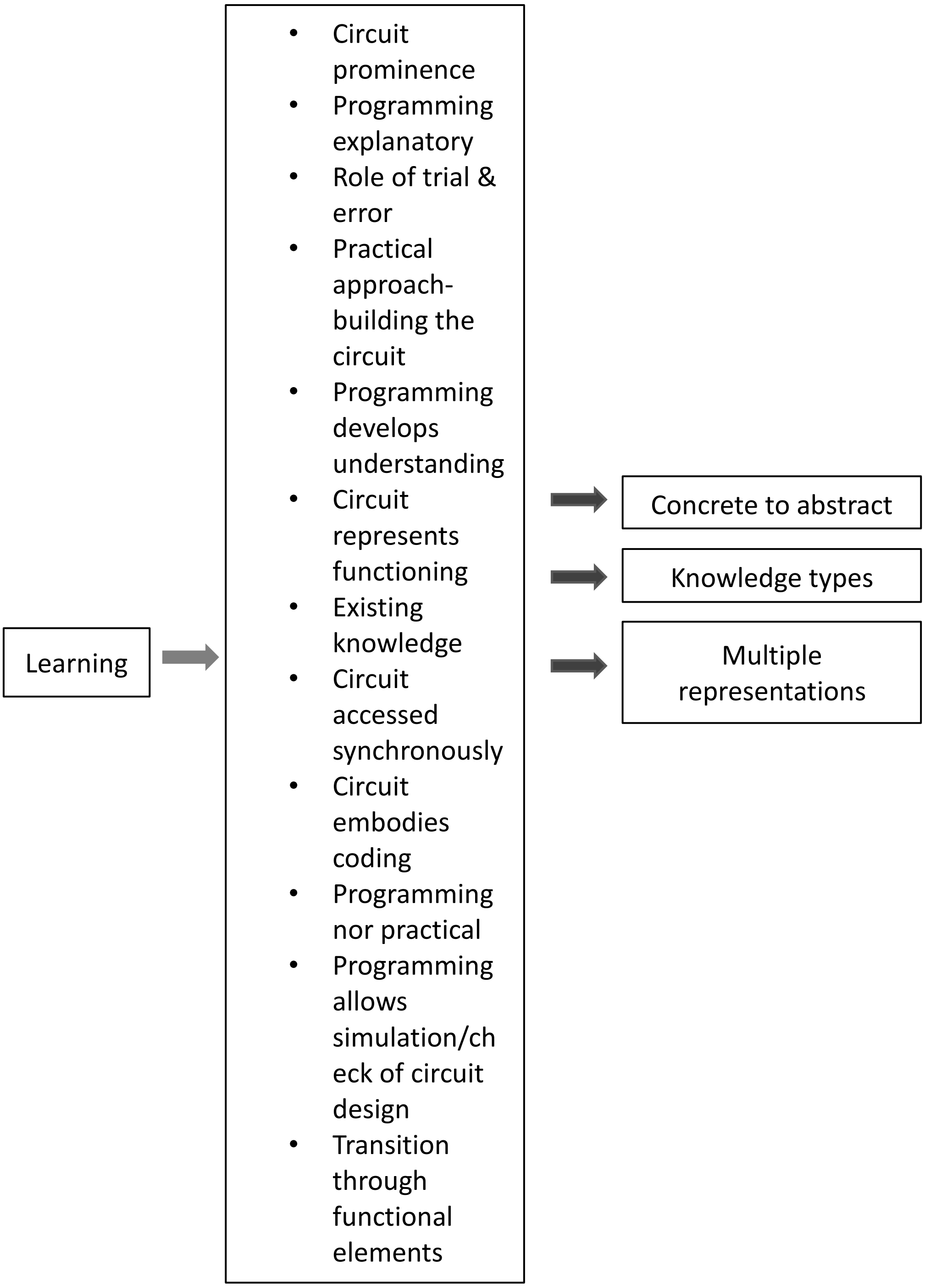


Figure 10: Learning with representations concept diagram showing category, themes and key observations

4.9 Conceptual understanding: Cognitive mapping

The cognitive maps in this section are my representations developed from the analysis of transcripts discussed above and each map represents one of four profile types (Operative, Logician, Programmer and Dialectic). The cognitive maps draw from Solsona et al.'s (2003) development of conceptual profiles and are presented drawing from

Jones's (1985) cognitive mapping. The cognitive maps relate to participants' conceptual constructs relevant to representation use, conceptual understanding and learning (themes representative of the research questions). The maps reflect my interpretation of participants' perceived type of conceptual understanding, as determined from their individual transcript, based on a development of Wu et al.'s (2001) levels of representation (as discussed in Methodology, Section 3.6). Each map contains an overall classification of the participants' level of conceptual understanding, expressed as 'Wu's Level', a classification of their related 'Conceptual Construct' (e.g., functional, programming) and an indication of participants' level of concrete/abstract thinking as determined by their interview responses.

My development of four profile types represent exemplary, differentiated approaches to participants' constructions of electronics concepts. There is a fifth profile, David's, which represents an exception to the cognitive profile type, and is instead an example of a prominent approach, namely an exploratory approach to thinking and problem solving. It was felt that this was significant enough to include as a cognitive representation and also includes examples of thinking in relation to programming, analogue and digital understanding and logic.

The participants featured in each profile represent the exemplary cases, which are representative of several participants in most instances. Although those featured bring to light a particular conception, they also reveal some of the other participants' key conceptions in most cases. For example Ben, Luke and Oliver are all considered to focus on functional (Operative) aspects; Luke however is considered to be particularly practical in his approach and he is discussed from this perspective. Each map is explained in light of the previous analysis and categories (Sections 4.2-4.8) and draws on examples from the participants' transcripts. The map topics are presented within numbered boxes where the number is used to link the map with each participants' commentary. Following Jones (1985), the boxes are linked with an arrowed solid line where one topic is tentatively considered causative of another and a broken line where topics have some, again tentative, non-causative link. The labels in upper case and underlined are categorisations which link with the categories emergent from the thematic analysis in Section 4.4-4.8. Table 26 summarises and provides a comparative overview of each participants' construct and relationship with Wu et al.'s (2001) levels.

Participants' Cognitive Constructs (n=10)				
	Level of Understanding (from Wu et al. (2001)			
Name	**Observable**	**Symbolic**	**Abstract**	**Key Conceptions**
Ben (A)				Functional/Voltage Levels (Operative)
Connor (D)				Programming/Logic (Programmer)
David (D)				Functional/symbolic/abstract (Explorer)
Ethan (A)				Functional/Digital (Logician)
Feidhlim (A)				Functional/Programming (Programmer)
Fergus (A)				Analogue/Digital/Programming (Dialectic)
Jacob (A)				Functional/Symbolic/Programming (Programmer)
Luke (A)				Functional/Practical (Operative)
Oliver (D)				Functional/Simple-Complex (Operative)
Sam (D)				Functional/Logic (Logician)

Table 26: Summary of participants' cognitive constructs

4.9.1 Profile 1, Connor: The Programmer (Digital Task)

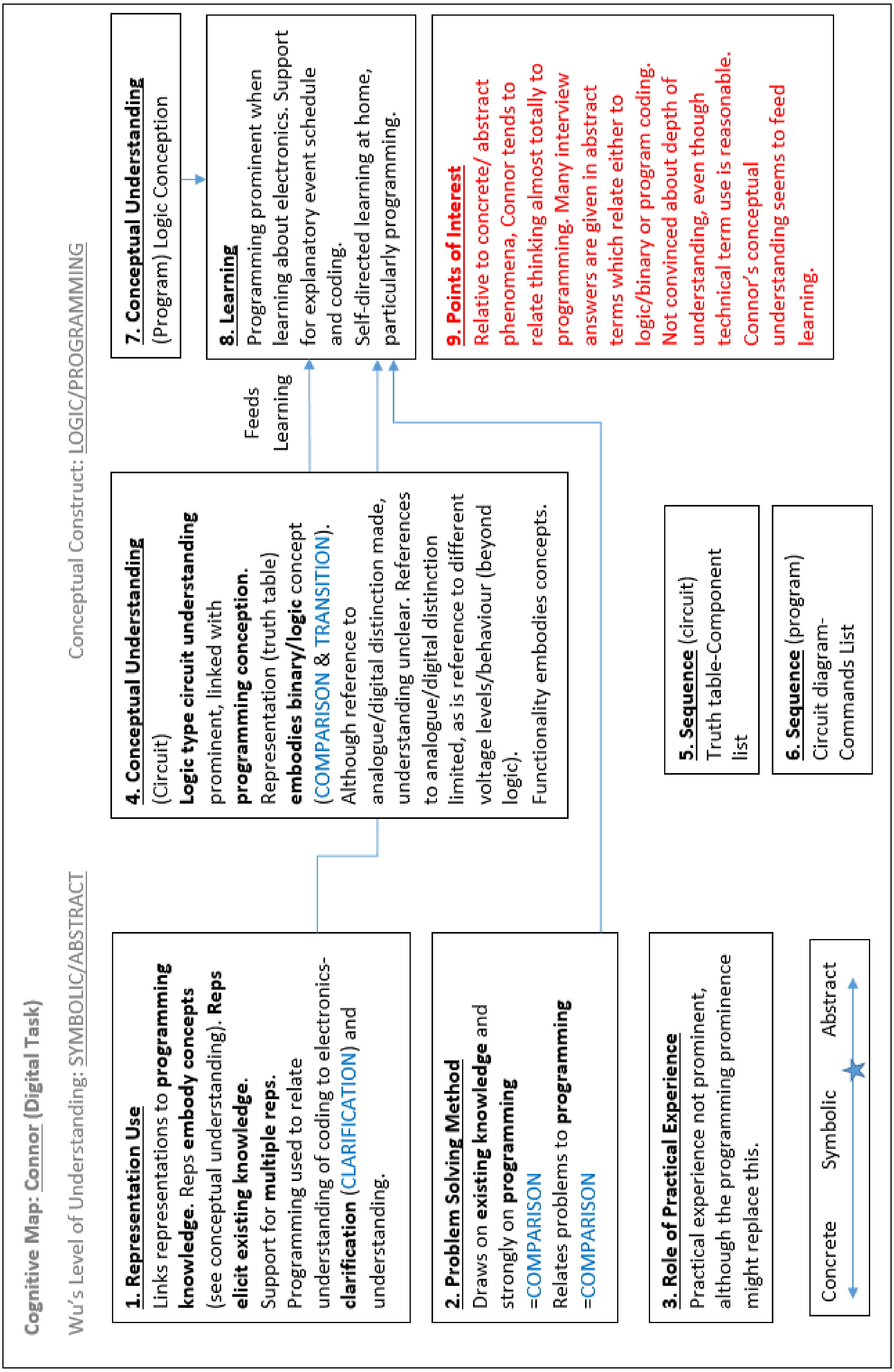


Figure 11: Cognitive Map 1 – Connor

Connor's use of representations (Box 1) elicits a connection with existing knowledge, for example from Interview Question 1 in relation to the paired image/word task Connor suggests:

> ". . . when I think of a transistor *I just think of an RC network* . . . because it was the thing that was mentioned the most when we came to work on transistors so . . . *we just associate transistors with RC networks now*".

Here Connor's engagement with the formula, a symbol-based representation, T=RC elicits an understanding about time delay and the need for a transistor to control the output voltage.

In using existing knowledge, Connor makes strong links with his knowledge of computer programming, stating that ". . . generally I would just prefer programming . . ." (Interview Q7). The comment ". . . for this (the truth table), because it was in binary with the truth table, that's why I found it easier to relate this circuit to binary . . ." (Interview Q3) suggests that some representations, in this case the truth table, effectively embody electronics concepts for Connor (i.e., binary/logic concepts). This allows him to think about circuit operation in the abstract, for example he converts program coding into circuit operation by describing the outcome of the code when in use ". . . for this 'if-then-else', *that is like if this switch is flicked then it* [the voltage] *goes to here . . .*" (Interview Q1). This provides evidence for the use of representations in the clarification of programming knowledge and subsequently in the clarification of overall conceptual understanding.

Connor's approach to problem solving (Box 2) also makes use of existing knowledge and programming, and makes some use of the process of elimination, for example ". . . we just came to that conclusion *at the end* as that was . . . the only one left" (Interview Q1). This is particularly the case in the paired image/word matching task. Using existing knowledge and program referents enables Connor to compare the observed representation with these referents and therefore comparison also forms an important role in processing information for Connor. The role of practical experience (Box 3) is not prominent in Connor's responses, however the links with programming could be inferred to replace this.

The conceptual understanding linked with circuits (Box 4) however evidences the practical application of circuit function. Connor often refers to 'it' as a representation for voltage, for example "... *it* would just go through a resistor ..." (Interview Q1). This may reflect Connor's conception of voltage, which could be said to draw on a mind's eye visualisation of the voltage 'route' around the circuit. When describing circuit behaviour, Connor draws on conceptions of binary and logic. He makes a limited distinction between analogue and digital, for example "... the graph is increasing *gradually* to 100%, where it reaches full charge ..." (Interview Q1), however it is not clear whether this distinction is fully understood as Connor goes on to relate his observation to the Full Charge label on the diagram.

Reference to different voltage levels or variable voltage behaviour is limited; functionality is otherwise almost totally conceived as a binary/logic and programmed phenomenon, never an analogue conception. There is some conflation of the terms logic and digital. Conceptual understanding linked with programming (Box 7) follows that evidenced for the circuit in that reference is frequently made to binary, logic and programming code. The following is a good example of Connor's thinking which first explains program function and then compares this with the corresponding circuit function:

> "... so this one I thought like *programming wise if both the outputs are off then the light wouldn't turn on* but if even one of … the switches are on then the light must turn on" (program explanation); "So these are what I thought A and B would be, because this is A and B the switches to make it zero and one and the light turning on ... *if it gets a one through either leg then it lets out a one ..."* (Interview Q3).

Connor's use of representations in the construction of a circuit (Circuit Sequence, Box 5) follow his preference for logic type circuit references. He accesses the truth table first because it clarifies the operation of the logic gate, then uses the components list to determine circuit function using specific components. In the programming construction task (Box 6) Connor uses the circuit diagram to engage with the concrete aspects of the circuit function, in common with several other participants following the digital task (see Section 4.8.2).

Learning (Box 8) about electronics is clearly linked with programming. There is support for the explanatory benefits of representations, such as the event schedule in particular and program code, for example:

> “It [the event schedule] *tells you when the LED should be on*, because *it says D1 status and when it should be off*, and so if switch one is closed and then the circuit’s on, but the LED is still off” (Interview Q8).

The sequential medium, such as computer coding, appears to provide a strong referent in Connor’s electronics learning. Self-directed learning is inferred as a feature of Connor’s learning, thus:

> “Well it’s [computing] helped me understand … I do programming in my free time at home as well occasionally, so generally it’s just an easy way to relate something that sometimes I may find complicated to something that I find relatively easy it makes the topic more easy . . .” (Interview Q8).

In summary Connor’s learning process appears to first make a comparison with existing understandings about binary/logic circuit functioning, then use his logic and computer programming knowledge to make transitions between representation types to develop understanding and support problem solving at a position between the symbolic and abstract levels of Wu et al.’s (2001) Levels of Understanding. A fully abstract understanding is not warranted as Connor’s conception appears to be closely related to the symbolisation provided by logic systems and program coding only, making very limited reference to analogue systems.

It is interesting to note (Box 9) that Connor bases his conceptions almost totally in logic and programmed type systems. It could be argued that he followed the pattern offered in the digital task, however there were opportunities to expand on the analogue circuit type and concepts in the interview which were almost taken, but not developed. Connor’s concrete referents seem to be the symbols connected with logic, such as binary notation, program coding and the experience of circuit functionality. The particular conception that Connor holds (logic/binary/coding) seems to support his learning because, as discussed above, it appears to support the transition between representations which allows progress to be made, for example the transition between truth table and circuit diagram through the symbols of binary notation.

4.9.2 Profile 2, David: The Explorer (Digital Task)

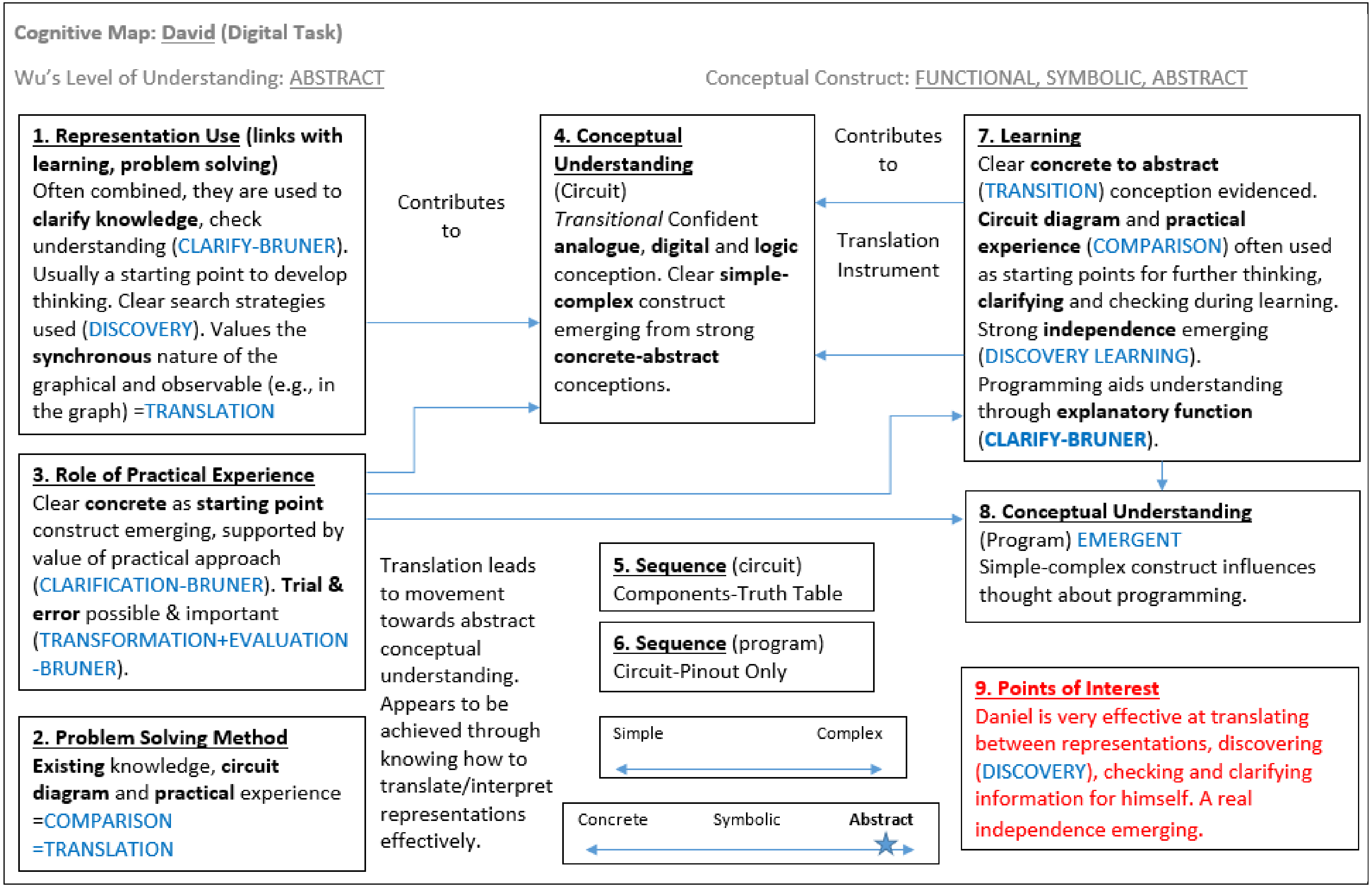


Figure 12: Cognitive Map 2 – David

David's comments surrounding representation use (Box 1) reflect their frequent use in clarifying existing knowledge. For example he states:

> "We could immediately pair that ['pulse' with square wave image] and then some of the graph ones as well were quite easy to tell and then *we knew* that this one would have some sort of element of current flow into it and this was the only diagram that showed that" (Interview Q1).

As with other participants, clarification of existing knowledge featured prominently in the use of representations. However David's responses suggested that he was open to allowing his growing understanding to develop thinking, for example in relation to programming from a circuit diagram he notes "You have to think more about what you want the circuit to do *and then look further into that to see how it would work*" (Interview Q8). Similarly he continues:

> "I think that if you have a larger more complex circuit it would be more beneficial [to write a program] you'd get more out of writing the program as well, because *you'd sort of develop an understanding of how the different gates work as well and you'd have to apply that*" (*ibid*).

Frequent comments surrounding exploration have led to the 'discovery' style of learning discussed further below.

David thus demonstrates his ability to search the representations to provide clarification for understanding. He values the representations providing synchronous access to information, for example:

> "Looking at the components and *how the circuit's constructed on a basic level at first* . . . *whereas in the program you have to sort of read it more* . . . if you didn't have the explanations here as well [the event schedule] *it would certainly be a lot harder to get the information from the program*" (Interview Q8).

Use of the circuit diagram and graph again link with his search strategies and discovery approach to learning.

Representation use and problem solving (Box 2) often combine to support understanding. David uses the circuit diagram as a prominent and concrete starting point and acknowledges that some representations, such as the graph, provide easier access to information when compared with the circuit diagram:

> “. . . [where] it may be more difficult [to problem solve] because *you might have to pick out a certain bit of the circuit diagram that’s relevant*” (Interview Q1).

The process of elimination was also an important approach for David when pairing images and words. David recognises and makes a distinction between what representations can offer in terms of concrete/abstract knowledge and uses his existing knowledge to interpret them. He seems to differentiate between functional representations and those that embody more abstract knowledge.

The role of practical experience (Box 3) has close links with problem solving. David refers to practical application often, using it to aid the translation of representations. He makes a distinction between what can be known about electronics 'in the real world' and what a circuit diagram can tell you. Again the notion of a clear concrete starting point is reflected in the pragmatics of practical application.

David has a good conceptual understanding of analogue and digital circuit types (Box 4), which is initially described in terms of *practical interpretation* (analogue) and *graph* (digital). David explains further:

> “. . . with this one [the analogue circuit] you’d have to talk about timing, *because there’s the capacitor and the resistor and the RC network,* so it’s discharging/charging and then the LED would come on after a certain time. Whereas this one [the logic circuit] it’s, *there’s no kind of element of charging in it,* so it would just be a logic circuit” (Interview Q4).

An alternative *simple-complex* construct is also employed in the responses during interview, for example:

> “. . . they’re both circuits that would light an LED, but they use different components and *this only has one input whereas this has two inputs* then if you had a different logic gate *it could obviously be a more complex circuit* whereas this is more of a, just a *simple* switch” (Interview Q4).

Here simple-complex reflects an analogue/digital conception. The analogue/digital conception is also later reflected in David’s confident use of technical terms including logic terms and concepts which are correctly differentiated from digital concepts. David moves from the concrete to the abstract, drawing on information from circuit diagrams and symbols and existing knowledge as starting points. The concrete-abstract sequence is supported by the sequence of representation use (Box 5,6). Practical experience is again prominent in the development of conceptual understanding.

The translation of representations is key to transition between them. In the interviews Question 5 asked how participants went about using representations to arrive at a program. David comments (Interview Q5):

ST: Well *I used . . . the circuit diagram to show . . . how the circuit's meant to operate* so *then I knew that if the output would be high*, to simulate that then one other of the outputs, inputs sorry in to the chip would have to high to, to have an output but there could only be one of them just showing how you would program a logic gate using a chip instead . . .

AT: Ok.

ST: *I first used the logic gate to show the basic function of how the circuit should work*, when you program it.

AT: Do you mean physically, using Circuit Wizard?

ST: No I didn't construct it I just used this diagram.

AT: Oh Ok.

ST: Because *I know what the function of the OR gate is.*

AT: Yes.

ST: So then it just . . . needs one of the two inputs to be high to have an output high as well.

AT: Ok.

ST: Which would turn on the LED.

AT: Right, alright so you used the circuit diagram in that way.

ST: Yes.

AT: And then constructed your program did you?

ST: Yes just around that, yes.

AT: Ok so did you use any of the other bits of information that I gave you?

ST: *Yes I used the pinout* [diagram] *here to show what pins I needed to be high or low at a certain point for the circuit to be on or off*.

AT: Ok and, yes go on.

ST: And then constructed it just using them and then I didn't use the truth table in this one because it, I already knew it was an OR gate there, so you don't really need it.

The translation of representations leads to a move towards abstract conceptual understanding, which appears to be achieved through knowing how to interpret diagrams, tables and pinout diagrams, as demonstrated in the quotation above. He supports the use of multiple representations, believing the combination to be most useful ("I think the image [in combination] makes it a lot clearer than just the words", Interview Q2). When considering conceptual understanding relative to computer programming (Box 8), this knowledge can be seen as emergent, in that it emerges through the development of the concept because it cannot be directly observed. David's conception of programming appears to be influenced by his simple-complex construct, where program coding is viewed as complex and circuit construction as simple, for example:

> "I think that programming kind of helps you to *understand it more*, then I think that constructing the circuit's good for, when you're first getting used to *how a component works*" (Interview Q7).

David suggests this is because ". . . it's [coding knowledge] not just something that you construct and then know how it works, you have to understand how it works to then apply it to write a program, so it's kind of the next level of understanding" (Interview Q7). Translation in the form of understanding therefore leads to a transition between circuit diagram and program code.

David's use of representations in the construction of a circuit (Circuit Sequence, Box 5) follow his preference for concrete starting points. He uses the component list to gauge circuit requirements, then uses the truth table to clarify the logic gate type, which was not possible using the component list. In the programming construction task (Box 6) David uses the circuit diagram, again to begin with the concrete aspects of the circuit, then uses the pinout diagram to clarify microprocessor pin numbers with input/output requirements.

A clear concrete to abstract transition ability seems to aid learning (Box 7) for David. He values the circuit diagram as a prominent starting point to provide a rapid synchronous link to observable elements and existing knowledge for comparison and clarification. He also values the explanatory nature of program coding:

> "I think it [programming] *helps you to understand* how the circuit works . . . if you're using a logic component as well because you can simulate how it should work by programming something . . ." (Interview Q6).

David suggests that the process of coding could be very instrumental in developing an understanding of circuits and therefore another opportunity for clarification of knowledge. Again the simple-complex construct is evident in portraying conceptual understanding. David’s learning also benefits from the practical circuit building experience. The circuit building provides an opportunity for the valued trial and error method of problem solving; the programming is seen more as a thinking task.

A particularly prominent aspect of the interview with David (Box 9) was the impression that he actively explores the information available to him. This emerged through comments such as those noted above, and the dialogue presented in Section 4.9.2, which were unique to David’s interview. He makes similar comments repeatedly, supporting an exploratory approach to the representations where he seems to genuinely look for information during problem solving and in making inferences. Thus a discovery style classification of learning seems warranted when describing David’s approach within the context of concept development, although it is recognised that this classification differs from the other four within the taxonomy as it does not represent a specific way of thinking about electronics, as do the others.

4.9.3 Profile 3, Ethan: The Logician (Analogue Task)

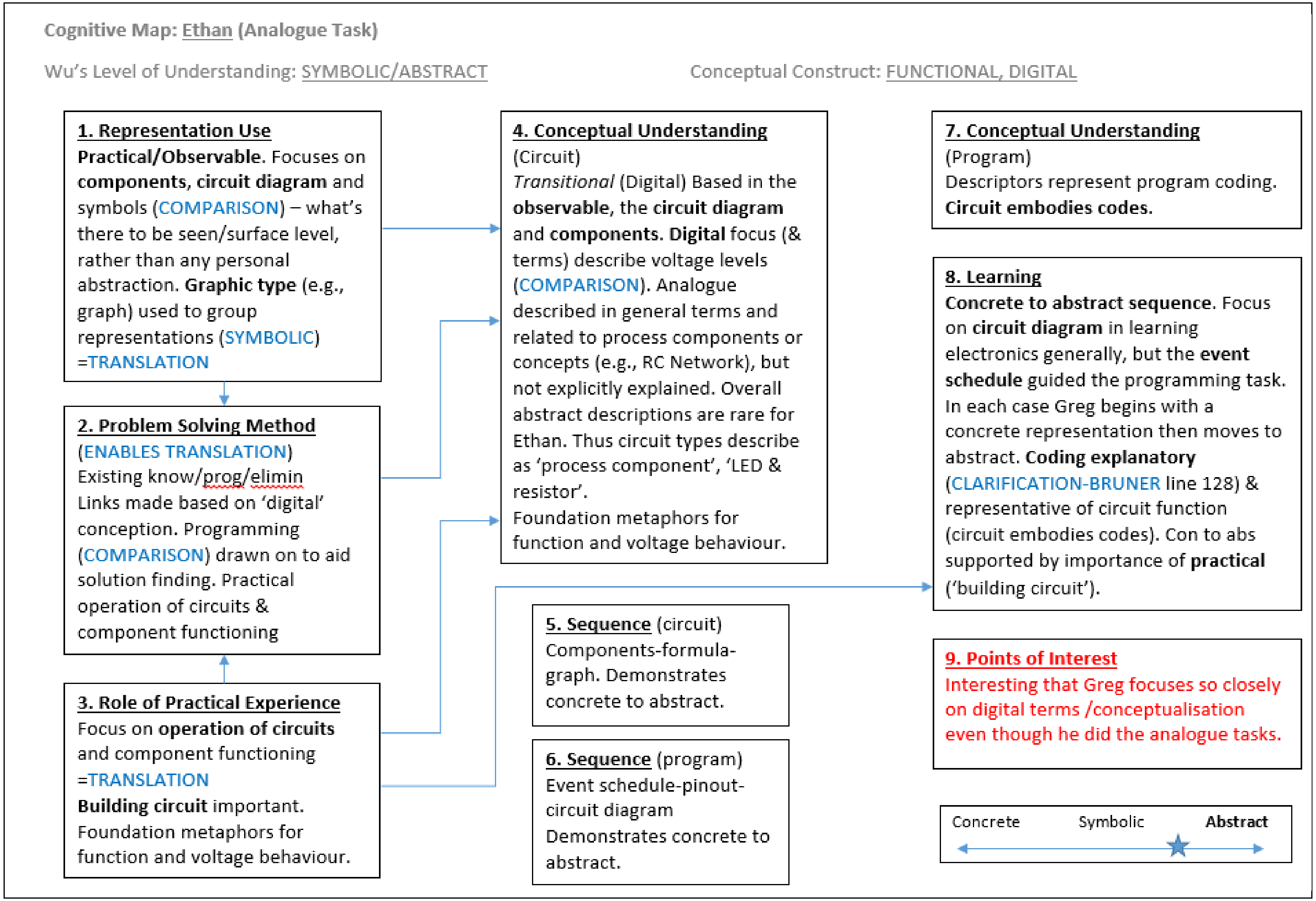


Figure 13: Cognitive map 3 - Ethan

Ethan tends to relate representations to observable phenomenon (Representation Use, Box 1). For some of the pairings during Task 1 the type of representation is used to group items together (e.g., graphs):

> ". . . I'd group these two because *they're a circuit diagram showing the components* and I'd also group these two just *because of the type of visual they are*, *they're both graphs*" (Interview Q2).

When viewing certain representations, Ethan focuses on the components, circuit diagram and symbols in a way that refers to what's there to be seen in concrete form and the operation of circuits in practice.

Ethan links the images and words partly using an association with programming code and partly referring to digital electronics (Problem Solving Method, Box 2), for example he makes an association ". . . because in *programming* when you want to switch something off you can say *LED low or input low . . .*" (Interview Q1). The process of elimination is also used to complete the few remaining pairs. Ethan makes a strong connection with logic circuits ". . . it's a *pulse* because the voltage was is *systematically on and off . . .*" (Interview Q1). Practical application is a key approach to problem solving and developing understanding, thus ". . . I started off by just *getting all the components* in this list on to where I was going to build my circuit . . ." (Interview Q3).

Ethan recognises digital circuit operation from the symbols, graphs and circuit behaviour in terms of voltage levels, such as with the use of the terms '0', '1', 'high' and 'low'. Conversely he describes analogue circuit behaviour using descriptions of components and their functions, without explicitly mentioning analogue or similar terms. This understanding of the analogue/digital concept is inferred from the following comment:

> ". . . this chip would generate more of a *pulse* I think so the LED would switch *on off on off* [digital concept) and this one [RC Network representation] is a … sort of time delay? … when you switch the switch the capacitor fills and the . . . resistor and that causes a time delay [analogue concept], so I think this is already doing what . . . a more complicated circuit would do for you. It's an integrated circuit kind of thing" (Interview Q4).

The Role of Practical Experience (Box 3) is emphasised through the operation of circuits in practice (e.g., "when you switch the switch") and their observable outcomes (e.g., LED turning on during "time delay").

A clear understanding of digital circuits is evident. It forms a strong conception for Ethan in relation to circuits (Conceptual Understanding, Box 4). Although no references to analogue are made, there is a statement to suggest an understanding of where one representation is and is not analogue ". . . the pulse and the charging *aren't really related*" (Q2). His understanding is described in mildly abstract terms. He suggests an understanding about the difference between digital and analogue concepts through the references to logic and descriptions of circuit functioning, as in the comment above. Circuit behaviour is described largely in terms of digital voltage levels. Conceptual understanding is partly grounded in the process component used in the circuit, for example:

> ". . . I'd say *the transistor's the one that really defines* … what the circuit does and what it is" (Interview Q3) and ". . . I would sort of visualise *what the PIC chip would do* if it was trying to um complete the same function in this circuit" (Interview Q8).

and the combination of components such as RC network (indicating an analogue understanding). The central process component therefore forms a key differentiating factor between circuit types. Conceptual understanding in terms of programming (Box 7) is manifested in terms of digital concepts and as already mentioned programming aids Ethan's understanding generally as it "helps you understand the processes in the circuit and what it's actually doing" (Interview Q8).

In common with other participants, Ethan generally describes a process of working from concrete to abstract, therefore focusing on the circuit diagram, components and observable elements of the representations first (Circuit Sequence, Box 5). This is evidenced in the use of representations to develop the circuit which followed a components→formula→graph sequence. Similarly, in the programming task the sequence was event schedule→pinout→circuit diagram (Program Sequence, Box 6), again Ethan begins with the observable more concrete event descriptions to aid problem solving. This concurs with the concern to identify central process elements discussed above.

Ethan is methodical which is evidenced through a focus on the verbal and sequential nature of some of the representations, used such as event schedule and component list (Learning, Box 8). He applies these when problem solving, particularly when translating circuits into programs. Programming is seen as descriptive and representative of circuit function (as previous comment Q8). Conversely the circuit is described as embodying the programming codes as in the following:

> AT "when reading the program how do you relate the program to this [circuit] information?"
>
> ST "with the commands you can then see what they're doing in the circuit and this is [the circuit] a more visual way of seeing what each of those … code lines actually is".

Programming is not seen as practical, the approach is ". . . different because obviously this [Task 3] is programming and that's [Task 2] building a circuit" (Interview Q7). The circuit diagram plays a key role in developing understanding about electronics (". . . for the overall understanding I find that building the circuit is more helpful", Interview Q7), but the program is also described as supporting this understanding with descriptive explanations of functioning, as discussed above. In the programming task, the descriptions of circuit function provided by the event schedule formed a key representation for Ethan, who only used the circuit diagram for clarification purposes. The program is described as taking understanding "to another level" (Interview Q6), which is inferred to mean a more developed level of understanding. Specifically, the program is described as *explaining* "the processes in the circuit" and "what it's actually doing" (as comment above Q8).

Building the circuit (or creating it using Circuit Wizard) is described as most useful for learning about electronics. Circuit types are described using different levels, for example "main component" describes one type (discussed in terms of process component above) and "LEDs and resistors" describes another (Interview Q3). The type of circuit is thus seen on different levels, as in the learning examples above. Ethan uses a number of foundation metaphors to describe circuit function and voltage behaviour. These allow the quantification and description of largely voltage levels in digital form (e.g., high, low, down, going up). It is interesting that the digital/logic focus is as prominent, considering that Ethan did the analogue task (Box 9). This supports the notion of personal construct choice/development, rather than constructs loosely based around the convenience of recent experience (Kelly, 1963).

4.9.4 Profile 4, Fergus: The Dialectic (Analogue Task)

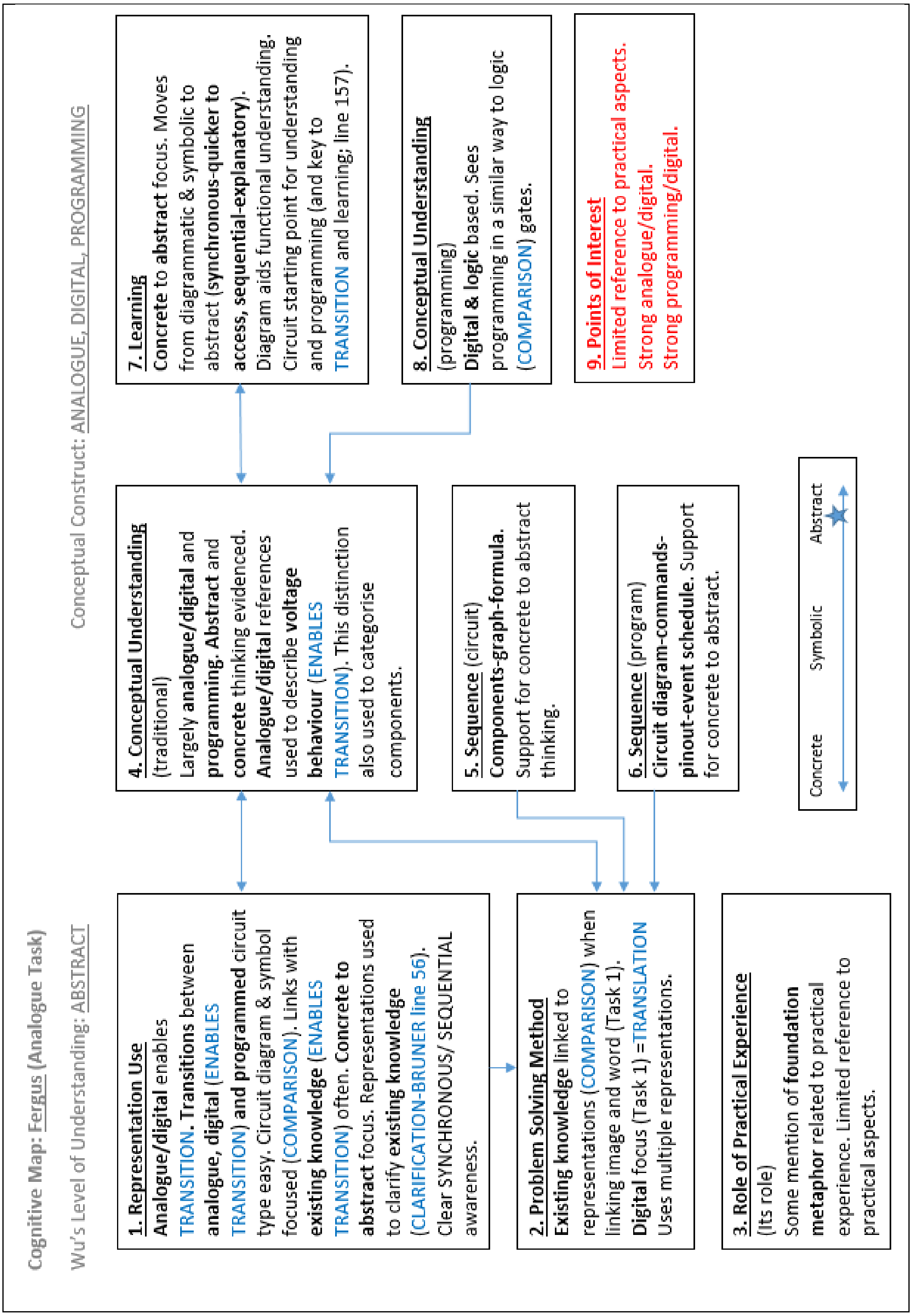


Figure 14: Cognitive map 4 - Fergus

The Dialectic takes its name from the closest term that is considered to represent, although not perfectly, someone who understands something 'of or relating to logical disputation' (CODCE, 1990: 322). In this research study, this relates to differentiating between analogue and digital circuits and understanding both of these oppositional concepts. Although others also evidenced this understanding, Fergus more than the other participants, evidenced a distinct understanding of the opposing voltage behaviours and clearly articulated this throughout the interview. The following is typical of the level of understanding and clarity offered by Fergus during his interview (Interview Q4):

> AT: If I asked you to try and characterise this circuit that the others built and the circuit that you built, are you able to say that this is one circuit type or this is another circuit type?
>
> ST: Well *that's a logic circuit*, *I would class that as a digital logic circuit and an analogue probably is to do with charging … and it's got a number of voltages and currents involved.*
>
> AT: Right so I was going to go back to … what you said there, so you're saying that analogue actually relates to charging?
>
> ST: I would say that *charging is analogue* yes.
>
> AT: Right OK, so … what is your definition of an analogue circuit?
>
> ST: An *analogue I would categorise as the opposite of digital, so it's more than multiple states, not just two.*
>
> AT: OK … and what creates those multiple states, what is it about the circuit that sort of provides the idea that there are multiple states?
>
> ST: Well in this case *the charging of the capacitor* but it could be a variable resistor or an LED in . . . with an operational amplifier.
>
> AT: OK … and then what about the logic circuit then that you've mentioned?
>
> ST: Right.
>
> AT: What's your definition of a logic circuit?
>
> ST: *A logic circuit I would say involves some sort of logic gate, two or more states* and then probably a function together to create an output state, in this case an OR gate I believe, so one or the other or both of switch one and two would provide an output at the LED.

Fergus evidences a preference for image based information, in the form of circuit diagrams, symbols and pictorial component representations. He promotes the circuit diagram as the central source of understanding about electronics, but recognises the important role of prior knowledge in their interpretation and references it regularly. The use of representations (Box 1) is often linked with abstract information. Fergus goes beyond the observable, concrete information provided, demonstrating an ability to think and converse on an abstract level. Representations characterise abstract information for Fergus; consequently a clear interaction was revealed between problem solving (Box 2) and conceptual understanding (Box 4).

Evidence reveals use of representations at the concrete level, for example:

> ". . . all you can see on those (charging trace) is graphs so *you can't see the circuit that links them . . .*" (Interview Q2).

Fergus acknowledges the flexibility of image use through the application of terms to more than one phenomenon. He differentiates between functional representations and those that display phenomena only (e.g., voltage). Fergus draws on existing knowledge frequently in problem solving (Box 2). Pairings during Task 1 were achieved by translating the observable elements of the representation, then making a transition between this and his existing knowledge, for example:

> "The next thing I saw is that *I immediately recognised*, before seeing the word, that that is a clock pulse so I matched that with the word pulse . . ." (Interview Q1).

He often verbalises understanding using abstractions (e.g., *digital path*) based on combinations of digital and analogue (e.g., *any number of voltages*) concepts, as follows:

> ". . . these um three here we saw as *digital path*, paths, so it was between *the 0 state and the 1 state*, so those three and were reasonably compatible together and these two are both high and low but they're not in a *direct digital state*, because that could be *any number of voltages powering the LED* for example" (Interview Q2).

The Role of Practical Experience (Box 3) references practical application only in connection with some of the components, rather than drawing on it to aid explanations or understanding (particularly in the early stage of the interview related to Task 1).

Fergus evidences an in-depth conceptual understanding of electronics in terms of analogue, digital and program-based references (Conceptual Understanding, Box 4). He has very well developed understandings based on analogue and digital circuits which are explicitly stated. The following comment is representative of Fergus's level of knowledge, which reveals digital, analogue and programmed concept understanding:

> "I started off with these two here, and immediately attached them to 0 and 1 before sticking everything down . . . because I can clearly see that's going from 1 to 0 and that's clearly going from 0 to 1 . . . and I next went to high and low, I saw that in a high state because it's turned on and that it's marked off with the switch so it was low and high. The next thing I saw is that I immediately recognised before seeing the word that that is a clock pulse so I matched that with the word pulse . . . and I used the word in the diagram for charging which is 'full charge' to match that up . . . and I saw this as an RC Network with a resistor and capacitor meaning T was RC and I was left with these two and I used my knowledge of logic and computing to recognise that [if-then-else statement] as a logic if-then . . . if switch 1 is down then the LED is high else A is high" (Interview Q1).

Programming is linked with logic at times and programming code is well understood. Fergus can make transitions between representations, his knowledge, computer programming and analogue and digital circuit types at an abstract level. He is able to make transitions between analogue and digital circuit types and can translate circuits into programs with ease.

Fergus evidences a transition from the concrete to the abstract when describing representation use and his approach to learning. This is evidenced in his described sequence of representation use in the circuit building task (components→graph→formula) (Box 5) and programming task (circuit diagram→commands→pinout→event schedule) (Box 6). Descriptions of circuit function from concrete representations support the notion of thinking at an abstract level, rather than that grounded only in the observable or practical, for example Fergus explains:

> ". . . the location of the RC network was apparent to me as to . . . make it . . . charge up the transistor [concrete observation] … in order to make the LED work and we used switch 1 as a discharge function for the capacitor … as a reset [abstraction]" (Interview Q3).

Abstract representation is also noted as useful in clarifying knowledge, for example (Interview Q3):

ST: The graph was quite helpful as well ... depending on what the actual task was.

AT: What's helpful about graph then do you think?

ST: I see it as a voltage charging ... I saw that … immediately as an RC Network.

The use of analogue and digital references make the clear distinction between different voltage behaviours, in terms of either analogue or digital circuit types. For example the analogue descriptions reflect a varying voltage and the digital tend to reference a binary '0' or '1'. Evidence also suggests that this distinction extends to the categorisation of components, for example a clear link is made between resistors and capacitors and analogue charging to create time delays (e.g., quotation above, Interview Q1).

In relation to programming, Fergus makes a connection between coding and logic circuits (Box 8). In opposition to other participants who conflate the terms, Fergus correctly uses the terms 'digital' and 'logic', thus "I would class that as a digital logic circuit" (Interview Q4) accurately represents the circuit. Although circuits and programming are suggested as equal contributors to learning, a clear preference for the circuit diagram and symbols comes across as a concrete starting point (Leaning, Box 7), for example:

> "I think the circuit diagram visually helps you understand it as, it goes, for example on this one it gives an idea of how a transistor works with the input voltage into it". "You can get that information from the program, yes, but sometimes particularly with long programs it might take … you a while to get your head around what's being done in the program [and] you can see what's going on very very easily without having to read through lines of code or writing" (Interview Q8).

Here clear support for Larkin and Simon's (1987) position on the immediacy and synchronous nature of diagrams is evidenced, which is supported by descriptions of the synchronous nature of viewing the diagram; coding representation considered by Fergus to take longer to access.

There is support for the program as aid to learning however, as Fergus comments:

> ". . . if there was something on the circuit diagram that you didn't recognise then it would be *easier to use the program if you knew what you were doing*, so then you can try and work out what . . . that component is doing from reading the [program] . . ." (Interview Q8).

Although some of the foundation metaphors used reference practical experience, Fergus's comments link largely with abstract thinking linked with circuits and components, making few references to practical experience. This may explain and support Fergus's obvious ability with the programming tasks and knowledge of this area.

However Fergus maintains that building the circuit is an important starting point for learning, particularly when developing a program.

The limited reference to practical aspects is interesting (Box 9). Perhaps because Fergus's knowledge is so good, it can be transmitted in ways that bypass the hands on experience. Fergus seems to interact between knowledge, observations and representations using well-formed abstract models. However having observed this student in the production of a high quality GCSE coursework outcome (see Table 11), I am aware of his frequent use of practical means to support his learning, the interview however did not reveal this. The strong analogue/digital understanding is unusual among the participants. A strong programming/digital understanding however parallels some of the other participants.

4.9.5 Profile 5, Luke: The Operative (Analogue Task)

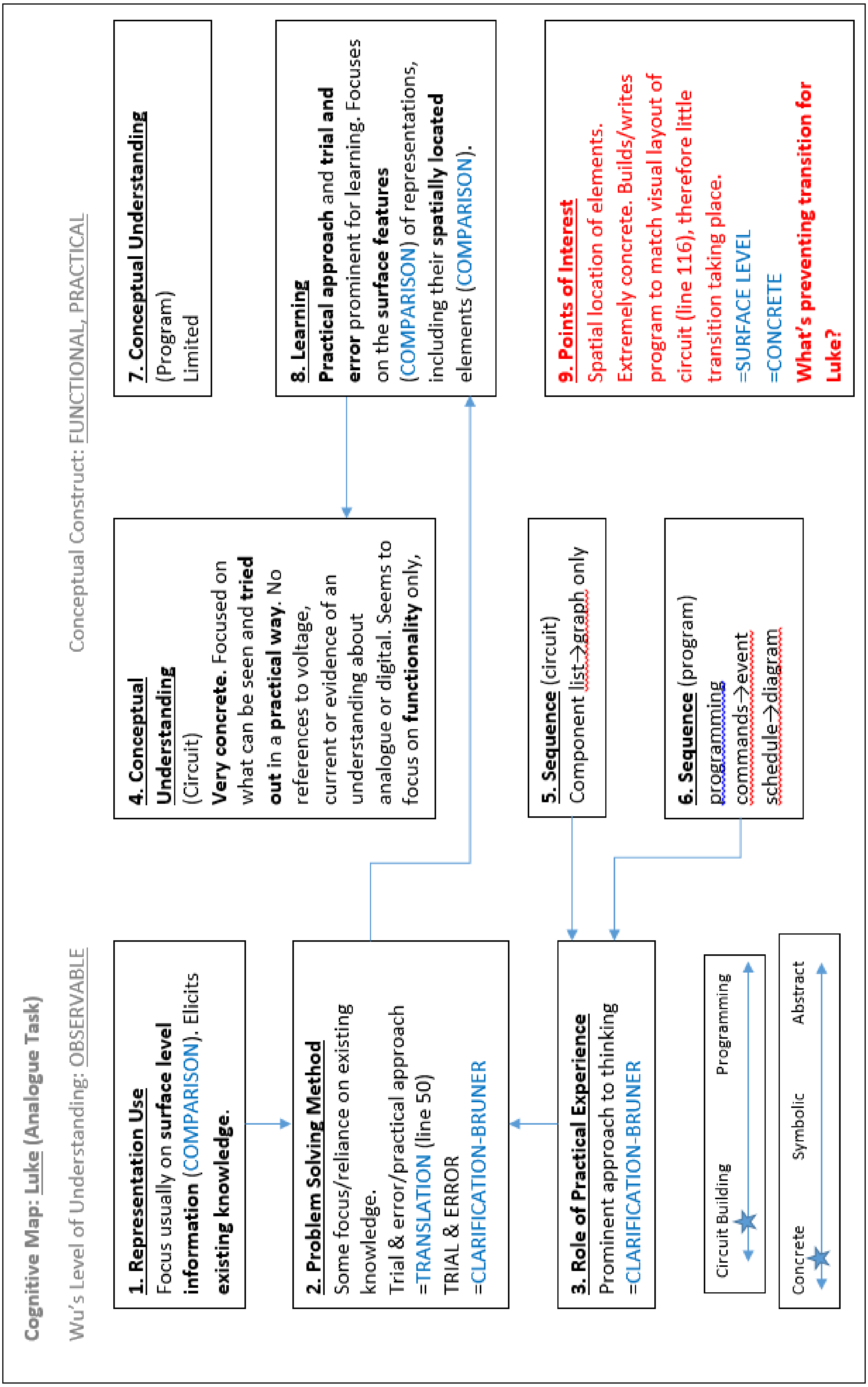


Figure 15: Cognitive map 5 - Luke

When using representations, Luke focuses on the observable, concrete (surface or graphical level) elements. He does not evidence a transition beyond the observable or use language which would suggest abstract thoughts during the lesson tasks. He relies on his existing knowledge and often discussion around a representation leads to links with practical electronics applications or a practical approach to tasks. Consequently Luke's conceptual understanding is considered to remain at the concrete, or in terms of Wu et al.'s (2001) levels, observable level. When translating representations (Problem Solving, Box 2), particularly during Task 1 (the paired image/word activity), Luke tends to focus on the practical application of components or circuit features ("high because *the LED's on* and pulse because *you can see it there pulsing*", Interview Q1), often using trial and error to achieve this. Thus pairing is achieved by relating what's known in a practical sense (Role of Practical Experience, Box 3) to observable features of representations and links with practical experience, for example:

> ". . . you can see that *it's getting bigger*, so you could associate that with getting like *more charged* and on the axis it goes from zero to a hundred and *when something's 100% it's on full charge*" (Interview Q1).

Conceptual understanding in relation to circuits (Conceptual Understanding, Box 4) is also grounded in the practical experiences and knowledge held by Luke (see interview comments Box 8 & 9 below); again discussion tends to focus on what's observable, either in a representation or real world application. In relation to programming (Box 5), Luke claims not to understand the area, although he explains his understanding in the following practical terms:

> "[It] Turns it on [the circuit] and then works so if pin 3 is on then it goes to this and if pin 3 and 4 are on then it goes to this and goes back to the start again" (Interview Q6).

Programming commands (Box 7) are related to "the different pins" (*ibid*), however when Luke was asked to make a direct link between programming command and associated position in the circuit diagram, this was not achieved in the interview. Luke therefore does not appear to have developed any methods for translating between, or dealing with a transition to, knowledge in another form on the basis of language use. However, as noted above, a transition can be considered to take place from the practical experiences cited and the circuit diagram representations used.

The sequence of representations (Box 5 & 6) used to complete the circuit building task (component list→graph only) and the programming task (programming commands→event schedule→diagram) follow the pattern identified in the Cognitive Map (Figure 15). Luke begins with the concrete component list to aid circuit building and the programming commands and event schedule which again provide concrete information to support the transition task.

When asked to clarify representation preference and associated task in learning (Learning, Box 8), the following discussion represents Luke's approach to learning clearly (Interview Q7):

> ST: I thought the first one [circuit building task] because well *I always thought electronics was making*, rather than programming because I always thought that was computing.
>
> AT: Ok.
>
> ST: So definitely the first task [circuit building, Task 2].
>
> AT: Right, what was it about the first task that is better than writing a program?
>
> ST: *Creating a circuit that works.*
>
> AT: Ok so are you saying that, so how different is that from programming then?
>
> ST: I thought that it was quite different.
>
> AT: In what way is it different?
>
> ST: Because *one's more practical* I guess and *one's more thinking about it.*
>
> AT: Ok.
>
> ST: A lot more with programming which I don't really understand anyway.
>
> AT: Right ok so I'm quite interested in this idea of it being practical so what aspect of what we did in lesson one was practical?
>
> ST: Making something that works because it's not really writing it down it's more getting the components and then finding the way that they work.
>
> AT: Ok.
>
> ST: Say if you were doing that on a breadboard or something it's definitely more practical.

Luke explains his preference for the practical work, where circuit functioning is revealed through "*Making* something that works" and ". . . *getting the components* and then finding the way that they work" (*ibid*). The use of trial and error, discussed above, also supports this practical approach to learning. It is interesting that Luke has developed a visual way to remember circuit functioning, on the basis of the location of key objects in the representation. For example Luke explains:

> AT: I'm interested in the process of converting the [component] list into the circuit diagram.
>
> ST: Well I knew that where the supply rails had to go and I knew roughly where the LED would go so I just based it around that, I knew where the capacitors go.
>
> AT: How did you know that, all of those things the supply rails, the LEDs?
>
> ST: Looking at previous circuits so then most of the ones I've seen the capacitor's around here, so I thought it might work there and same with the LED, *it's always . . . most of them are on the far right.*

Luke uses the spatial location of elements (Box 9) to identify their placement (Task 2) and also attempts to write his program (Task 3) by following the spatial location of the circuit components. This is a unique approach among the participants in this study, on the basis of the descriptions obtained, and indicates a specific approach to conceptualising the phenomena for Luke.

4.10 Analysis of technical terms

Table 27 reveals participants' use of technical terms, as determined from a concordance analysis using Antconc 3.4.4w (2014). The most useful figure is the number of different technical terms used during the interview (Column 1), because this reveals something about the level of participants' understanding. Perhaps unsurprisingly, knowledge of programming correlates with an overall high level of technical term use (i.e., Fergus, Connor and Feidhlim). However as I mention earlier, this does not always indicate good understanding as Oliver, who is positioned at the bottom of Column 1, achieved an A* overall in is combined GCSE and coursework. I make reference to Table 27 in the Discussion chapter to illustrate connections between the use of technical terms and conceptual understanding. As language use was not the main focus of this research study, Table 27 provides a starting point for further inquiry and this is discussed more fully in the Conclusion chapter.

	Total Individual Technical Terms	Individual Terms % of Word Count	Total Individual Programming Terms	Individual Programming Terms % of Word Count	Total Technical Terms	Word Count	All Terms % of Word Count	Total Programming Terms	Programming Terms % of Technical Terms	Total Standard Terms	Standard Terms % of Technical Terms
Fergus	64	3.3	17	0.9	211	1915	11	48	23	142	67
Connor	51	3	11	0.6	168	1702	10	24	14	119	71
Feidhlim	50	2.5	13	0.6	178	2016	9	53	30	119	67
Ben	47	4.2	7	0.6	139	1122	12	20	14	117	84
Ethan	46	3.6	14	1.1	122	1292	9	31	25	84	69
Sam	43	3.4	4	0.3	158	1257	13	27	17	107	68
David	42	2.4	8	0.5	181	1767	10	36	20	120	66
Jacob	37	4.4	6	0.7	90	843	11	13	14	72	80
Luke	34	3.3	6	0.6	61	1033	6	14	23	46	75
Oliver	31	4.3	6	0.8	96	720	13	15	16	51	53

Table 27: Analysis of technical term use

4.11 Summary of patterns and concepts taken forward to discussion chapter

Drawing on the summaries of categories and themes in Figures 8, 9 and 10, and the cognitive profiles (Section 4.9), this section provides an outline of patterns and concepts which represent relationships within the data (Table 28). Patterns or concepts are presented in the order in which they emerged during data analysis and lead to further discussion in Chapter 5. Question marks are shown where in particular the pattern or concept raises a query in relation to its application to learning and concept forming. The focus of the Discussion chapter will revolve around this knowledge construction process and attempt to reveal how this has occurred for the participants in this study.

Category	Pattern/Concept
Representation Use & Problem Solving Q1	▪ Individuality ▪ Synchronous/sequential engagement ▪ Common approaches ▪ Language use ▪ Diagram/representation embodies different knowledge types (e.g., function or concept) ▪ Learning & concept forming (Link?) ▪ Context & relevance important
Conceptual Understanding: Representation Use Q2-8	▪ Concrete to abstract thinking ▪ Individuality ▪ Clarification supports translation (through knowledge or process approach?) ▪ Synchronous/sequential engagement
Conceptual Understanding Q2-8	▪ Individuality ▪ Language use ▪ Synchronous/sequential engagement
Learning Q2-8	▪ Concrete to abstract transition (enabled through the following?) ▪ Knowledge types (concept=knowledge and/or concept=process) ▪ Multiple representations important for transition (therefore are multiple perspectives key to learning?)
Cognitive profiles Q1-8	▪ Individuality & bipolar constructs ▪ Clarification-translation-transition sequence ▪ Personalised conceptions (allow transition?) ▪ Context & relevance important ▪ Wu et al.'s (2001) levels a prominent enabler generally

Table 28: Summary of patterns/concepts emerging from categories

Chapter 5 Discussion

5.1 Introduction

The research study aimed to describe the different ways students use external representations to construct their understandings of abstract electronics concepts and reveal their specific approaches to learning those concepts. Through the study of a specific case of representation use and the analysis of translations of and transitions between representations, I aimed to gain insights into participants' differentiated constructions of knowledge and the processes used during their learning. The research study was guided by the following four research questions:

1. How do students describe their use of electronics representations when translating and performing transitions between multiple representations?
2. How do students describe their conceptual understanding of electronics in relation to 'traditional' circuits and 'programmed circuits' and how do these differ?
3. What is the role of practical experience in translating and performing transitions between electronics representations?
4. How do students relate learning to their experiences of translating and performing transitions between electronics representations?

The literature review (Chapter 2) reveals that there is very little research describing secondary school age students' specific methods of developing electronics concept understandings. A significant amount of research has been carried out to identify students' misconceptions of electronics (Engelhardt and Beichner, 2004; Streveler et al., 2008; Chen, 2013), but little which focuses on their processes of understanding. Similarly the process of conceptual change has been well documented in the literature (Chi, 2005; Ozdemir and Clark, 2007; Treagust and Duit, 2008), but little has been applied to the field of electronics. This literature emerges largely from an experimental methodology and often focuses on control/experimental groups and the isolation of specific variables which do not expose participants' actual understandings or learning approaches. Solsona et al.'s (2003) research presents an exception to this, however, in the development of conceptual profiles which define differentiated approaches to knowledge construction relative to the concept of chemical change, as observed at different stages of the learning process. The following discussion aims to add further insight into these differentiated approaches, in relation to learning relative to the achievement of a GCSE in Design and Technology: Electronic Products. It draws on overlapping waves theory (Siegler, 2005) which proposes that learning is achieved using different methods at different times during the learning process by learners (see Literature Review, Section 2.4.1).

The discussion is arranged to follow the research questions outlined above, which emerged from the review of literature (see Literature Review, Section 2.8). To provide greater clarity, Figure 16 summarises the key outcomes of the discussion, which explains the relevance of the research study in relation to the Literature Review (Chapter 2). The diagram is designed to reflect the three key areas of: Mental Representation, Mental Processes and Learning. Each key area reflects a number of outcomes from the Findings and Analysis (Chapter 4) and these areas have been colour coded to indicate their connection. Broken lines connecting individual boxes indicate an association between outcomes, and these have been colour coded to enhance visual clarity.

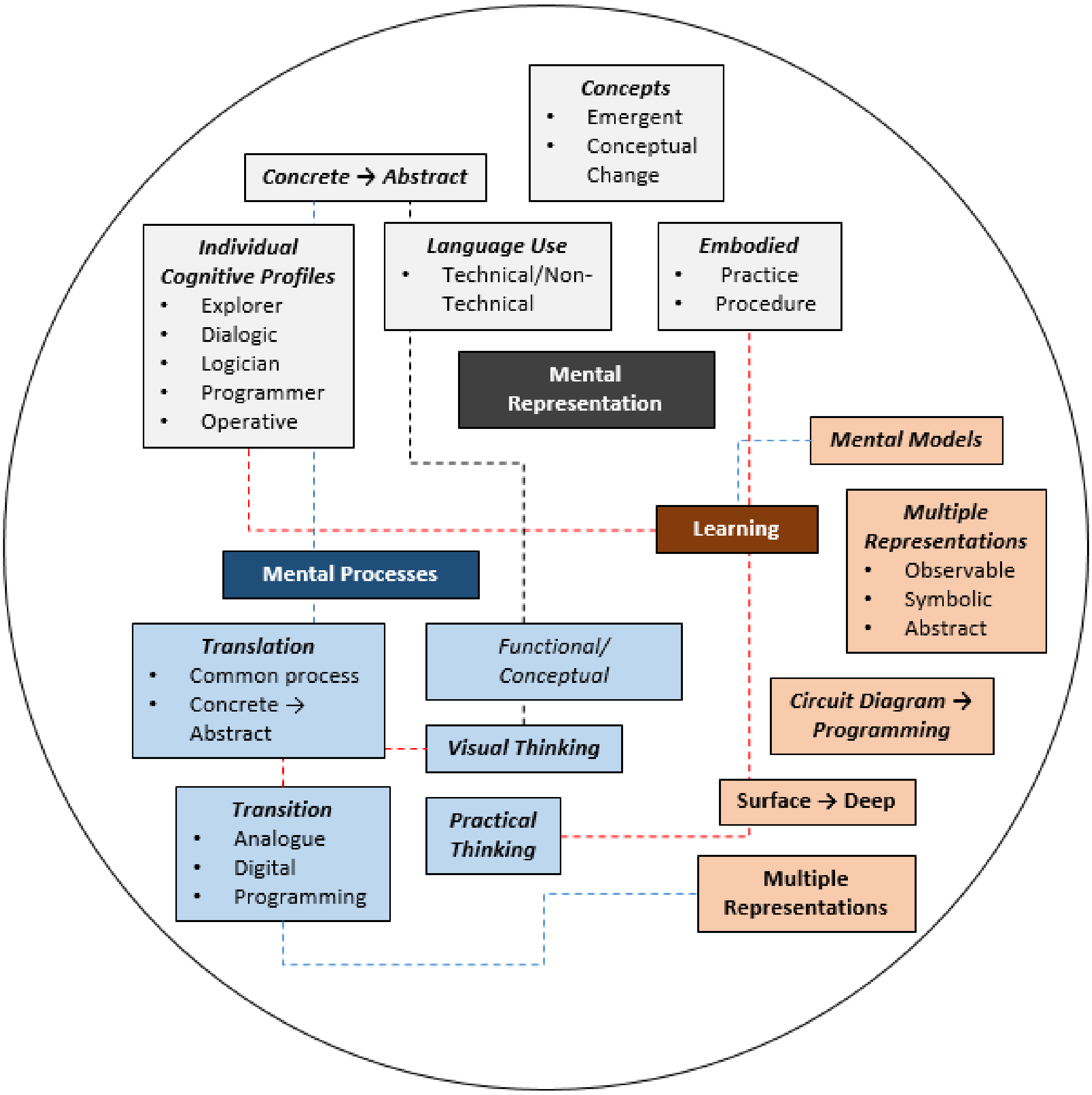


Figure 16: Summary outcomes from discussion chapter

5.2 Q1 How do students describe their use of electronics representations when translating and performing transitions between multiple representations?

5.2.1 Concreteness and translation

The analytical framework incorporated the key theoretical perspective that representations of knowledge occur at three broad levels: macroscopic (observable), microscopic (abstract and invisible) and symbolic (symbols, formulae) (Johnstone, 1993; Wu et al., 2001). The findings were considered in accordance with these levels of knowledge. Findings from research Phase 1 (lesson observations, documents and screen recordings, Section 4.5) and Phase 2 (Interview Q1, Section 4.7) suggest participants use representations to focus, at least initially, on the observable (macroscopic), concrete features of the representation.

There was an almost even division between those who focused on words and those who focused on images as their starting point in the paired matching task. However, the interviews revealed a preference for words even for those beginning with images. This might be explained by the relatively concrete nature of words, which tend, at least in relation to theoretical knowledge, to hold definitive meanings. Word association with programming code was shown to support this position. Thus words provided an explanatory function as representations, agreeing with Paivio (1986) and Larkin and Simon (1987), and support Petre's (1995) findings that programming code is more beneficial to learners than graphical representations, such as flow diagrams.

From this position an assumption is made that for many learners, words explain phenomena, whereas images are open to interpretation. It would be interesting to explore whether participants would benefit from the addition of a mathematical representation in the paired matching task. This may have provided the additional explanatory information needed for some learners, provided in another form. However in subsequent tasks a formula was provided (see Appendix 3) which was generally found not to be useful, on the basis of interview responses. This was claimed to be because participants' were already able to problem solve on the basis of two of the three representations offered, the third being the formula. Focusing on technical terms, therefore, suggests that language is an important learning vehicle for some of the learners in this study and provided a concrete referent for their thinking. This assertion is considered again in Section 5.5.3.

The association with concrete features as a starting point was a common characteristic of the circuit building and programming task during the lessons and was supported by interview responses. The programming task showed that participants tended to focus on the central process component within the referent given as their starting point for program writing; findings from the analysis of the sequence of representation use supported this and showed that component lists and circuit diagrams were the most favoured starting points in the tasks, possibly due to their more concrete nature in relation to the other representations provided. Connecting with something assured and relatively fixed would seem therefore to be an important starting position from which to approach problem solving. This concurs with the general sequence of events advocated by several constructivists discussed in the literature review (Piaget, 1955; Bruner, 1977; Kolb and Fry, 1974). Drawing from Piaget (1955), it suggests that new knowledge is gradually integrated with existing knowledge (assimilation) and schemas are adjusted which represent the learner's modified ways of thinking about the phenomena (accommodation).

Although researchers have suggested that focusing on concrete features indicates lower ability (Seufert, 2003), this has not proven to be a common phenomenon in this study on the basis of comparisons between learners' profiles and their GCSE outcomes (Tables 10 and 11, Sections 4.3.and 4.4). Siegler's (2005) overlapping waves theory (Section 2.4.1) suggests that learners employ both existing strategies and new strategies at different times during learning. Focusing on concrete features represents one existing strategy which emerged at several points during the learning tasks. As a rival explanation to notions of low ability, it is perhaps natural, particularly when talking about working with representations in an interview when participants may be slightly nervous, to focus on the observable features and use these as a basis for ascribing meaning (Seufert and Brunken, 2006). Therefore, as explored below in Section 5.5.3, this meaning may be explained in general terms, particularly for the purpose of communication, supporting Halliday's (1993) notion of a general language of learning, and Kolb and Fry's (1974) proposition that learning processes begin with concrete experiences.

5.2.2 Existing knowledge

Another commonality among participants, on the basis of the interview responses in the study, was the use of representations to elicit existing knowledge. This tended to follow concrete observations in the referent, as discussed above, and was common across the themes generated during the analysis of findings (Chapter 4). Participants cited existing knowledge, based on component types and their functionality, as a prominent starting point and vehicle for problem solving, with indications that this followed concrete observations of elements of the representations (see Section 4.5). Findings from the paired image/word matching activity suggest that the difference in starting points on this task links with the variation in existing knowledge and therefore provides support for personalised approaches to learning across the group. The process of elimination adopted by half of the participants responding to interviews (Table 12, Section 4.5) as a method of matching known and unknown images and words supports observations of existing knowledge use and corroborates the constructivist process advocated above (Piaget, 1955; Bruner, 1977; Kolb and Fry, 1974).

There seems to be therefore a close relationship between engaging with concrete aspects of representations, using existing knowledge for comparison with the viewed object and problem solving method (Figure 17); what I refer to as the translation of representations. The following sections develop the idea that translation leads to transition between representations and knowledge forms through comparison and clarification, as a key ability leading to the development of conceptual knowledge (i.e., Chen's (2013) gradual integration of new knowledge). Findings show that many of the participants did move on from observable elements, using the representation to elicit a more abstract understanding. This tended to be achieved in personal ways. For example Ethan focused on logic features of the electronics and discussed electronics through an understanding grounded largely in logic circuits (Section 4.9.3). Findings in relation to personal learning led to the development of five profile types which are discussed more fully in the next section (Q2, Section 5.3). Seufert and Brunken's (2006) notion that learners engage with surface and/or deep features of the representations seems to relate to their level of existing knowledge and ability to move beyond the observable features presented (I note here that 'deep features' are possibly constructions by the learner, rather than features of the representation). It has been suggested that this is achieved through existing knowledge and spatial ability (Seufert and Brunken, 2006).

5.2.3 Diagrammatic representations elicit concept or function

As a development of the observation that existing knowledge is a key starting point when viewing a representation and making inferences, findings also show that generally the inference made led to either a conceptual or a functional understanding of the referent. This may indicate and support Kirschner's (2002) suggestion that cognitive load is reduced by learners through the group of elements of representations leading to greater automation in their use and participants' thinking. The observations in Sections 4.5-4.8 reveal that those who move on to make more abstract connections from the representations do so with the use of an individual translation/transition vehicle. In the example above (Ethan), logic is used for the abstraction and provides the translation/transition vehicle (*ibid*), providing more efficient thought processes. This phenomenon is discussed in the next Section (Q2, Section 5.3) in relation to concept development and represents one of the key indicators for the development of individual cognitive profiles (Section 4.9). As I note above, the use of technical language, or common terms, does not tend to reveal a particular level of understanding. Participants' understanding of abstract concepts were portrayed using common terms, as well as those participants using technical terms. Here the observation relates to the phenomenon embodied by the representation by the participant; either conceptual or functional, often in terms of voltage behaviour.

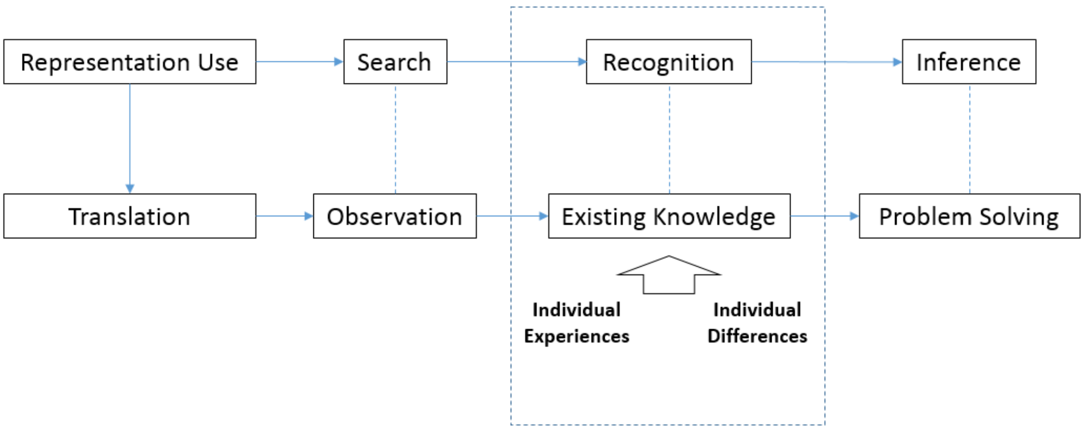


Figure 17: Summary of relationships between elements of representation engagement from Task 1

So far I have discussed a common pattern of events describing what occurs when learners view a representation. This pattern is displayed above in Figure 17. A sequence of events is activated involving engagement with observable elements, *comparing* observations with existing knowledge and subsequent problem solving following *clarification* (Figure 17). This concurs with the learning process described by others (Piaget, 1955; Kolb and Fry, 1974) and particularly Bruner's (1977) taxonomy which posits a process of new knowledge acquisition, transformation of the new knowledge into another form and clarification of outcome to check the plausibility of the new knowledge. The representation element focused on, and the existing knowledge elicited, was shown to depend on individual differences in learners' electronics schemas. Learners can be shown to draw on Wu et el.'s (2001) levels differently dependent on learner approach and task (see Cognitive Profiles, Section 4.9). Support for the position that different levels of representation are needed to enable access to complex conceptual ideas (Ainsworth, 2006; Johnstone, 1993; Wu et al., 2001) is explored in the next section (Q2, Section 5.3), particularly in relation to learners' cognitive profiles.

5.2.4 Synchronous and sequential search strategies

Engaging with a representation is said to involve a search → recognition → inference strategy (Larkin and Simon, 1987). The findings discussed above parallel this strategy with learners tending to focus on concrete, rather than abstract features as their starting points for translating and performing transitions between representations. Researchers have noted that learners accessing abstract, or deep, levels of information within representations are more able to make transitions between representations (Seufert and Brunken, 2006) and consequently perform a transformation of knowledge (Bruner, 1977). Searching and recognising representations has been characterised by access using either synchronous or sequential means (Larkin and Simon, 1987; Paivio, 1986). Examples in this study include the circuit diagram and computer program respectively.

The preference for words revealed during Task 1 may suggest a preference for sequential representation, as noted they may have provided specific meanings in relation to image/word matches. However David claimed that use of the graph, a synchronous representation, provided specific information in relation to the circuit diagram (which did not), making the circuit diagram more difficult to interpret (Section 4.7.4). David's observation appears relative to the representations available however, as later in the interview the circuit diagram is held as more useful in comparison with a computer program (Section 4.8.8). This can be interpreted as support for Kirschner's

(2002) position that some representative material (i.e., sequential) increases cognitive load as the learner has to work harder to extract the information required.

The interview responses were much more enlightening than the lesson task outcomes with respect to the efficiency of representations, possibly as these could be explored and explained in more detail. Synchronous, graphical examples such as the circuit diagram were generally viewed as much more efficient and quicker at depicting information, concurring with Larkin and Simon (1987). Fergus (Section 4.8.3), for example, highlighted the spatial location of elements as the useful factor. Ben (Section 4.8.5) inferred that the circuit diagram is more memorable than a computer program. The consensus was represented by an immediacy in the diagram and therefore translation was supported by synchronous representation use for these participants.

The computer program however was generally positively supported as a source of explanation, confirming the position that explanatory tasks are beneficial to learners (Aleven and Koedinger, 2002; Chen, 2013). Ben (Section 4.8.8) maintains that the program provides a functional explanation which is missing from the circuit diagram. Others support this assertion, but recognise that reading the sequentially presented program takes longer and, as David notes, you still need to know how the components function relative to the programming commands to make a link between the two in practice, or to support practical application (section 4.9.2). It may have been that words were treated as symbols and therefore accessed synchronously. I explore the explanatory nature of program coding in more detail in the next section (Q2, Section 5.3).

5.2.5 Individuality determines learners' knowledge development

I have already alluded to participants' individual approaches to representation use. This prominent theme, along with other findings such as the nature of existing knowledge, led to the formulation of individual profiles (Section 4.9) representing the different ways participants' conceived of electronics. Participants' links with existing knowledge when explaining representation use contributed significantly to the generation of this theme. The fact that individual approaches are adopted to representation use and the application of existing knowledge, might suggest that learners would benefit from an awareness of the alternatives available in relation to their preferred approach, to enhance learning. For example, knowing that some learners refer to their practical experience more than their theoretical knowledge (discussed in Q3, Section 5.4) would broaden awareness and learner application.

It was clear from the interview responses that forming knowledge was a highly individual process (see Cognitive Profiles, Section 4.9). Task type, analogue or digital, did not affect the way participants constructed their knowledge. This is confirmed by the comparison of cognitive profiles with task type (Table 26, Section 4.9) which reveals variability among those completing the analogue and digital tasks. This means that although participants have been taught specific phenomena over the GCSE course, they adopt very individual ways of constructing meaning. An interesting outcome from the findings is that in general participants adopted similar processes in relation to representation use and problem solving, regardless of task type, whereas the existing knowledge drawn on and the outcomes reached can be shown to differ among participants. This might indicate a natural processing ability which parallels those discussed below (Learning Processes, Section 5.5.1) and a differentiated approach to knowledge construction based on individual differences and experiences.

The individuality theme is also pronounced in other sections of the findings. For example participants used general or technical terms during the more extended phase of the interview (Interview Q2-8) to describe electronics understandings. The approach adopted did not correspond with a particular ability and may relate to notions of the interplay between 'common grammar' and the 'synoptic mode' of more formal writing (Halliday, 1993: 112). I interpret this to mean that common language (general terms) can be equally effective in transmitting understanding as synoptic language (technical terms) and this is supported by the findings which demonstrate the efficiency of common language in portraying understanding (see Cognitive Profiles, Section 4.9). However this phenomenon relies on an understanding of the phenomenon by both parties during communication and is subject to the receiving party's interpretation.

5.2.6 Common approaches found to problem solving

The preceding discussion has focused largely on the act of viewing representations. Findings show that the problem solving process, as noted above, generally began with elicitations of existing knowledge on the basis of concrete observations of elements of the representations. As previously noted (Section 2.6.2), I refer to problem solving as the procedure of using representations during the process of engaging with the lesson-based tasks employed in this research study (as shown in Appendix 3). The findings, particularly from Sections 4.5-4.8, reflect an even division between using existing knowledge and a process of elimination as methods of problem solving (Table 12, Section 4.5). Although these were cited separately, it is recognised that the two strategies are linked however. Additional approaches included the consideration of practical application and associations with programming code, discussed below in Section 5.3.

Therefore this may be an indication that although existing knowledge is a strong referent for many of the participants, there is also a contextualising process evidenced in the links with practical application and programming. This offers support for the suggestion that helping students to identify appropriate starting points in problem solving procedures may improve problem solving ability (Rittle-Johnson and Koedinger, 2005). Linking with practical application, as I discuss further below (Q3, Section 5.4), suggests a procedure-based (thinking related to a practical experience), rather than a knowledge-based (thinking related to theoretical elicitation) approach to solving problems. Although the process of elimination was mentioned explicitly by 4 out of 10 participants (Table 15, Section 4.7.3), in reality those only suggesting existing knowledge as their key problem solving method may have also approached the task heuristically (i.e, experimenting or trial and error).

5.3 Q2 How do students reveal/describe their conceptual understanding of electronics in relation to 'traditional' circuits and 'programmed circuits' and how do these differ?

5.3.1 Analogue and digital electronics, conceptual understanding and individuality

The previous section discussed some of the specific ways participants used representations as a part of translating, problem solving and the learning process. This section focuses on the use of these strategies in the development of conceptual understanding more generally, taking into account traditional approaches to representing electronics and computer programming approaches.

Analogue and digital circuit types are common vehicles for thinking about electronics; circuits tend to belong to one type or the other (Duncan, 1997). Findings show that participants' conceptual knowledge in relation to these circuit types tended to be grounded in digital, or both of these. For example, Ethan (Cognitive Profile, Section

4.9.3) had a very good digital understanding grounded in logic type circuits and terms, but discussed analogue circuits in general terms. Fergus (Cognitive Profile, Section 4.9.4) had a very good understanding of each type, both revealed using technical terms. However none of the participants discussed analogue circuits without also revealing a good digital understanding. There seemed to be strengths in conceptual knowledge revealed in the use of technical terms and in the use of general terms (see discussion in Language and Learning, Section 5.5.3). This leads to the consideration that a procedure analysis of learners' approaches to understanding would be a useful tool for the teacher in determining support strategies and focusing skill development (discussed further in Conclusion chapter).

5.3.2 The creation of cognitive profiles

On the basis of the learner strengths revealed in the findings, I developed four cognitive profiles (Section 4.9), which are largely based on degrees of analogue or digital understanding. The analogue/digital concepts can be said to be bipolar in that they adopt opposite ends of the voltage-behaviour continuum (Kelly, 1963). The cognitive profiles reflect this attraction towards one pole or the other, partly in their analogue/digital focus, but often in ways very specific to the participants (see Cognitive Profiles, Section 4.9).

The profiles are considered to reflect metaphorical, mental constructs (Wu et al., 2001) in that they are constructions based on metaphors (e.g., programming or circuit operation) which emerged during the interviews as themes and categories. The profiles therefore represent, to a large extent, the differences between participants in relation to Research Question 2 and individual concept development. An additional characterisation presented in the profiles is the extent to which participants reveal their understanding in relation to Wu et al.'s (2001) levels of understanding (observable, abstract and symbolic). A strength of the cognitive profiles is that they reflect the nature and level of participants' electronics understanding. Accordingly I named the profiles Operative, Logician, Programmer and Dialectic to reflect the nature of participants' knowledge construction and the use of significant referents to explain their understanding. During the later stages of the analysis of findings, a fifth category was created (the Explorer) which, it was realised, does not represent a way of thinking about electronics knowledge, but is an attitude to the procedure of working with such knowledge. The references to this category remain within the Findings and Analysis chapter as they provide a specific insight into one 'nested' (Thomas, 2011a: 153) case of learning procedure, which provides an interesting contrast with the other participants in this study.

This develops a similar approach by Solsona et al. (2003) which revealed four general levels of conceptual understanding on the basis of the chemical change phenomenon. Solsona et al.'s (2003, 9) profiles reveal an understanding closely described in relation to the 'accepted model' of chemical change. The profile concept has been developed in the present study with a focus on personal representations of conceptual understanding, in addition to revealing understanding in relation to the analogue/digital concept. Consequently the cognitive profiles in this study can be used to develop awareness about the approaches to teaching and the strategies for learning, which are likely to link with and enhance learners' individual understandings. The use of profiles as an approach compliment others' experimental approaches (discussed in Literature Review, Section 2.6.5), as they provide the specific nature of understanding described in a way that is useful to the teacher in developing learning materials. It would be useful to consider what leads learners to develop a particular strength or adopt a specific conceptual approach, particularly as the early phase of the analysis of findings highlighted individuality as a strong theme, but found this difficult to explain in terms of its development. This is explored below.

5.3.3 Considerations of the influences on learning

One possible approach is to make a comparison between participants' characteristics data and their cognitive profile type (Table 9, Section 4.2). The comparison does not reveal a clear relationship between the Yellis component scores and particular strengths. However those who score well on spatial ability (represented by higher scores on the Patterns component of the Yellis test) tend to be the more abstract thinkers, as I have identified them on the cognitive profiles. This trend was noted by Seufert and Brunken (2006, 330), who cite spatial ability as a key aptitude when developing 'coherence formation', that is the ability to bring together different aspects of several representations to 'reach the goals of elaboration, abstraction, flexibility and coherence' (Seufert and Brunken, 2006: 322). Those with the lowest spatial scores (Ben, Feidhlim and Luke) have been noted as particularly concrete thinkers, who tend to focus on the observable features of representations. Spatial ability, which has been shown to be improved through teaching with engineering undergraduates (Akasah and Alias, 2010), may therefore be an important contributing factor to the development of abstract conceptual ability. Therefore if spatial ability can be developed in relation to electronics learning, a key question concerns the nature of the development and when this should be introduced to assist learners with abstract concept understandings. Developing the ability to understand concrete aspects of representations and the ability to use these to perform transitions between representations may support this aim (discussed further in Conclusion, Chapter 6).

Secondly, comparing participants' average course-based assessment marks (Year 10 assessments, Table 10, Section 4.3) with GCSE outcomes (Table 11, Section 4.4), unsurprisingly, reveals an association between success in Year 10 and success in the final GCSE outcome. The marks for the 'dual transistor prototype plan' homework, a largely spatial task (Appendix 12), also follows the observation made surrounding spatial ability above. However although participants who generally performed well across the research-based tasks also performed well in the GCSE overall, the pattern of marks do not reveal a link with a particular conceptual approach as identified on the cognitive profiles. Indeed Oliver, who gained the highest average marks during Year 10, was noted as one of the most concrete thinkers who used largely general terms to describe understanding during the interviews.

A third consideration, in terms of the development of strengths, is the course structure followed during Year 10 (Table 2, Section 3.5.2). This undoubtedly had an impact on participants' development, as it was mostly through this sequence of learning that participants developed the electronics knowledge evidenced in the findings. The sequence began with analogue electronics, moved to digital electronics and then programming. This sequence of teaching tends to be replicated in instructional textbooks (Duncan, 1997; Hiley et al., 2008; Fischer-Cripps, 2014), but may not always be the most efficient approach to learning electronics, as I discuss further below. Nonetheless a product of the learning during Year 10, whether related to the sequence of delivery or not, is the focus of interest used for the coursework project.

A comparison between participants' GCSE coursework focus of interest and cognitive profile type (Table 11, Section 4.4; Table 9, Section 4.2) indicates some link between interest and profile in that those identified as strong on programming or logic applications tended to use these approaches to electronics in their coursework (e.g., Feidhlim, Fergus and Jacob). Those who focused more on approaches other than programming in the interview tended to avoid its use in the coursework (e.g., Ben and Luke). However Connor chose not to use programming despite his apparent interest conveyed during the interview. Nevertheless overall it might be that the coursework focus was chosen due to a particular interest relative to strengths in understanding or learning. This would indicate that decisions were made about coursework by participants on the basis of individual interests and that the influence of the Year 10 course is difficult to determine in this context. Further discussion on learning and development is provided in the three sections following Research Question 4 below.

A key consideration in relation to learning is the belief that different levels of representation are needed from multiple sources (Ainsworth, 2006; Johnstone, 1993; Wu et al., 2001) to support abstract concept development. This seems to be a promising area for understanding participants' conceptual development. Findings from this research study show that those who are able to translate representations and use this translation to make transitions between several representations appear to reveal a more abstract understanding than those who tend to focus on single representations and concrete observations (Cognitive Profiles, Section 4.9). This may return the discussion to the assertion above that existing knowledge and learning processes ground the ability to translate and make transitions between representations. This process has been evidenced across the discussions around traditional and programmed approaches to electronics and consequently indicates support for both strategies. Developing understanding through the translation/transition process supports the view that learning in Technology fields tends to involve procedural knowledge through problem solving and has been considered to be central to conceptual development in Technology education (McCormick, 1997). I develop this theme further in Learning and Modelling (Section 5.5.2) below.

5.3.4 Programming and conceptual understanding

5.3.4.1 Programming is sequential and explanatory

Computer program code consists of written statements which represent actions taken by, in this case, a microcontroller when making connections between electronic inputs and outputs. The program represents the sequential representation of fragmented knowledge (Paivio, 1986) and is accordingly accessed through a sequential search → recognition → inference strategy (Larkin and Simon, 1987). As discussed in the literature review (Section 2.6.4), the use of computer code, particularly where this draws on natural language, has been found to support learning with school-age children (Lauria, 2015). The discussion above indicates that diagrammatic representations tended to be accessed by participants with reference to a concrete, observable aspect of the representation. This then led to an inference either closely associated with the observation or led to a translation on the basis of more abstract thoughts during the process of meaning making (e.g., through an understanding of 'logic' processes). Either way the inference has been shown in this study to be highly individual and personalised.

Accessing programs sequentially on the other hand requires the viewer to read through each line of code separately. Responses from the interviews indicated that this aids learning about electronics because the codes or statements tend to explain circuit functioning (Section 4.8.8), supporting the notion that the requirement to explain understanding to someone else supports learners as a learning strategy (Aleven and Koedinger, 2002; Chen, 2013; Siegler, 2005). Therefore meaning is constructed through the connection of fragments (individual codes) into a coherent whole (the program). There was strong support for this notion from the interview responses (Section 4.8.8). However it was recognised by participants that reading code takes longer than viewing a synchronously accessed representation such as a circuit diagram and that this may impact and possibly limit its use. A further observation noted that program code only represents circuit function and does not reveal anything about the physical features of the circuit. Programming may consequently be contextual, in that it supports learning but only in certain situations where the circuit is known, or as a supplement to circuit functioning. Where interview responses noted the use of programs in explaining circuit function where this function is not known, participants favoured the circuit diagram as the most useful starting point. Program code therefore may not fully replace circuits for the purposes of learning about electronics, but may provide a useful supporting role when teaching and learning about traditional electronics, following the pattern of delivery commonly found in instructional textbooks (Duncan, 1997; Hiley et al., 2008; Fischer-Cripps, 2014). Programming may consequently support both the notion that this type of knowledge is emergent (Chi, 2005) and that knowledge is gradually introduced into the learners' conceptual understandings (through conceptual change), also over a period of time (Chen, 2013).

In some cases the interview responses reveal the use of programming as a metaphorical construct for voltage and logic. Connor in particular explicitly related what he viewed as complex electronics to the easier, as he saw it, form of programming which he valued as a learning strategy. Feidhlim, similarly, explained that voltage is embodied within the program code, whereas voltage behaviour within discrete components by comparison is invisible. In these cases the program is used as a translation tool and rather than providing an explanation only, seems to be used to trigger more abstract meanings to support understanding. This may indicate that the external sequential nature of the program is converted to an internal synchronous mental construct by some participants and provides support for the notion that all higher order thinking can be explained in terms of visual thinking (Arnheim, 1970). Adopting a metaphorical construct, through the use of program code, may be viewed as a strategy which reduces cognitive load through the combination of elements to form a more efficient referent for the learner (Kirschner, 2002).

An interesting outcome of the circuit building and programming tasks, revealed during the interviews, was the similarity in approach which reflected an initial focus on the concrete aspects of the representations provided, then the use of a clarifying representation which was often in a more abstracted form, such as the graph or event schedule (Section 4.8.1-4.8.2). This seems to reflect the aforementioned interplay between external representation and the process of inference which follows engagement with several representations. The role of clarification is indicated as an important part of developing understanding, both at task level and more widely. The screen capture data from the programming task confirms this approach for both the analogue and digital groups. Participants begin with a focus on the central process component, then translate this into program code. The virtual simulator is then used to clarify program operation, for most participants at least twice (Table 13, Section 4.6). David however departs from the programming software to explore code stored on the ICT network and produced previously during the Year 10 course. As discussed in his cognitive profile (Section 4.9.2), this is characteristic of David's approach to learning, discovering information for himself where possible and in this case clarifying outside of the demands of the task. The process adopted is therefore similar, whether circuit building or programming, when considering procedural strategy. It involves thinking which shifts from concrete to abstract and employs a mechanism of clarification through the simulation of electronics functioning.

It is useful to consider whether programming leads to conceptual change, on the basis that it has been introduced following earlier learning grounded in traditional electronics during the GCSE course. The focus of the research study's aims and questions did not take account of this perspective specifically, however certain tentative inferences relating to this phenomenon can be made on the basis of the findings. Firstly it can be inferred through participants' use of programming terminology that a conceptual change has occurred, whereby the adoption of terms later in the course replaces earlier conceptions based around non-programming or general terms. Examples of this include the understanding and use of the program code 'if-then' to replace the logic gate symbol (digital group), or transistor symbol (analogue group) during the programming task (Task 3, Appendix 3). However it is difficult to determine the level of programming knowledge, early in the GCSE course, from the findings. Connor for example made a revealing comment during Year 10 which indicated a very good understanding of programming on the basis of the 'if-then' code (Appendix 13). This, however, was an isolated occurrence.

Secondly the use of a subprogram by most of the participants in Task 3 (Table 13, Section 4.6), indicates their understanding of the separation in the code between the decision making element ('if-then' statement) and the output element ('high' statement), again reflecting participants' alternative knowledge of the equivalent discrete component-based circuits used earlier in the course and an indication of conceptual change. However the level of participants' initial programming knowledge cannot be easily determined on the basis of this study's findings. Therefore the inferences above rely on the assumption that the majority of participants held limited knowledge of applying programming in an electronic circuit design context at the point of entry to the course; probably a reasonable assumption to make for most.

Recognising that knowledge is likely to be held differently at different phases of learning within one GCSE course carries the implication that the presentation of topics needs to match learners' particular phase of learning to support and encourage conceptual changes. An awareness of the different conceptions held by learners at different phases of their learning could support teaching in that learning can be reinforced with the presentation or discussion of the alternatives during learning activities. Conceptual change theory therefore lends itself to both determining learning pathways for learners and the likely start/development points adopted by learners.

5.4 Q3 What is the role of practical experience in translating and performing transitions between electronics representations?

The role of practical experience was evidenced in both references to existing knowledge (see image/word matching task, Section 4.5) and in the process used to attach meaning to concepts through a hands-on approach (see Cognitive Profiles, Section 4.9). For many it was the method used to translate representations, which sometimes led to a transition between representations and a demonstration of deeper understanding. Following the translation with a transition was therefore possible as abstract phenomena was made explicit and accessible through the physical experience. Therefore two aspects of practical application seem important to teaching practice, learner interpretation (translation) and inference making. Firstly that through a hands-on approach meaning is revealed through the experience (Davis and Markman, 2012) and secondly that the process used to make inferences generates what has been described as procedural knowledge (McCormick, 1997), knowledge which would otherwise be less accessible without the experience.

Consequently the role of practical experience can be linked with the learning processes discussed in the next section (Research Question 4, Section 5.5), because they provide a method of making a transformation (Bruner, 1977) and a method of actively experimenting with a concrete experience (Kolb and Fry, 1974). This has been evidenced in this research study through the heuristic approach to problem solving during Task 1 (Section 4.5) and in the interview responses. It could be inferred that the practical approach replaces, through procedural understanding, the elicitation of existing knowledge for those who did not refer to this during the tasks or in the interviews. The use of trial and error (although acknowledged as aligned, but not necessarily strictly practical) was also a useful strategy for those who evidenced a good understanding in other areas of the findings (e.g., David) and therefore the trial and error approach does not seem to be restricted to limited understanding.

One of the considerations during the analysis was whether practical experience was a replacement for theoretical knowledge. Feidhlim for example tends to hold a conceptual view of circuit types based on functionality and practical application, which is used instead of technical terms in his responses. He thus holds a very good understanding of electronics, but describes this mostly in functional terms. Conversely Luke explicitly described practical experience in terms of a necessary referent when thinking about electronics. He tends to make a practical/cognitive distinction (see Cognitive Profile, Section 4.9.5). He does not however hold a good understanding of the underlying electronics concepts. It is interesting that Fergus, although referring to the practical application of component function early in the interview, does not reference it elsewhere as he in particular tends to apply an in-depth knowledge in abstract terms (see Cognitive Profile, Section 4.9.4).

Generally practical application is indicated as allowing a) a link with existing meaning, b) the generation of meaning through physical engagement and c) meaning to be communicated in an effective way. One of the difficulties in analysing responses from interviews is knowing whether these references were actually gained through a practical experience. For example some of the responses could be regarded as cases of foundation metaphor (Lakoff and Johnson, 1980). I make an assumption in this study that participants have actually experienced the stated practical action, which includes experience gained from the production of circuits using the software Circuit Wizard by the participants. Where comments linked with Circuit Wizard, they related to the benefits of the visualisation of phenomena and simulating circuit options. Some of the approaches observed during the lesson tasks, particularly the programming task, in this study were indicated as supporting the use and value of practical application to support meaning making. The next section explores programming in relation to practical application and developing understanding.

5.4.1 Programming and practical application

When considered as an electronics process, computer programming is itself an abstracted link between physical outcomes (the human interface with the product) and the mode of operation (the computer program). Some of the participants regarded programming as distinctly non-practical, even though the trialling of program code using the virtual simulator during Task 3 was clearly valued (Section 4.6), although admittedly not in the strictly physical sense. In some instances (e.g., David, Ethan and Luke) Circuit Wizard was used to try out a circuit prior to the programming task (Section 4.6), although the task did not stipulate this strategy. Luke's comment that programming is 'thinking' and practical work is 'doing' resonates with some of the participants.

However there are examples where participants consider programming as an embodiment of physical experience in the form of circuit functioning (Section 4.8.8) and which link closely with the use of foundation metaphor (Lakoff and Johnson, 1980). For example use of the code 'high' (switching on an output) embodies the notion that the voltage will be higher than the off ('low') condition. High also links with foundation metaphor through the link with dimensional space; with the height of a voltage trace on a graph being physically higher than the off condition, as represented on the x axis of the graph. This would suggest a link between practical application and language-based approaches to learning (see Language and Learning discussion Section 5.5.3) and indicates an alternative method of holding a concept of voltage behaviour.

Programming consequently offers an alternative method of representing electronics, with the terms used in most cases providing a convenient and explanatory, referent for programming's equivalent in the area of traditional electronics. Writing a program may therefore support the earlier suggestion that a translation/transition event, through active simulation, is necessary to affect a development in conceptual understanding and consequently may influence a conceptual change in the learner's electronics schemas.

5.5 Q4 How do students relate learning to their experiences of translating and performing transitions between electronics representations?

A key assumption in this study is that participants construct understanding and knowledge on the basis of the experiences they encounter, both during formal learning and during other informal activities. This draws on Piaget's (1955) theory of assimilation and accommodation. A connection has been made between the individual constructs and the cognitive profiles developed from the research questions. The cognitive profiles are considered to represent participants' electronics schemas. Two key aspects related to learning have been the focus when considering how the profiles have developed; these are the nature of mental representations, particularly in relation to Wu et al.'s (2001) levels of representation, and the processes used to create them.

Participants' profiles emerged from their engagement with representations (Q1), an assessment of their conceptual understanding (Q2) and physical engagement with electronics (Q3). It would be reasonable to assume that these profiles represent meaningful depictions of participants' constructions of knowledge on the basis of the questions asked during the research study, and that these three areas are representative of this construction *process*. In the next section I discuss some possibilities which may explain how learning development takes place through the following three themes: learning processes, learning and modelling and learning and language.

5.5.1 Learning processes

5.5.1.1 Concrete to abstract transition represents the learning process

Throughout the previous sections in this chapter a clear pattern has been discussed which represents a process involving concrete observations, elicitation of existing knowledge and the use of these to solve problems. I have used the term problem solving in the widest sense to include completing tasks requiring moving from the unknown to the known in their completion. The process has strong affiliations with the constructivist perspective on learning. Ausubel (2000) states that existing knowledge is the most important element influencing learning and should be regarded accordingly. This would certainly appear to be supported by the themes emerging from this study which have shown that, through a problem solving process, understanding involves the strong elicitation of existing knowledge as a starting point for further learning, or schema modification (Piaget, 1955).

In this research study, following Ainsworth (2006), translation has been used to describe the *connections made between representations* when attaching meaning to phenomena and developing understanding. The *process* of transition describes participants' ability to use translation to move between representative models on the basis of their understanding of knowledge in different forms (such as circuit diagrams and computer code). This parallels Piaget's (1955) notion of assimilation and accommodation of representations in learning; Bruner's (1977) thoughts on learning, correspondingly, involve a process of knowledge manipulation and clarification with existing understanding to check plausibility (i.e., acquisition, transformation and evaluation). One of the key outcomes of the cognitive profiles was the clear identification of such a process which has been shown to be very individual in nature (Cognitive Profiles, Section 4.9). For example the use of clarification was shown to be strong during the programming task, with participants using the Circuit Wizard's virtual simulator to achieve clarification (Bruner, 1977) or a reflective stage (Kolb and Fry, 1974). Bruner (1977, 48) stated that 'Transformation comprises the ways we deal with information in order to go beyond it'. These 'ways' have been clearly explained where participants have made a transition and are evidenced in the four differentiated cognitive profiles (Section 4.9).

This process can be more clearly illustrated with Kolb and Fry's (1974) Experiential Learning Cycle (see Literature Review, Section 2.5). The individual approaches represented in the cognitive profiles are characteristic of Kolb and Fry's (1974) observation, reflection, conceptualisation and experimentation process. Although the process is considered to support entry at any stage of the cycle, the findings suggest that observation, usually of concrete features of the representation, tends to be the starting point. The advantage of Kolb and Fry's (1974) taxonomy is the emphasis on levels of knowledge held at different points on the concrete/abstract continuum; this parallels the approaches adopted by participants in this study.

Strong support for Kolb and Fry's (1974) learning strategies emerged in the form of the cognitive profiles which reflect the extent to which participants move from actor to observer and specific involvement to analytic detachment (*ibid*) using the strategies of simulation and practical application. Therefore the extent to which participants' converged on or diverged from representations was indicated as a combination of level of existing knowledge, personal learning strategy and the demands of the tasks in terms of the possibilities for simulation and practical application.

This general process has been described more recently, as discussed above, as a process of conceptual change (Treagust and Duit, 2008; Chen, 2013). Change is inherent in participants' development of knowledge schemas. There are several areas of the findings which reflect participants' gradual integration of knowledge (Chen, 2013) and changes in conceptual understanding. For example the earlier discussion around the integration of programming code is a good indication of Chen's (2013) model of conceptual change. The process of change seems to be restricted to knowledge development, however, with the processes used to achieve this shown in the findings to be commonly applied.

But in summary the findings suggest that translation processes and transitions between representations are important events in concept development and schema modification. The findings indicate a fairly linear representation → translation → transition → concept sequence in this respect (Figure 18). Converting knowledge to another form has been shown to apply a number of individual vehicles (see Q2 above and Cognitive Profiles, Section 4.9) however, which reflect the personal learning applied by individuals in differentiated ways. The following sections consider two areas of the literature which may suggest how this mental construction occurs.

5.5.2 Learning and modelling

5.5.2.1 Knowledge development through procedure leading to conceptual understanding

In the Literature Review I emphasised that knowledge is often conceived differently in the natural sciences to that in technology and engineering (Section 2.2.1), where it is applied more pragmatically to systems and what works. This type of knowledge has been termed situated and procedural (McCormick, 1997; 2004). The descriptions of participants' approaches to tasks and personal learning generally in the cognitive profiles (Section 4.9) strongly reflect both procedural approaches and specific learning situations. Where learning has been considered in relation to the 'practical organisation of knowledge' (Smithers and Robinson, 1994: 37), as in engineering and technology fields, models of representation have been suggested which account for the input from practical experience (Kimbell, 1994; Baynes et al., 2010). It has been suggested that some of this knowledge is difficult to represent in other ways (Baynes et al., 2010), for example phenomena needs to be drawn or physically modelled. Modelling thus supports Siegler's (2005) suggestion that variability in presentation and engagement enhances the learning experience (see Section 2.4.1). Through different models, for example, electronics can be simulated in different ways, thereby providing the learner with a variety of procedural approaches to engage with phenomena.

Referring to the cognitive profiles (Section 4.9), I suggest that modelling supports a dual process. It is used as a part of the iterative process of 'imaging and modelling in the head' and the 'confrontation of reality outside the head' (Kimbell, 1994: 62), for example in the development of a virtual circuit design. Modelling also enables phenomena to be represented and communicated (Baynes et al., 2010); circuit diagrams and symbols are good examples. The process of modelling in technology type tasks parallel very closely the learning processes outlined by Kolb and Fry (1974). Thus imaging and modelling are enablers which allow the learner to interact along the processing continuum, actively experimenting with and observing the model, as a part of the experiential learning cycle (see Figure 1, Section 2.5).

The cognitive profiles reflect a range of models which emerged during the interviews. For example Ethan modelled his conceptual understanding around Logic type circuits and Connor around programming (Cognitive Profiles, Section 4.9.3 and 4.9.1 respectively). Some of the participants relied on the connection with tangible aspects of the phenomena, such as Ben and Luke. As discussed above these enabled participants to understand functional characteristics of the circuit, differentiate between analogue and digital circuits and communicate these ideas. Modelling may have therefore supported meaning making through the interaction between knowledge types and practical application. The translation of and transition between representations is considered in this research study to play a significant role in the development of a mental model.

It is very difficult however to determine the precise nature of a mental model, beyond the cognitive constructs proposed above (Cognitive Profiles, Section 4.9). In the literature referred to above, Kimbell (1994, 62) relates mental modelling to some of the processes highlighted in the previous section (Learning Processes, Section 5.5.1); thus impression forming, speculating and exploring, validating and appraising are considered to reflect what is actually going on in the mind, particularly when practical solutions are the outcome of problem solving. It would be natural to propose that some of these model types are visual in nature; thus visualisation reflects the generation of a mental picture of the engineering or technology based solution. This may also be the case when considering some of the concepts in this research study, such as the analogue/digital dichotomy or time delays as a product of a computer program. Thus participants have referred to diagrammatic and symbolic elements in communicating their understanding of these (Fergus, Jacob), or have referred to practical experiences in revealing their mental models (Ben, Luke).

It would be interesting to explore in more detail the specific methods employed by learners in developing procedural knowledge (McCormick, 1997). Do learners always need to enact the procedure in some way to recollect the knowledge, or is the knowledge converted to another form when developing understanding? In the next section I consider language use as an alternative approach to developing concepts and learning in electronics education.

5.5.3 Learning and language

5.5.3.1 Technical and non-technical language use

The use of language by participants to describe concepts was particularly interesting because it indicated a difference in the application of technical and non-technical, or general terms. In this section I briefly consider the findings which relate to the use of general and technical terms. The development of understanding represented by the technical term closely parallels conceptual change theory (Chen, 2013; Treagust and Duit, 2008), as it assumes the gradual acquisition and application of technical terms, and therefore change in the learner's underlying conceptions represented by those terms. Halliday (1993) believed individuals construct knowledge on a continuum of everyday spoken language at one end, to technical terms, phrases and more formal prose (synoptic level) at the other. I consider this notion in relation to this study's findings.

Technical terms were used often and confidently by some of the participants, for example Fergus and Connor (Table 27, Section 4.10). Their understanding was communicated through these 'synoptic' terms, as Halliday (1993) refers to them. It is possible that participants have developed an understanding of, for example, logic systems or programming through the specific language of these technologies. As I discuss above (Q2, Section 5.3), the findings can be interpreted to show a development in language use when considered within the case as a whole. This is particularly the case when considering programming as a development of conceptual understanding as participants have undergone a transition from understanding and describing electronics in terms of traditional electronics terminology, to applying programming terminology to the same phenomena. Even if participants began the course with good programming skills, they would have had to learn the connections between programming code and electronics terminology, reflecting a conceptual change.

Many of the participants adopted the specific language of a particular electronics knowledge area (e.g., logic, programming), of which each area has its own specific language of terms and usage, known as grammatical metaphors (Halliday, 1993: 111). It is interesting to note that several of the participants adopted a non-technical approach to describing their understanding and that they tended to rely on references to practical application in their interview responses (see Ben, Feidhlim, Luke and Oliver, Cognitive Profiles, Section 4.9). Findings show that there is a correlation between describing electronics in practical terms and the use of non-technical language, which may suggest that where practical application is important to participants' learning, their language is applied at Halliday's (1993, 111) 'dynamic level'; in other words learners develop an understanding through thinking about 'reality as process, as the spoken language does' (*ibid*). This may explain some of the participants' detailed descriptions of functionality (Ben, Feidhlim, Luke), as opposed to other's developed use of technical terms (David, Fergus). It is worth noting though that the understanding of Jacob and Oliver, noted as non-technical language users (Table 27, Section 4.10), was excellent on the basis of their GCSE outcome (A*) and therefore the use of non-technical language does not necessarily correlate with poor understanding.

5.5.3.2 Language and the learning process

The consideration that a conceptual change occurs through language use is compatible with the conclusion drawn above that learners adopt a common process of engagement with representations, leading to translation and transition between them and corresponding knowledge types. Ausubel (2000) stresses that this process begins with what is already known as a first mental referent, then follows the common process outlined above (Figure 18). In Ausubel's (2000) theory concept development begins with simple naming and vocabulary building, which are then used as referents when new concepts are applied in new situations. This process of assimilation leads to the development of the learners' cognitive structure, or schemata Piaget (1955), which is in turn drawn on to facilitate comprehension and meaning making (*ibid*).

This line of thought would suggest that the early experiences of learning component names and terms related to electronic functioning is an essential part of developing this schemata and a foundation for later concept development, when the new knowledge is presented in a meaningful way to learners. Meaningful in this context means presentation in a way that allows new knowledge to be connected with existing knowledge. In this research study the findings show that those participants who use a wider range of technical terms tend to hold a more advanced understanding of the subject; although this is not always the case, as Oliver's responses during interview show.

However it is interesting that David and Fergus, arguably two of the most competent participants on the basis of their detailed interview responses, differ noticeably in the way their descriptions represent learning processes. David, although using technical terms, refers often to the practical application of electronics. Fergus on the other hand makes limited reference to practical application and tends to rely on his in-depth knowledge referred to through technical terminology. In terms of language development, this may reflect their approach to learning, with David preferring to apply and discover (Cognitive Profile, Section 4.9.2) and Fergus tending to develop his understanding of analogue/digital systems on the basis of his knowledge of voltage behaviour (Cognitive Profile, Section 4.9.4). Thus there is a difference in the development of schemata (Piaget, 1955), David's based around practical application and

Fergus's based around technical terminology, emphasising the differentiated approach to knowledge development.

Both of these approaches can be assumed to involve the processes of categorical naming, thought organisation and communication through verbal codes (Arnheim, 1970). Learning on this basis involves the 'elaboration or modification of cognitive structure' when learners are confronted with incomprehensible phenomena (Smith, 1975: 35). In practice this necessitates creating meaning on the basis of categories that comply with a specific set of properties identifiable in the object (Smith, 1975) and it is possibly here that the benefits of language can be identified. In Pinker's (1998) view, conceptual thinking requires caption-like instructions to support the interpretation of phenomena; a suggestion not incompatible with the suggestion above that computer programming code may provide this type of support to learning. It is useful to note that the findings demonstrated that Fergus has a very good understanding of and a keen interest in programming and it might be that this ability enables his thought processes to operate without the need to refer to the practical application of phenomena. Figure 18 below develops the earlier model (Figure 17, Section 5.2.3) with the addition of a transition process leading to conceptual development, representing key ideas in the discussion above.

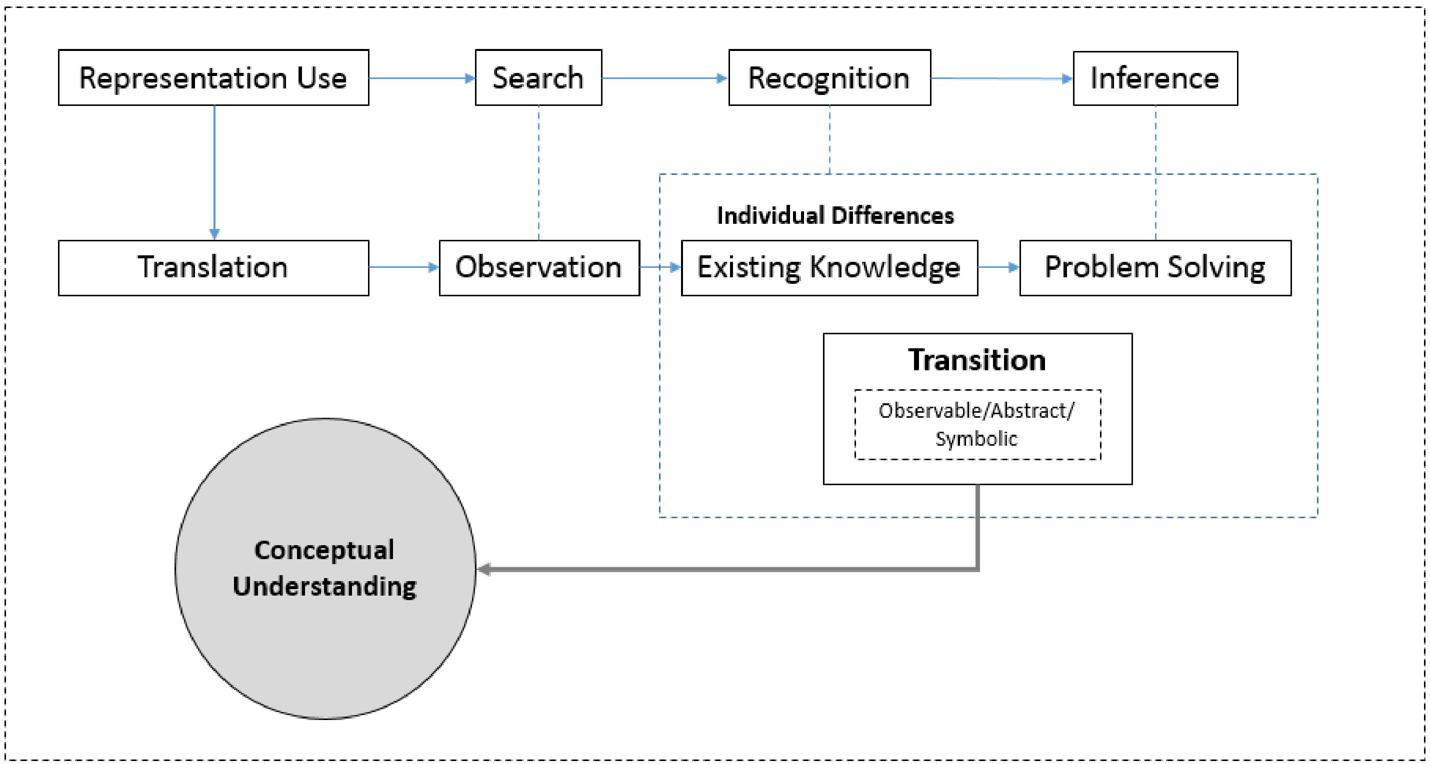


Figure 18: Relationships between elements of representation engagement leading to conceptual development

5.6 Summary of discussion chapter and relevance of this research

The aim of this research study was to identify the nature of mental representations, or conceptions, of electronics knowledge and the processes used in the construction of those conceptions. Adopting an interpretative methodology based around the context of learning, realistic activities related to learning and discussion during interviews, it was hoped that a contribution could be made to the research on electronics learning which has tended to focus on experimental approaches to research, learning interventions or the identification of misconceptions of knowledge (see Literature Review, Section 2.5).

5.6.1 The microgenetic approach

Focusing on the context and realistic activities through close observation has been termed the microgenetic approach (Siegler, 2005). According to Siegler (2005), the microgenetic approach is the only way to reveal how children learn. I focused closely on several individuals of interest in this study, which parallels the microgenetic 'trial-by-trial' approach (Siegler and Crowley, 1991), which is considered to provide the individual change data in sufficient detail to analyse the learning processes of interest. As discussed earlier (Section 3.6.1), Wu et al. (2001) provided a model framework with which to approach data collection. As the analysis of findings developed and clear outcomes were generated, the parallel between this study's methodology and the microgenetic approach became apparent. In particular using a trial-by-trial approach, the outcomes of which I represented as four cognitive profiles, I drew upon the concept of close observation, high densities of recording of actions during activities and intense analysis of those actions (Siegler, 2005), which led to my observations about learning processes.

The microgenetic approach provides a framework to support my contention that this study presents a snapshot, through the four cognitive profiles, of participants' actual approaches to learning during the learning process. Retrospective awareness of the microgenetic approach is considered to strengthen the reflexive nature of the study and indicate its ongoing developmental nature. Throughout the remaining Discussion and in the Conclusion chapter I refer to the microgenetic approach, where appropriate, making links with the theory and the methodology used in this study.

5.6.2 Mental representation and modelling knowledge

Solsona et al.'s (2003) research identified different levels of understanding which are useful in explaining how far along a learning trajectory any learner may have progressed and how they arrived at those points. A strength of the present research study is that in addition the cognitive profiles describe the nature of participants' conceptual understanding, which should be useful in designing future learning activities in relation to electronics education and to other fields where a reliance is placed upon the learning of abstract concepts. It is interesting and surprising that the Year 10 course did not seem to influence participants' construct development in predictable ways, for example there was not a reliance on explanations related to the current topic of logic; rather individual differences were reflected through a range lenses, all of which relate to the course, but were the choice of the individual in applying meaning and understanding. Thus mental representation was revealed as a highly differentiated phenomenon and although this was generally grounded in conceptions of voltage in some way, they reveal a much wider conceptualisation than that proposed by Metioui and Trudel (2012).

The way knowledge is modelled mentally will have implications for the way learners are presented with information during teaching. For example participants' revealed different ways of using language to convey meaning and understanding which suggests that although in some situations, particularly examination-based situations, technical terms are considered important, meaning can be conveyed as well using non-technical terms. The notion that concepts emerge (Chi, 2005) and that conceptual change (Chen, 2013; Treagust and Duit, 2008) is often apparent and necessary when learners make progress, has been supported by this research study, most notably in the way participants used language to describe conceptual understanding and in the transitions to programming code from traditional electronics understandings. It would be useful to take greater account of the different phases of concept development, to make these more apparent to learners and to support the design of learning activities to match approaches to learning tasks by learners. Some of these approaches have been shown to involve understanding based around different electronics concepts, such as logic, digital or computer programming. Others demonstrated their need to actively simulate, or model, the understanding in a physical sense. A microgenetic approach would support the exploration of learning phases.

Programming code was revealed as an explanatory support for developing electronics knowledge, but may be restricted to its use in conjunction with existing knowledge as circuit diagrams were considered to provide the most useful starting point for learning and problem solving. This was possibly due to learners' reduced cognitive load in viewing the synchronously presented information in the circuit diagram. When the transition between these representations was successfully achieved, participants revealed a deeper understanding of the concepts involved and this supports claims that the use of multiple representations is beneficial to learning, particularly when they encompass observable, abstract and symbolic types of representation (Johnstone, 1993; Wu et al., 2001). There was some evidence to suggest that abstract thinking in relation to transitions between traditional and programming methods occurred in visual form (see Section 5.4), supporting Arnheim (1970), which may indicate the relevance of visual spatial ability in developing abstract conceptions. Therefore modelling electronics using computer programming, rather than traditional electronics components, may provide the necessary transition opportunity for learners to develop a deeper conceptual understanding and provide an alternative way with which to model and actively simulate their understanding.

An interesting outcome of the wider consideration of the research as a case of representation use, and support for Seufert and Brunken's (2006) similar observation, was the identification of a tentative link between spatial ability, as depicted by the Patterns component of the Yellis cognitive ability test (CAT) score and the tendency for abstract thinking (Table 9, Section 4.2). Conversely low scores on this test tended to correlate with concrete thinking. It would be useful to explore this in more detail, particularly as at the time of writing (2016), the use of CAT scores continues as a prominent feature of assessment in contemporary education.

Finally in this section the role of practical experience was a valued method of embodying knowledge through procedural approaches and physical contact with the component parts of electronics. The inclination was strong enough for some participants to adopt this approach even though it was not a requirement in some of the research based tasks. It provided Luke with the agency he needed, for example, to engage with the programming task which he saw as a problematic activity (Luke, Screen Capture, Lesson 2, Section 4.6). Providing this opportunity was indicated as supportive to both engagement and problem solving skills for some learners. The subsequent reference to practical experience, in a similar way to observations about general or technical language use, may provide some learners with an alternative referent to theoretical knowledge and consequently an alternative access point and way to construct personal schemata during the learning of difficult concepts.

5.6.3 The process of knowledge construction

In the Methodology chapter I proposed a consensus view of knowledge which suggests that reality and truth relate to the observer's interpretation and approximation of experience with observation. This has been referred to as a mechanism of collective acceptance (Searle, 1999; Fleer and Richardson, 2008) which grounds the reality shared by individuals and knowledge frames. A notable outcome of this research study is the common approach adopted by participants when engaging with representations and problem solving. This common approach concurs with a significant body of research, a consensus, which proposes a process of knowledge construction broadly moving from accommodation to assimilation (Ausubel, 2000; Bruner, 1977; Kolb and Fry, 1974; Piaget, 1955).

The process identified in this research study began with concrete observations of elements of representations, made links with existing knowledge in relation to representations and used this to support problem solving and task completion (Figure 18). I have referred to the first two aspects of the process (observing and existing knowledge) as translating and this has been shown as a necessary first step by all of the participants. This first step is likely to provide learners with an assured and fixed starting point, where the central processing component of the circuit diagram forms the focus and any words used provide an explanatory function. This concurs with research supporting the use of text and image in forming mental concepts (Paivio, 1986) and indicates that multiple representations are often necessary to support meaning making by the learner (Wu et al., 2001). This is a point of disagreement with the literature on this topic however, which suggests the use of multiple representations cognitively overloads learners (Ainsworth, 1999; Seufert, 2003). In this study participants regarded multiple representations as a necessary support for identifying meaning which enabled them to progress beyond the initial observations of concrete features of single representations, which often do not provide sufficient information for learners. The high attaining nature of the participants in this study may explain the capacity to process multiple representations.

Participants' translations were shown to reflect either functional or conceptual inferences. Where conceptual inferences occurred participants demonstrated a transition from one mode of representing knowledge to another. For example between a logic gate circuit symbol and a truth table on the basis of the concept of binary. A strength of the cognitive profiles (Section 4.9) created from the findings of this research is the diversity of methods shown to be used to perform transitions of a similar nature. These build on the use of cognitive profiles by Solsona et al. (2003), to depict learners' mental representations of knowledge in electronics. An awareness that learning about, for example, logic circuitry can be conceived as or modelled using binary notation or programming code and that this can aid learners in making progress with learning through multiple levels of representation, as claimed by Wu et al. (2001), may provide an additional support for learners who struggle to develop these concepts. Conversely, the practical application of electronics, evidenced in the functional descriptions of circuits provided by many of the participants in this study, may offer an alternative for some learners who exhibit a preference for this mode of thinking and representing. This research study shows that working with multiple levels of representation provides the degree of information needed to problem solve, progress learning in electronics and ultimately to modify existing schemas through the development of new conceptual understandings.

5.6.4 Representing knowledge in electronics education

This research study has shown that knowledge which is regarded as applied technology can be represented and understood in multiple ways and sometimes enables scientific understanding through the development of the technology (France et al., 2011). An example of this phenomenon in this research study includes the application of microcontrollers and computer programming enabling the understanding of traditional electronics. In other words through the development of microcontroller-based activities, an understanding of the concepts of electronics can be developed. The study has also shown that knowledge should be presented in different ways (e.g., Wu et al.'s (2001) levels), to support the learning of abstract concepts and contributes to a need to better understand learners' actual representations of electronics knowledge (Metioui and Trudel, 2012). A fundamental difference between participants in this study was the vehicle used to perform transitions between representations and construct meaning for themselves and consequently support learning. This assertion concurs with McCormick (2004) who identifies a difference between scientific and technological knowledge in the way context is associated with the learning and the findings from this research support this view of knowledge as fundamentally situated within the practical application of electronics technologies.

Chapter 6 Conclusion

6.1 Introduction

The key aim of the case study research described here was to explore the relationship between learners' use of external representations and their constructions of knowledge, in connection with conceptual understanding and the learning process. The study examined a specific case of representation use through the cross-case synthesis (Yin, 2014) of learners' translations of, and transitions between, representations and the application of procedure during this process. The study therefore explored the interplay between learning processes and mental models, observed in the use of representations drawing on Wu et al.'s (2001) observable, symbolic and abstract levels. The case focused on learners' understanding of the concept of voltage types in terms of analogue and digital voltage behaviour and was guided by the following research questions:

> Q1 How do students describe their use of electronics representations when translating and performing transitions between multiple representations?
>
> Q2 How do students describe their conceptual understanding of electronics in relation to 'traditional' circuits and 'programmed circuits' and how do these differ?
>
> Q3 What is the role of practical experience in translating and performing transitions between electronics representations?
>
> Q4 How do students relate learning to their experiences of translating and performing transitions between electronics representations?

The use of representations (Q1) was shown to follow a common pattern in terms of the procedure of learning and a differentiated approach to knowledge development, presented as four individual cognitive constructs (Q2). Traditional electronics representations, such as circuit diagrams and symbols, were cited as key representation types, providing concrete associations with existing knowledge. Computer programming was valued as a secondary, explanatory representation supporting learning and was considered to provide a conceptual change (Chi, 2005; Ozdemir and Clark, 2007; Treagust and Duit, 2008) experience for the learner (Q2). Practical experience emerged as a key method with which to develop and model knowledge and subsequently a strong referent for recalling existing knowledge (Q3). Learning (Q4) was shown to comprise a clear process of learner experience, transformation of representations used, and knowledge and reflection on the process of representation use, in line with the work of Piaget (1955), Bruner (1977) and Kolb and Fry (1974), as applied within electronics education. The process of learning was enhanced through the use of multiple representations, simulation experiences and visualisation methods to automate the learning process (Q4). This developed my understanding of the procedure of learning within the context of Design and Technology-based electronics and revealed the specific nature of learners' conceptual understanding of the subject.

6.2 Summary of main findings

This research study has revealed a common approach to engaging with representations displayed in different forms, such as diagrams, truth tables and graphs. I refer to the process of making connections between these representations and attaching meaning to phenomena as translation following Ainsworth's (2006) definition (see Introduction, Section 1.2). Learners began with concrete aspects of the representational referents to make links with existing knowledge, as a starting point for new knowledge acquisition. Abstract thinking was shown to follow observations of phenomena based on concrete elements of the representations, including for those participants who displayed deeper abstract thinking ability. I found some evidence connecting abstract thinking ability and spatial thinking skills, in support of suggestions that conceptual knowledge is grounded in visualisation ability and visual metaphor (Mathewson, 1999; Pule and McCardle, 2010; Wu et al., 2001). The common approach adopted by participants follows Kolb and Fry's (1974) processing continuum as described within the experiential learning cycle. Practical experience was found to play a key role in visualising, or modelling, actively experimenting with and simulating knowledge, then reflecting on observations leading to the creation of meaning. These experiences were most commonly recounted through functional electronic-component referents, or associations with theory through component functionality. Practical experience, therefore, provided the twofold purpose of revealing knowledge to the learner through an active model and embodying the knowledge through the physical experiential process.

Knowledge development, on the other hand, was shown to be a personal and differentiated phenomenon. I identified four cognitive constructs describing participants' mental models of electronics knowledge - which were termed Operative, Logician, Programmer and Dialectic. The models are described as follows:

- *Operative* – understanding is modelled on the physical experience of handling electronics components and tends to focus on concrete, observable phenomena.
- *Logician* – understanding is modelled on logic process which are grounded in digital systems.
- *Programmer* – understanding is modelled around computer programming, often using terms from coding and operating a microcontroller. Constructs based on programming tend to also focus on digital electronics.
- *Dialectic* – understanding draws on both analogue and digital electronics, modelled in the language and descriptions used by the participant. Constructs reflect an understanding of the concept of voltage behaviour, which can be either fluctuating (analogue) or fixed (digital).

A fifth construct, the Explorer, related to the active self-discovery of knowledge as an individual approach, which is discussed fully in Section 4.9.2. The constructs represent the specific nature of personal understanding in relation to electronics knowledge, and build on Metioui and Trudel's (2012) position that all electronics understanding is conceived in terms of the behaviour of voltage and current. Wu et al.'s (2001) observable, symbolic and abstract knowledge types were found to be useful during the analysis of each participant's approach to learning and their construct was positioned according to these levels of understanding. Wu et al.'s (2001) levels therefore represented an analytical framework for both the learner's approach and a description of the learner's understanding.

I found that participants' differentiated constructs supported the transition between representations, and I was able to show that these were more effective where participants applied their personal construct to the task. The cognitive construct is thus viewed as a vehicle for understanding and making the transition between multiple representations within the learning context. The construct was shown to be a key vehicle enabling the transition between concrete and abstract thinking and represents a point of progression on Kolb and Fry's (1974) perception continuum. Accordingly progression towards the abstract end of the continuum indicated an increased ability to make transitions between representations and knowledge types and consequently a deeper conceptual understanding of electronics phenomena.

Simulation as a tool for learning was closely linked with participants' tendency to adopt a practical approach to support their learning through active modelling. This was particularly the case where software-based tasks were completed and simulation tools were readily available as a part of the software. As an example of this learning strategy, computer programming was used to represent functioning shown in a circuit diagram and testing and trialling was enabled through the software-based output simulation tool (Appendix 14). Practical application, through computer programming-based modelling, is therefore effective at revealing electronics knowledge and simulating its meaning and plausibility in context, in accordance with the notion of an experiential learning cycle.

The discussion of the findings (see Discussion chapter, Section 5.2.4) considered the relative merits, as described by Larkin and Simon (1987), of synchronous and sequential representation types. Circuit diagrams were found to be key and primary representations for the elicitation of existing knowledge, because this synchronous representation type makes search and inference easier due to the reduced demand on learners' cognitive effort (Kirschner, 2002). Computer program code, accessed in sequential mode due to its instruction-like format, was shown to be a supporting representation which provided an explanatory function for electronics understanding. This supports Ainsworth's (2006) suggestion that multiple representations provide specific benefits to learning. In this study I identify these benefits as learners' use of both traditional and programming means of representing electronics knowledge.

Finally developments in understanding that require the transition between representation types, specifically between 'traditional' and 'programming' domains, represent a conceptual change (Chi, 2005; Ozdemir and Clark, 2007; Treagust and Duit, 2008) on the basis that the schemata held by the learner has been adjusted to accommodate the new knowledge from the secondary domain. Conceptual change is considered to be advantageous because knowledge has been transformed, in the manner described by Bruner (1977) and Kolb and Fry (1974), through the cycle of action, observation and reflection. For this reason learners' understanding of phenomena is emergent (Chi, 2005) and may not be readily observed until the cycle of experience has been completed.

6.3 Recommendations from this research study

6.3.1 Procedural learning through modelling and simulation

A prominent finding demonstrated the importance in electronics education of knowledge differentiated around analogue and digital electronics systems. Findings show that the analogue/digital phenomenon is often at the root of understanding, which can be externally modelled in several ways (e.g., physical output components, on-screen simulation), but relates to an internal conceptual understanding based around personal constructs of the phenomenon in question. Emphasising how the analogue/digital phenomenon associates with electronics topic areas, such as timing, counting or microcontrol would provide learners with an additional thinking strategy and modelling tool when learning about these topics.

The use of programming code as a helpful and explanatory representation for electronics phenomena was shown to support learning because it explains, using indicative coding terms, the functioning of real-world components and circuit function. This supports empirical evidence for the benefits to learning of explanatory tasks generally (Aleven and Koedinger, 2002), and the use of language-based programming approaches with school-age children (Lauria, 2015). Consequently the structure of the GCSE course outlined above (Table 2, Section 3.5.2), could benefit from opportunities to explore traditional and program-based electronics in parallel, rather than the current sequential traditional-then-programmed approach. A parallel approach could provide the opportunity for learners to benefit from the explanatory representation and an alternative opportunity to model knowledge, while drawing on the advantages of the concept of variability learning, as described by Siegler (2005). Further research is needed to explore the potential of a parallel model.

Modelling and simulating can be shown to apply at three levels. Firstly, the findings show that the learner's opportunities to actively engage with the procedure of learning, through simulation, can support concept development because through the process of testing and trialling, the learner creates a personal mental model of the phenomena under study and consequently develops their knowledge and understanding (Figure 19). Computer programming was shown to be a successful way to actively engage with learning through the simulation of electronics on screen, increasing learner agency and supportive of previous research on the benefits of computer simulation by Chen et al. (2013). Opportunities to simulate phenomena in as wide a range of alternative ways as possible should be encouraged as this allows the learner to think about the phenomena in multiple ways, therefore increasing the learner's opportunity to modify personal schemata. This is considered to enhance learning (Siegler, 2005). The findings suggest that the practical application of phenomena should be encouraged to externally model what is otherwise represented only at the level of Wu et al.'s (2001) symbolic and abstract representation types. Thus the findings show that when thinking involves multiple perspectives, at different representative levels, transition between representations is enhanced and a deeper conceptual understanding is achieved. Emphasising the options for active simulation should therefore increase the learner's agency in choosing to use the range of tools available.

Secondly, according to Kolb and Fry's (1974) experiential learning cycle, learning strategy is a process of choice on the part of the learner. Emphasis of the strategies available by teachers, such as physical modelling, simulation and verification of outcome, could aid the learner in developing confidence with the choice of learning processes to be made (Figure 19), particularly where new problems raise uncertainty in the learner's approach. For example, modelling strategies to support learning about electronics-based time delays could involve the use of prototyping boards and real-world components, on-screen simulation, measurement using a multimeter or program-based time delay using a microcontroller. At another level of representation (symbolic), calculation would provide a model of expected outcomes when combining components (i.e., in an RC Network) to create the time delay. Each modelling strategy has a specific advantage and the choice of use will be determined by the context and stage of the learning. Similarly, identifying learner preference for particular strategy use and encouraging its use may enhance learning for the individual. In practice this might involve the observation of a learner preference and discussion with them about the plausibility of a strategy. Pointing out the benefits of the strategy and the potential for application in other tasks may enhance the learner's agency in applying self-directed learning in new situations.

Thirdly, the modelling and simulating strategy has implications for developing pedagogical approaches (Figure 19). These could support teachers in recognising learners' approaches and managing feedback which is helpful in integrating appropriate strategies which relate to the context and stage of learning.

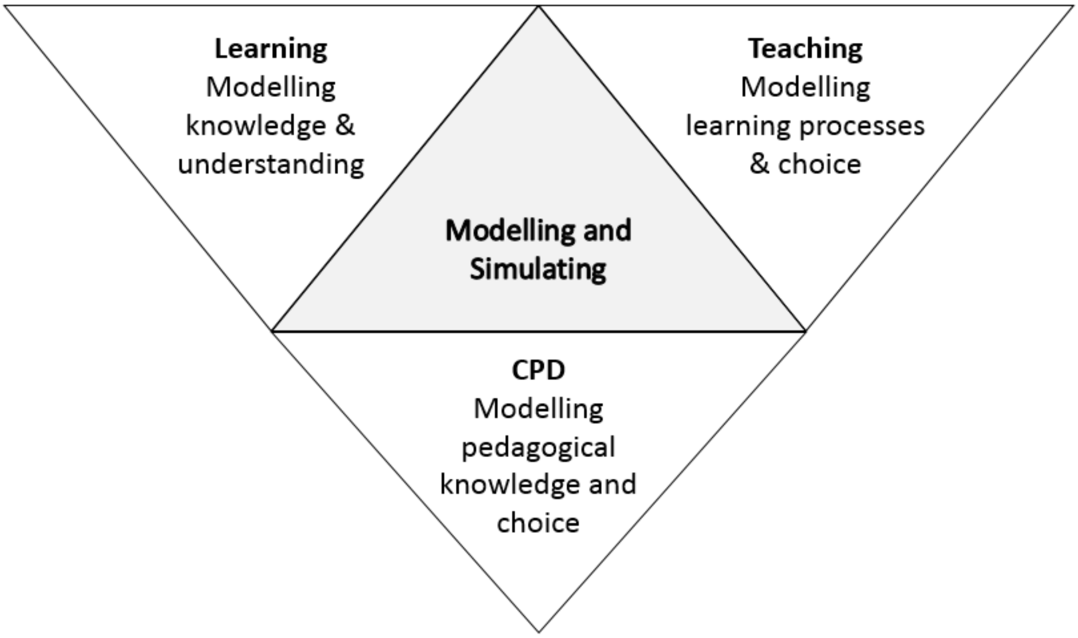


Figure 19: Modelling and simulating concept applied at three levels

6.3.2 Learning and cognitive load

Cognitive load theory suggests that mental effort can be reduced through coding multiple elements of information as one element, by automating aspects of the task and by presenting information in several ways (Kirschner, 2002). The findings indicate that learners reduce cognitive load by accessing information represented in the simplest format, for example a circuit diagram. Learners accessed several information elements coded within the representations to recognise a concept more efficiently (e.g., recognising a resistor and capacitor connection leading to the concept 'RC Network'), or to make initial links with their existing understanding prior to problem solving. The reduction of information to its most basic form can be practiced (e.g., through transition tasks which involve modelling knowledge in alternative ways) and the attachment of information to appropriate referents (e.g., knowledge of the timing concept attached to the term RC Network) demonstrated and encouraged to develop overall schemata. In another example, logic systems can be recognised through truth tables which display information about a number of elements such as the logic gate's inputs, outputs and gate type which are all contained within one representation. Opportunities for transitional tasks can be provided which encourage efficiency with the translation strategy applied (i.e., practical or logic based), when using multiple representations. This can lead to the refinement of the learners' cognitive construct, or mental schemata.

The findings in this study thus suggest that presenting information in several ways leads to understanding which becomes refined to the simplest form by the learner. Automation is therefore achieved through the combination of elements at the point of representation use, which leads to reduced cognitive load on the learner. The findings in relation to computer simulation tasks (here using Circuit Wizard to model circuits or PICAXE Programming Editor to model program code) also suggest that removing elements (termed *redundancy*), such as the need to recognise both real-world components and their characteristic features, leads to increased task automation through reduced cognitive load. Automation through the computer-based simulation tool, such as the output simulation pane provided by Circuit Wizard (Appendix 14), therefore frees up thinking capacity which provides greater capacity for new knowledge acquisition and problem solving.

6.4 Evaluation of methodological approach

In the Introduction I explained my interest in visualisation skills and how these supported learning generally in Design and Technology education. A gradual shift of emphasis occurred as the project progressed, which developed the focus of the research around conceptual understanding and learner strategy. I wanted to understand and explain how visualisation supported the context of learning in terms of representation use and knowledge construction and therefore I was interested to explore what visualisation skill represented for the learner in practice. The research questions above therefore evolved to include inquiry within the learning context; an approach regarded as a strength in this study and a desirable research aim more generally due to the paucity of context specific research into conceptual understanding relative to Design and Technology education (McCormick, 2004; Metioui and Trudel, 2012).

The methodological approach taken in this study focused closely on the learner's point of contact with representational materials. This is considered to make a contribution to, and develop existing understandings of, knowledge which has often emerged through experimental approaches highlighting learners' misconceptions of knowledge (see Literature Review, Section 2.5). Focusing closely on the context has enabled inferences to be drawn around learning procedure and learners' personal epistemologies. This was possible because the research encompassed observation data from the classroom, learners' working documents and subsequent individual interviews. As the research progressed I realised that this approach, based around close observation, paralleled Siegler's (2005) microgenetic approach, although based on one cycle whereas Siegler (2005) argued for many. The outcomes provide an insight into the learners' constructions of reality and how that reality relates to engagement within a GCSE Design and Technology: Electronics course.

To support observations of individual learning, this research study drew on overlapping waves theory (Siegler, 2005) during the analysis and discussion of findings. The theory suggests that learning is approached differently at different times by learners, with some strategies overlapping due to their collective use in certain tasks. The overlapping waves approach can be applied in future research by introducing further data collection points in the research process so that the nature of variability, choice and change in electronics learning can be described in further detail. Findings in this area would assist in explaining the temporal nature of conceptual change and might support the design of learning materials which are more accurately matched to individual and learning phase-based needs. This might support the suggestion made above that traditional and programming approaches to electronics learning could be run in parallel. Knowing more about learners' strategies and how these are used at different times may provide more clarity and support for a parallel model.

Findings from the interview stage of the study were particularly insightful. The lesson observation data and participant's lesson-based documents were valuable in triangulating the interview data. However acting as both researcher and teacher in parallel proved particularly difficult due to the demands of this dual role. In addition the technical support arranged for the research worked only partially and this led to some disappointment during this data collection phase (see comments documenting this in

Journal Summary, entry 01/07/14, Appendix 5). On the other hand the lesson tasks formed an essential component in the research overall, particularly useful in the discussions during the interview phase. In line with the previous suggestion on developing further data collection points, the application of a longitudinal approach may overcome these difficulties as it would allow the researcher/teacher to gradually collect data about students' learning and therefore overcome, to some extent, the difficulties of role conflict.

6.5 Alternative approaches to the research

As the research progressed it became clear that inferences surrounding learning would be complicated. It is extremely difficult to determine precisely what is going on in the mind during learning and what the influences are leading to knowledge construction. A large proportion of the data collected revealed answers to the 'what' type questions. These were appropriate, particularly for Research Questions 1 and 2 which aimed to reveal descriptions of participants' approaches and understandings. The 'why' type questions require further study to build on the tentative explanations emerging from this study's findings, relative to specific ways of learning. One way to further the research in this respect would be to explore conceptual understanding in terms of conceptual change, as described by Treagust and Duit (2008), taking specific account of learners' default knowledge positions (Searle, 1999) when determining the nature of, and influences on, any change. Understanding learners' default knowledge positions at the point of entry to the GCSE course would support this aim because it would provide a base line with which to compare further data collection. The approach adopted by Solsona et al. (2003), who use an essay writing task to gauge learners' pre-course understanding, could form the basis of a data collection method to complement the methodology adopted in the current study. This would support the aim to understand in more detail learners' initial level of understanding and subsequent change in knowledge schemas.

To support understanding about why learners develop knowledge in particular ways, a longitudinal approach would support the suggested increase in data collection points while maintaining the design incorporating the microgenetic method (Siegler, 2005). This would achieve the aim to illuminate conceptual changes, while supporting more effectively the dual role of researcher/teacher. A longitudinal approach would continue the benefits of a context specific approach (Thomas, 2009), as adopted in the current study, and would allow the focused interaction (Siegler, 2005) between individuals over time, including the teacher, to inform the findings. This approach would be designed to reveal 'trends' in relation to a 'developmental course of interest' (Yin, 2014: 53).

Engaging in a microgenetic-based longitudinal study raises certain questions alluded to above. For example what is the nature of learners' knowledge on entry to a GCSE course of study in electronics? What are learners' default positions in relation to their understanding of electronics phenomena? What are learners' subject related interests and what do learners' expect to achieve on the course? Recording learners' key conceptual ideas as they progress through the topics, activities and milestones offered by the course content would provide a map of learners' constructions which could be compared with their point of departure. Superimposing this with learner interactions between teaching resources, application and outcomes would develop the findings in the current study with a more in-depth representation of learning within the context.

Finally this study focused on learners' conceptual understanding of voltage types (analogue and digital). I identified four cognitive constructs representative of learners' individualised understandings in relation to this concept. Adjusting the focus to other phenomena may reveal a rival explanation (Yin, 2014), an alternative pattern of understanding, and support a different interpretation of learning behaviour. Data collection at another point in the learning trajectory, in accordance with conceptual change principles, may reveal different outcomes. Similarly, although language use is discussed to some extent in this study (see Discussion, Section 5.5.3), approaching the analysis of data from the perspective of learners' use of language as the main focus may also reveal a different perspective on the learning process.

In this respect, the brief analysis provided in this study suggests that language use may be a promising area of further exploration and could lead to interesting insights when compared with the key findings of this study. It would be interesting, for example, to compare meaning making through language, and that achieved through procedural means. Do learners always enact the use of language, even when learning in the procedural mode, as discussed in the current study? Or does procedural learning involve alternative mechanisms? What is the role of the technical term, given the variability with which it was evidenced relative to understanding in the current study? And what is the level of meaning attached to understandings of electronics discussed in general terms? These questions lead to considerations of methodological selection and indicate that knowledge generated from the research is closely associated with the choices made in approach and method.

6.6 Case study as an approach to research

This research study has focused on one class of students, their problem solving during two lessons and subsequent individual interviews. Findings from these phases of the research were subsequently compared with participants' key assessments recorded during their GCSE course and discussed within the context of their programme of learning. The study therefore draws on and is representative of learners' approaches to knowledge construction bounded within a two year time period. It has consequently been possible to reflect on participants' documents and interview responses within the wider context of learning during the GCSE Electronics course, adding depth to the analysis. Presenting the research as a specific case of representation use is therefore considered to complement, through a description of learners' actual understandings and approaches to learning, the extensive literature highlighting learning misconceptions often drawn from experimental methodology (see Literature Review, Section 2.5).

The case could have drawn participants from the field of natural science. This would have removed the close association of the researcher, but distanced the procedural aspect of the findings since in the natural sciences electronics is typically explored through theory (Hiley et al., 2008). The case therefore benefits from the close association with Technology education and the individual contribution made through the practical application of ideas. The close involvement of the researcher is considered to be a strength of the study, particularly in the lesson and interview phases where greater depth of exploration could be achieved through an in-depth knowledge of the subject.

The outcomes presented in this thesis are expected to have specific application within the context of the new Design and Technology GCSE subject content which requires learners to engage with specific 'mathematical and scientific knowledge, understanding and skills' (DfE, 2015: 5). For example the requirement to calculate area and volume (mathematics) and the action and effects of forces (science), both link with physical application in either materials or the functionality of components. Applying the principles of practical application, simulation and multiple perspectives on modelling reality outlined above may support learners in developing these skills and understandings in the Design and Technology environment, using Design and Technology specific simulation models.

6.7 The wider significance of this research

The wider significance of this research study relates to a long running debate relating to the nature and importance of knowledge types. Philosophical debate has often placed theoretical knowledge, what Russell (1961) referred to as 'definite' knowledge, at the centre of scientific endeavour. In Education knowledge has been upheld within the domains of school subjects and regarded as powerful knowledge which enables young people to succeed through the interplay between everyday experience and the theoretical concepts based in those subjects (Young, 2012). In this view the goal of education is to maintain the traditions of education embedded within the subjects, as Young (2012) suggests, partly due to the trust and stability attached to such an approach.

Procedural knowledge relative to Design and Technology education, on the other hand, has been regarded as an empowerment which enables the creative change of the made world (Kimbell and Perry, 2001). This type of knowledge is relatively new, when compared with the 'traditional' subjects, and has not always been supported or valued (DATA, 2011). Because technological knowledge has '[exploded] exponentially', acquiring that knowledge is said to require the development of 'task-related knowledge' (Kimbell and Perry, 2001: 8). This has implications for the development of curricular which includes opportunities to engage with technology and the procedures for learning about it. Kimbell and Perry's (2001) edict emphasised that the product of Design and Technology education is not the artefact, but the empowerment of the young person who is able to implement the procedures of design and production.

In recent debates about the Design and Technology curriculum, DATA (2011) first highlighted the challenges faced by practitioners focusing on procedural knowledge, setting out a manifesto which was designed to emphasise the benefits of learning in the way discussed in this research case study. More recently concerns over the value placed on procedural learning have been renewed, as curriculum plans have emphasised, through the elevation of certain subjects contained within the English Baccalaureate (EBacc), the traditions of learning related to theoretical knowledge (Green, 2015). Procedural knowledge has been emphasised as necessary and important if the needs of the economy are to be met, particularly in relation to engineering expertise (Claxton, Hanson and Lucas, 2014). This case study research suggests that opportunities to engage with learning based within the procedures of activity, application and experience can enhance understanding, particularly understanding which requires the learner to comprehend abstract concepts not apparent in the observable world.

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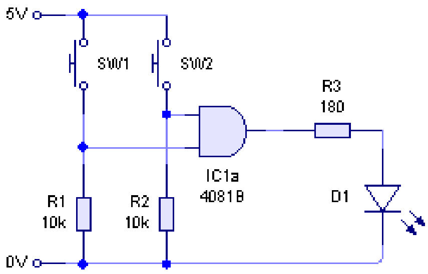
Appendices

List of Appendices

Appendix 1

Example question from pilot study (Question 1)

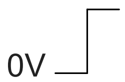
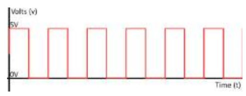
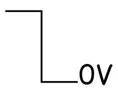
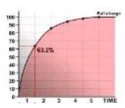
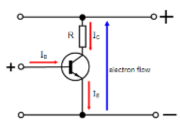
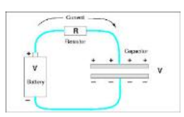
<table>
<tr><th>Activity No.</th><th>Figure</th><th>Activity</th><th>Participant Response</th><th>Concept Explored</th></tr>
<tr><td>1</td><td>

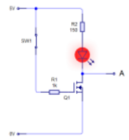
Circuit 1: Basic AND gate
<table>
<tr><th></th><th>A</th><th>B</th><th>Q</th></tr>
<tr><td>IS1</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>IS2</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>IS3</td><td>1</td><td>0</td><td>0</td></tr>
<tr><td>IS4</td><td>1</td><td>1</td><td>1</td></tr>
</table>
Table 1: Truth table</td><td>Using words and sentences, explain how Table 1 represents the circuit operation shown in Circuit 1.</td><td></td><td></td></tr>
</table>

Appendix 2

Paired image/word matching activity worksheet

Image/Word Matching Task used in Lesson 1. This version includes the images and words for information. In the activity the images and words were provided individually on 63.5 x 38.1mm sized address labels so that they could be arranged by the participants and stuck down when satisfied with the pairings.

Image	Word	How have you linked the images and words?	Common Linking Themes
	High		
	'1'		
	Pulse		
	'0'		
	Low		
	T=RC		
	Forward Bias		
	Charging		

	If … then …else		

Instructions: Activity1, Lesson 1

Task 1

Task 1: Pair Matching Task – match images and terms by placing the images next to the relevant words in columns 1 and 2

Task 2

In column 3 – Against each pair, write down how you have linked the elements, therefore identifying different ways to link the images and words

Image	**Word**	**How have you linked the images and words?**	**Common Linking Themes**

Task 3

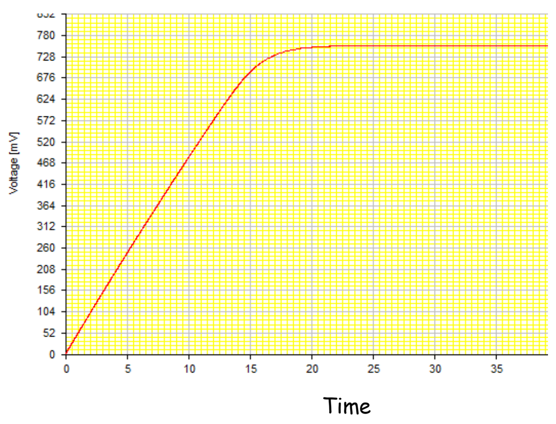
Using the highlighters to colour code the words in column 3, group your words together and try to find patterns/common ways to describe the pairings

Write down the themes that describe the pairing methods?

Appendix 3

Circuit Construction Task A

Use the graph, formulae and component list provided to construct a circuit which satisfies the conditions given

Graph (LED On after time delay)	Formulae
	T=RC T=20KΩ*1000μF T=20 sec

Circuit A Components
SPST Switch
20K Resistor
150Ω Resistor
1KΩ Resistor
LED (Red)
BC548B Transistor
1000μF Capacitor
5 Volt Supply Rail
Zero Volt Rail

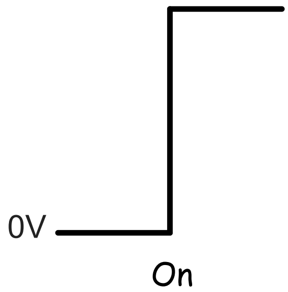
Explain how you **used** the reference materials in the box below
Indicate how **useful/not useful** you found each representation

Representation Use:

Useful/Not Useful?

Circuit Construction Task B

Use the truth table, logic signal and component list to construct a circuit which satisfies the conditions given

<table>
<tr><th>Truth Table</th><th>Logic Signal (Output Q when LED on)</th></tr>
<tr><td>
<table>
<tr><th>A</th><th>B</th><th>Q</th></tr>
<tr><td>0</td><td>0</td><td>0</td></tr>
<tr><td>0</td><td>1</td><td>1</td></tr>
<tr><td>1</td><td>0</td><td>1</td></tr>
<tr><td>1</td><td>1</td><td>1</td></tr>
</table>
</td><td>


</td></tr>
</table>

Circuit B Components
SPST Switch 1
SPST Switch 2
LED
150Ω Resistor
Logic Gate
5 Volt Supply Rail
Zero Volt Supply Rail

Explain how you **used** the reference materials in the box below
Indicate how **useful**/**not useful** you found each representation

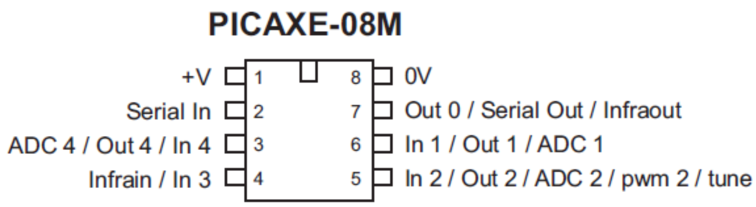
Representation Use: Useful/Not Useful?

Programming Task A

Use the circuit diagram, event schedule and PIC pin-out diagram to write a program, using Picaxe Programming Editor, which performs the same function as the circuit shown.

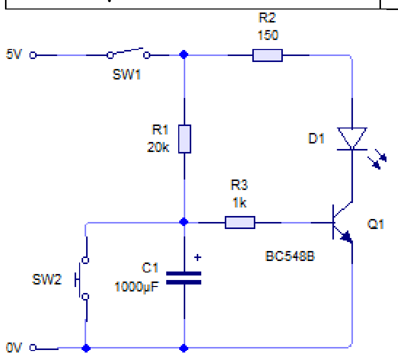
Common programming commands are given below.

PIC pin-out diagram:



Event Schedule

Event	Action	D1 Status
Sw1 Closed	Circuit On	0
R1/C1 charging	T=RC	0
Q1 forward biased (fb)	Emitter/Collector 'fb'	1
Output on time 5sec	LED On	1
Sw2 Closed	LED Off	0
Sw1 Open	Circuit Off	0



Common Programming Commands

Goto	If pin3=1 and pin4=1 then 'label'
High	Label (sub-procedure name)
If pin3=1 then 'label'	If pin3=1 or pin4=1 then 'label'
Let pins%='add outputs required'	'+' (add)
Low	'-' (subtract)
Main	'*' (multiply)
Pause (milliseconds)	'/' (divide)
Wait (seconds)	

Explain how you went about using the representations to write the program in the box below

Consider the individual representations (circuit diagram, event schedule & pin-out). Which have been useful/not useful?

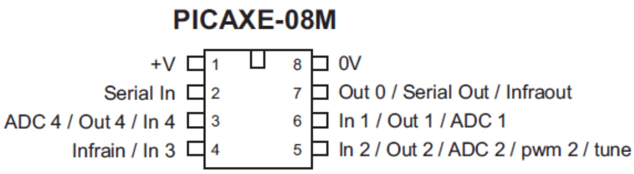
In what order did you use them?

Programming Task B

Use the circuit diagram, truth table and the PIC pin-out diagram to write a program that performs the same function as the circuit shown.

Common programming commands are given below.

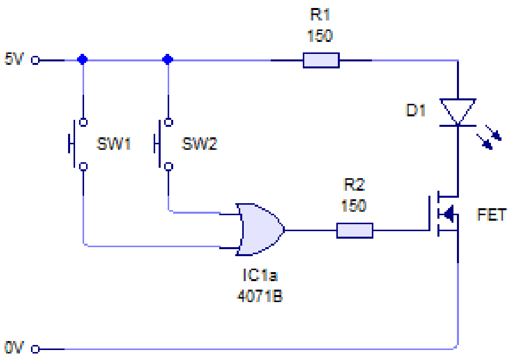
PIC pin-out diagram:



Truth Table

Sw1	Sw2	D1
0	0	0
0	1	1
1	0	1
1	1	1

Circuit Diagram



Common Programming Commands

Goto	If pin3=1 and pin4=1 then 'label'
High	Label (sub-procedure name)
If pin3=1 then 'label'	If pin3=1 or pin4=1 then 'label'
Let pins%='add outputs required'	'+' (add)
Low	'-' (subtract)
Main	'*' (multiply)
Pause (milliseconds)	'/' (divide)
Wait (seconds)	

Explain how you went about using the representations to write the program in the box below

Consider the individual representations (circuit diagram, event schedule & pin-out). Which have been useful/not useful?

In what order did you use them?

Appendix 4

Observation Form (Lesson 1)

ACTIVITY 1 (PAIRS)

Pair Abcdefg	Question	Notes
	How are you going about linking the images and words? Is the image or word your starting point? Is the image or word more or less helpful? What themes are you beginning to identify?	

Observation Form (Lesson 1)

ACTIVITY 2 (INDIVIDUAL STUDENTS)

Student **A … Q**	**Question**	**Notes**
	Do you find one representation type more useful than others? Why? Did you combine representations in any way? Did you use the representations in any sequence? How does using the software help to solve the problem?	

Observation Form (Lesson 2)

ACTIVITY 1 (INDIVIDUAL STUDENTS)

Student A … q	Question	Notes
	Do you find one representation type more useful than others? Why? Are you combining representations in any way? Are you using them in a sequence? How does using the software help to solve the problem? How does the activity compare with the previous (yesterday's) circuit building task? Is one task easier or more difficult? Why?	

Appendix 5

Journal Summary

Summary of Entries from the Research Journal

The following are summaries from the research journal which was kept alongside the research activities. These are necessarily brief, but provide some of my key thoughts about the research process, how well things worked, my reflections on activities such as interviews, transcription or analysis, worries about the data and so on. I have drawn on these at points in the preceding text to provide an overview of how my involvement in the research process has affected my interpretations and decisions along the way.

Date	Entry/record	Issue/question/reflection/comment
27/05/14	Meet with supervisor	Clarified case study approach focusing on a sequential model for data collection. Focus on the phenomenon of concept formation.
17/06/14	Distribution of participant information sheets (18/06/14)	Unanticipated responses. Some suspicion (will there be cameras?), and excitement (will it be like an interrogation?). Some don't take it seriously, probably expected.
18/06/14	Reflection on information sheet	Some fully on board, some not. Slight confusion over 'agreeing' involvement, then answering 'no' to each condition (2 or 3 only). Overall good level of participation agreed and signed.
30/06/14	Setting up data collection	Setting up raises issues. ICT department concerned over size of data storage needed. Students to control the software for recording (not a good idea, they will forget). Avoiding calendared activities difficult. Year 6 induction day falls on chosen data collection day.
01/07/14	Lesson 1 reflection	Good start. Lesson went well and preparation paid off (e.g., name cards and instructions helped the flow). Identification of themes difficult for some. Prompting needed to ensure written elements are completed. ICT a problem-the recording didn't work, but assured will be ready for Lesson 2! Audio recording using iPad worked well. Worries-have I collected the right data/enough data? Managing lesson and data collection difficult (e.g., talking to students and note making).
02/07/14	Lesson 2 reflection	Good start. ICT technician late, but enables the screen recording. Worries-managing lesson and recording (as Lesson 1); again, knowing if the questions/activities are adequate; worries about 'seeing a pattern' at this stage; will the data be retrieved by the ICT team?
04/07/14	1st interview reflection	I realise that I have strong views and expectations about the data I think I will collect. I took great care to develop questions which were objective, but the questioning does lean towards my agenda, for good or bad. I make a mental note to allow participants to talk as much as possible and make it as open as possible.

07/07/14	Interviewee re-scheduled	Thankfully only one participant forgot the appointment and rescheduled.
08/07/14	2nd interview	Again I worry that my expectations are not met and try to focus on allowing the participant to speak as much as possible, probing only when necessary. I realise that I need to focus on data collection and leave the analysis until later.
09/07/14	3rd interview	Some restructuring needed as participants find themselves with other commitments. Maintaining the schedule is a dynamic activity. I realise that participants understanding will emerge in ways not known at the moment and worry less about the nature of the data collected.
10/07/14	4th interview	A difficult interview as participant couldn't answer the questions, however this will provide a good contrast with the other interviews. This interview reinforced the need to modify the questions to suit the participant.
29/09/14	First attempt at transcription	Pro-forma worked well. A lot of forward and back to clarify what was said. Had not expected the dialogue to be so unclear, which was due to the clarity of speech, not the recording. 7 minutes of dialogue takes about 1 hour to transcribe. Laptop setup helps. In the first interview I transcribe every utterance.
09/10/14	Frist attempt at analysis	I begin some analysis with the first interview 'to see what I've got'. I follow Thomas's (2009) advice on the constant comparison method. I read the whole interview first making notes in the margin, then begin considering themes. I think beyond the electronics and consider the cognitive skills used to problem solve, based on the framework of translation and transition.
18/10/14	Notes on analysis	I consider the significance of the interview. This one was very detailed- I could tell the participant was very knowledgeable. Did the interview questions work though? Yes they did, I feel confident about the approach. I realise that much more will emerge once the transcripts are compared.
20/10/14	Consultation with McMillan & Schumacher (2010)	I return to McMillan and Schumacher (2010), which includes an excellent section and examples of coding. I am perhaps slightly concerned that everything I retrieve from the data is my interpretation of events and the meaning attached is all mine! I realise the significance of the researcher at the centre of the research and very much a part of meaning making in interpretative research. The textbook examples help to clarify the approach.
21/10/14	Reflection on analysis	Linking codes with categories seems to be a problem as I am inclined to want to develop new categories each time and end up with an overwhelming number.
22/10/14	Reflection on analysis	I listen to 2nd and 3rd interviews and the category problem is resolved as I realise that the categories will

		emerge from several or all of the interviews taken together.
17/02/15	Reflection on transcribing	Care is needed to clarify some terms (‘really’, ‘a lot’), because in written form they look very different when viewed at a later date.
16/04/15	Reflection on analysis	I begin to think about the theories. How does my data link with the theories I have written about earlier?
20/04/15	Reflection on analysis	I wonder if the whole interview should be read and different research questions considered as I go. Or should I focus on one question at a time, rereading for each question.
21/04/15	Reflection on analysis	I opt for breaking down into interview questions, then focusing on main research questions later, once the themes and categories have been created. The lesson activities are also good guides for analysis, which can be linked with the research questions.
22/04/15	Reflection on analysis	I spend a lot of time dwelling on main themes and sub-themes. I try to create main themes that relate to the research questions and sub-themes that the ‘real’ themes. This relates well to setting up in NVivo.
24/04/15	Reflection on analysis	Thoughts arise about comparing aspects of the data, i.e., different stages of the research, tasks and people.
29/04/15	Reflection on analysis	Supervision leads to further focus on issues around concrete/abstract thinking. What is relationship between con/abs. need to sequence through, or can some go straight to abstract?
03/05/15	Reflection on analysis	I use Thomas’s (2009) ideas about summaries and use the memo function in NVivo to create analytic memos for each participant as the ideas about them form. I gradually expand each memo as thoughts develop.
05/05/15	Reflection on analysis	I notice a difference in observers’ data. Hand written notes are quite precise and link well with questions (Kevin). My recordings are more detailed, but the tradeoff is poor quality sound because of the background noise.
06/05/15	Reflection on analysis	Ideas form about cognitive constructs. I start to see a pattern linked to analogue, digital and logic systems in the transcripts. A way of understanding specific to each participant.
12/05/15	Reflection on analysis	I start to think about sequence of rep use and other learning evidence.
18/05/15	Reflection on analysis	I am aware of the temptation, later in the analysis, to just opt for current codes, rather than create new ones. Suggest a fresh look at the data would benefit.
19/05/15	Reflection on analysis	Some thoughts about procedural knowledge and ideas about knowledge placed into ‘containers’, discussed by Arnheim (1970).
20/05/15	Reflection on analysis	Again the issue about using current codes emerges as I go through further stages/interviews. Thinking can be narrowed by existing codes. Again suggest revisiting interviews with fresh eyes.
22/05/15	Reflection on analysis	I realise the importance of the analytical frame, as without this you end up with a disjointed theme

		mapping. I direct thinking to the analytical frame to support meaning making.
25/05/15	Reflection on analysis	Thoughts about the participants' use of comparison, such as comparison with concrete things/features. Link with Bruner's (1977) taxonomy.
30/05/15	Reflection on analysis	Link previous with inference procedures. Thoughts about conceptual change and gradual integration of knowledge. Thoughts about the 'brain as comparator' idea.
05/06/15	Reflection on analysis	Thoughts about moving from coding to themes and theories. Linking in with theory seems problematic. Difficulty seems to be 'seeing' beyond the coding.
06/06/15	Reflection on analysis	Problem: you need to return to previously analysed interviews when new considerations arise from coding later pieces. Could overcome in future research with coded/labelled/differently identified sections to aid returning to the data to check.
07/06/15	Reflection on analysis	I focus on translation and transition. This aids the linking between coding, themes and theory. Considerations of learning also seem to tie down to Piaget/Bruner.
10/10/15	Reflection on analysis	Again I have thoughts about the interpretative approach and how untidy everything seems, compared with the neatly presented research I have read for the literature review. I consider beginning the Discussion chapter to try to help tidy things up.
02/07/15	Reflection on analysis	I consider how the participants' course marks contribute to the analysis. A range of concepts and themes emerge from the various classwork/homework tasks.
12/07/15	Reflection on analysis	I realise the temporal nature of analysis. As you develop your analysis, returning to earlier previously analysed interviews leads to a different interpretation because your thinking is affected by the gradual development of your knowledge.
20/07/15	Notes on monitoring interview	Encouraged to look up Treagust who has worked in the area of conceptual change.
20/07/15	Notes on supervisory meeting	Learning and language discussed. I begin to think about programming, not only as procedural, but as learning based within language use.
13/09/15	Reflections on analysis	Yin (2014) provides some guidance on the quality of the analysis. I look at the way others have presented their data for guidance.
30/09/15	Reflections on analysis	I record my observation that the cognitive maps I created can be misconstrued and make some amendments accordingly
17/10/15	Reflections on analysis	The presentation of representation use is considered and I play with ideas about conceptual diagrams to help present these ideas.

Appendix 6

Interview Schedule

Name: …………………………………………………………………….

Interview Questions

1. *Thinking back to the matching images with words exercise in lesson 1, how did you go about linking the images and words?*

2. *What consistencies can you identify in the way you have grouped the images and words?*

3. *This is the circuit [circuit shown to participant] you prototyped during lesson 1 using these traditional representations [shown]. Imagine you were explaining to someone else the method you used to complete this task. Can you describe your explanation to me?*

4. *This is the circuit some of the others built. How would you describe the differences between this one and yours?*

5. *Thinking back to the programming task in lesson 2 [program shown], imagine you were explaining to someone else the method you used to complete this task. Can you describe your explanation to me?*

6. *Is there anything particularly helpful to learning about electronics in writing the program?*

7. *Having both built a circuit and written a program, which method of representing electronics is most useful to learning about electronics and why?*

8. *If I show you this circuit and this program, how do they visually help you to understand the electronics?*

Do you have any questions?

Thank you for participating in this interview.

Appendix 7

Full Ethical Approval

Screen shot of letter received from UREC to confirm full ethical approval.

OXFORD BROOKES UNIVERSITY

Ms Georgina Glenny
Director of Studies
School of Education
Faculty of Humanities and Social Sciences
Oxford Brookes University
Harcourt Hill Campus

17 June 2014

Dear Ms Glenny

UREC Registration No: 140830
Mental representation, learning and the construction of conceptual knowledge in technology education

Thank you for email of 13 June 2014 outlining the response to the points raised in my previous letter about the EdD study of your research student Adrian Twissell and attaching the revised documents. I am pleased to inform you that, on this basis, I have given Chair's Approval for the study to begin.

The UREC approval period for this study is two years from the date of this letter, so 17 June 2016. If you need the approval to be extended please do contact me nearer the time of expiry.

In order to monitor studies approved by the University Research Ethics Committee, we will ask you to provide a (very brief) report on the conduct and conclusions of the study in a year's time. If the study is completed in less than a year, could you please contact me and I will send you the appropriate guidelines for the report.

Yours sincerely

Hazel Abbott
Chair of the University Research Ethics Committee

cc Graham Butt, Second supervisor
Adrian Twissell, Research Student
Maggie Wilson, Research Ethics Officer
Jill Organ, Research Degrees Team
Louise Wood, UREC Administrator

UNIVERSITY RESEARCH ETHICS COMMITTEE, FACULTY OF HEALTH AND LIFE SCIENCES

Headington Campus Gipsy Lane
Oxford OX3 0BP UK

Tel: 01865 482639
heabbott@brookes.ac.uk

INVESTORS IN PEOPLE | Gold

www.brookes.ac.uk

Appendix 8

Consent letter from Headmaster confirming approval for study.

10:04 AM
9:36 AM
8:59 AM
8:56 AM
8:48 AM
8:47 AM
8:42 AM
7:54 AM
Mon 10:59 AM

From: S Lehec
Sent: 10 March 2014 08:50
To: A Twissell
Cc: V Kennedy
Subject: RE: Request for Permission

Dear Adrian

Having read your email (below) I can confirm that I give my consent for your project to proceed as you have described.

Kind regards,

SR Lehec
Head Master
Aylesbury Grammar School

A Twissell	Dear Stephen Thank you very much. Kind regards, Adrian	Mon 11:42 AM
S Lehec	Dear Adrian Having read you email (below) I can confirm that I give my consent for your project to...	Mon 8:50 AM
A Twissell	Dear Stephen I write to gain your permission for the next stage of my EdD research project entitled...	2/19/2014

12:45
11/03/2014

Appendix 9

Participant Consent Form

OXFORD BROOKES UNIVERSITY

Headington Campus
Gipsy Lane
Oxford
OX3 OBP

Consent Form

Research Project Title:

Mental Representation, Learning and the Construction of Conceptual Knowledge in Technology Education

Investigators:

Mr A Twissell (Principal Investigator) Aylesbury Grammar School, Walton Road, Aylesbury, Bucks, HP21 7RP, atwissell@ags.bucks.sch.uk

Ms G Glenny (Director of Studies) Oxford Brookes University, Harcourt Hill Campus, Oxford, OX2 9AT

Prof G Butt (Supervisor) Oxford Brookes University, Harcourt Hill Campus, Oxford, OX2 9AT

		Please initial box	
1.	I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions.	☐	
2.	I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason.	☐	
3.	I agree to take part in the above study.	Please tick box ☐ **Yes**	☐ **No**
4.	I agree to the interview being audio recorded	Y	N

5.	I agree to the lesson activities being audio recorded	Y	N
6.	I agree to the lesson activities being video recorded	Y	N
7.	I agree to the use of anonymised quotes in publications	Y	N

Name of Participant Date Signature

______________________________ __________________ __________________________

Name of Researcher Date Signature

______________________________ __________________ __________________________

Appendix 10

Participant information sheet

Headington
Campus
Gipsy Lane
Oxford
OX3 OBP

Participant Information Sheet

Study title:

Mental Representation, Learning and the Construction of Conceptual Knowledge in Electronics Education

Researcher: Mr A Twissell

Background to the study

You are being invited to take part in a research project which is part of a doctoral study being undertaken by the researcher (Mr A Twissell) in conjunction with Oxford Brookes University, School of Education. The study has been approved by the University Research Ethics Committee, Oxford Brookes University and Mr Lehec, Headmaster, Aylesbury Grammar School. Before you decide whether or not to take part, it is important for you to understand why the research is being undertaken and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?

Electronics education involves understanding about abstract concepts; that is concepts that cannot be readily observed in the real world. This study aims to explore the use of representations, such as circuit diagrams and formulae, used to support learning in electronics. The study will explore the value of various representations, their combination and sequencing, in an attempt to develop improved ways to support students' learning. The study involves an interview which will follow a lesson forming a part of the normal curriculum that you will follow on the GCSE electronics course. Therefore no adjustments have been necessary to what you will need to know to complete your coursework or the written examination.

Why have I been invited to participate?

You have been invited to participate in the research element of two electronics lessons as you are able to contribute to this area of the curriculum, and therefore this study, through your knowledge of electronics. All students studying GCSE electronics this year will be invited to participate in the audio and video recording of parts of the two lessons and an interview following these lessons. Recording, either audio or video recording, will only take place with your permission (see separate consent form). I am interested in the patterns and trends across the group and different activities only in this study, not the assessment of individuals or abilities as such. Therefore no part of the study will have any effect what so ever on your future assessment or progress on the GCSE Electronics course.

Do I have to take part?

It is up to you to decide whether or not to take part in the interview and whether to give consent for lesson tasks to be audio or video recorded. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason. Choosing to either take part, or not take part will have no impact on marks, assessment or future studies.

What will happen to me if I take part?

The interview questions will ask about your experience of the lessons. The interview will be conducted at lunch time, at a time convenient to you, will be audio recorded and last approximately 20 minutes. The interviews will be conducted in one of the D&T rooms and will maintain auditory privacy. A transcript of the interview will be made available to you for checking and you will have the opportunity to amend any aspects which you think may not reflect accurately what you said.

What are the possible benefits of taking part?

Participation in an interview will be followed by verbal feedback explaining the answers you give in the context of the lessons and research, therefore you may benefit from an additional insight into your learning and study on the electronics course. Your contribution will also develop our understanding of the use of representations in electronics education to support students' conceptual understanding. This understanding may be of benefit to other teachers of electronics in other schools.

Will what I say in this study be kept confidential?

Answers to questions audio recorded during interviews will be transcribed and de-identified. The transcripts will be available to the researcher only, for analysis purposes. The future use of quotes taken from transcriptions will be anonymously presented, for example in written feedback and journal publication (although you will be aware that you are a part of the only electronics group at AGS this year and therefore potentially the class is identifiable; extremely unlikely to occur). Subject to legal limitations, interview records will be kept securely, protected by password access, and will remain strictly confidential. Any data generated by the study will be kept securely for ten years following the completion of the research.

What should I do if I want to take part?

If you agree to participation in the audio or video recording of the lesson and/or you would like to participate in an interview, you should keep this information sheet and fill in a consent form. The consent form should be completed, signed and returned to Mr Twissell prior to the electronics lessons.

What will happen to the results of the research study?

The results of the study will be used to support the thesis element of an educational Doctorate. The results will be reported internally at AGS through a written paper for staff and students (particularly participants) and externally through an appropriate journal (to be decided). Participants will be notified of the chosen journal.

Who is organising and funding the research?

I am conducting the study as a research student at Oxford Brookes University, School of Education. The research is not externally funded.

Who has reviewed the study?

The research has been approved by the University Research Ethics Committee, Oxford Brookes University.

Contact for Further Information

Further information about the study can be obtained from Mr A Twissell by email at atwissell@ags.bucks.sch.uk. If you have any concerns about the way in which the study has been conducted, you should contact the Chair of the University Research Ethics Committee at ethics@brookes.ac.uk.

Thank you for taking the time to read the information sheet.

Mr A Twissell
Aylesbury Grammar School
Oxford Brookes University, School of Education

Date: June 2014

Appendix 11

Summary of Lesson Observations

Observation Form (Lesson 1)

ACTIVITY 1 (PAIRS) ADRIAN

Pair **Abcdefg**	**Question**	**Notes**
	How are you going about linking the images and words?	
E Kai/Ethan	Try in sentence then relate to diagram	
A David/Jacob	Do obvious then process of elimination	
D Luke/Fergus	Elimination	
B Sam/Connor/Krishan	Method-binary, linking 1/0 with high/low	
	Taking the representation at face value e.g., it says ‘full charge’	
D Luke/Fergus	Obvious first then elimination	
	Previous knowledge from Computing/logic	
Connor/Sam	Process of elimination (other suggestions unclear on recording)	
Kai/Ethan	We translated it into a sentence, so ‘if the switch is closed, then the voltage passes through the transistor and the LED will be on‘ then related it to the diagram	
	Just see which one fits best	
	Using our previous knowledge	
A David/Jacob	Looking at the ones which are obvious like the pulse one	
	Process of elimination	
	Previous knowledge of how the circuits work and how the components work	
	‘If-then’ suggests two different states-matching two states inherent in circuit diagram with the two states contained within ‘if-then’	
	Worked out what went best with what	

Feidhlim B Oliver/Sam Sam B Oliver/Sam E Kai/Ethan Ethan A David/Jacob	Connection by recognising two states in the circuit Recognising states in the coding These four I believe are binary (e.g., 1, 0, low, high) These are pulses With this one there's a resistor and transistor Finding time, RC network **Is the image or word your starting point?** Words Words then check image to see which one is best described by that word **What themes are you beginning to identify?** Previous knowledge of how circuits work Two state that relate to one another	

Observation Form (Lesson 1)

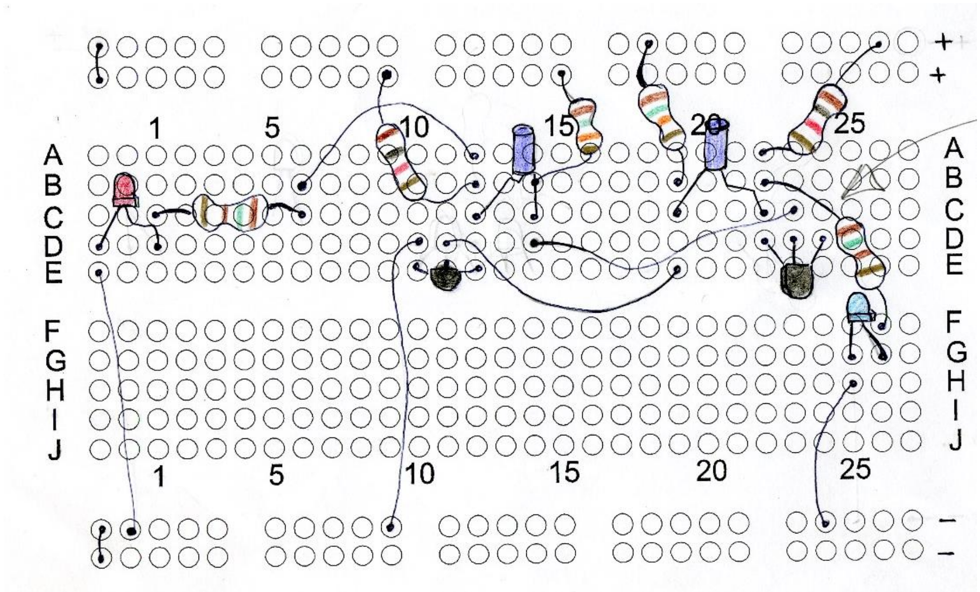
ACTIVITY 1 (PAIRS) KEVIN

Pair Abcdefg	Question	Notes
  F Richard/Martin G Chris/Charlie H Amir/Alex D Luke/Fergus	**How are you going about linking the images and words?** Previous knowledge Understand image then look for word Words then search for image Image then word, process of elimination	
 F Richard/Martin G Chris/Charlie H Amir/Alex D Luke/Fergus	**Is the image or word your starting point?** Word then find image Image then word word image then word	
 F Richard/Martin G Chris/Charlie H Amir/Alex D Luke/Fergus	**Is the image or word more or less helpful?** Not sure Image more helpful word image	
 F Richard/Martin G Chris/Charlie H Amir/Alex	**What themes are you beginning to identify?** Only simple i.e. in words (e.g., 0=low) 5 are linked to voltage-just on or off 5 linked to voltage-on or off 2 to do with charging 2 to do with transistors	

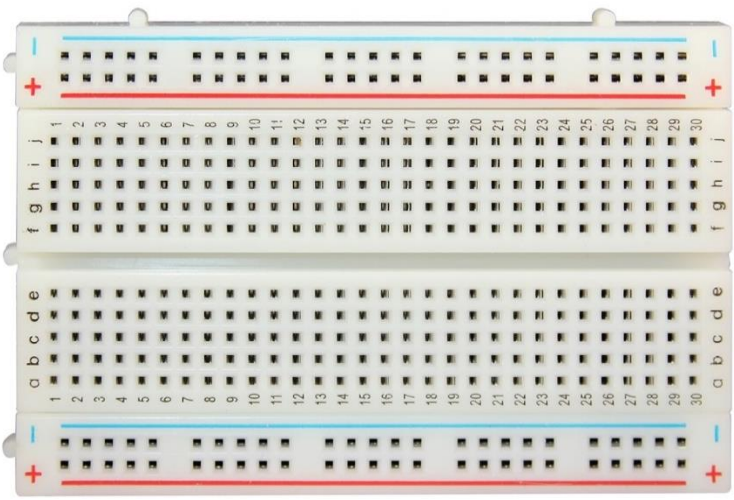
Appendix 12

Prototype board plan homework (example from research participant Oliver)

Copy of worksheet depicting a circuit design for a dual transistor oscillator. The worksheet demonstrates a largely spatial task, where component positioning and orientation are paramount.



Corresponding real-world prototype board



Appendix 13

Record of Connor’s comment

6th November 2013

Researcher notes from conversation with student.

Figure 1 shows a battery tester circuit which employs a Zener diode in reverse bias mode. When the reverse voltage rises above the stated value, the diode is said to be operating at its breakdown voltage and current flows at a stable level in relation to the stated value (Duncan, 1997); this is a difficult abstract concept for some students to grasp. In a discussion surrounding the use of Zener Diodes in the battery tester circuit, Connor, experiencing difficulty in understanding the concept, asked “is a Zener Diode like an ‘if … else’ statement in programming?”. The answer to this question is ‘yes’.

Table 1 shows the Zener Diode concept using BASIC programming commands, which represent the concept in sequential linear form, and in the way Connor intended when raising the question during the lesson.

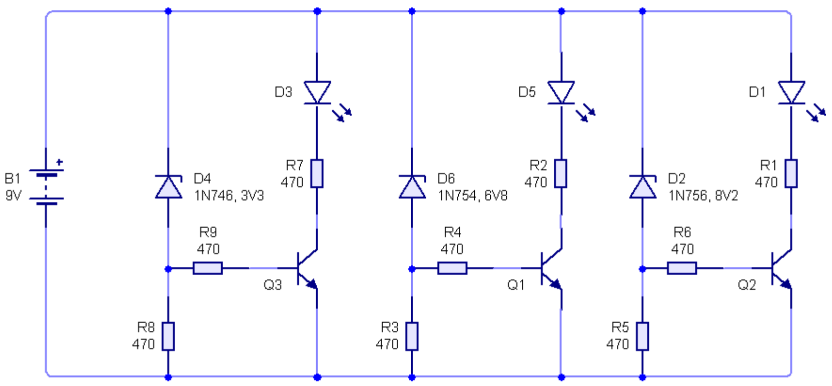


Figure 1 Zener Diode based battery tester circuit under discussion during lesson (using Circuit Wizard Software)

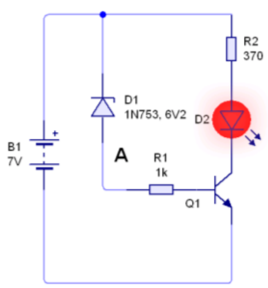
BASIC Programming Command Representation	**Verbal Description of Operation**	**Zener Diode Traditional Circuit Diagram Representation**
Main: Let b1 = Pin 0 If b1 = >20 and <50 then output Else goto Main Output: High 1 Wait 2 Goto Main	Main procedure label Read the voltage on pin 0 and store in b1 Move to sub-procedure labelled ‘output’ if voltage level correct Go back to main procedure if voltage not correct Sub procedure label Output a voltage to output Pin 1 Apply a time delay of 2 seconds Return to main procedure	

Table 1: BASIC Program representing the time constant concept operating on a microcontroller

Appendix 14

Output simulation tool from Circuit Wizard software (New Wave Concepts, 2012).

The simulation panel shows outputs B.0, B.1, B.2 and B.3 on, in response to the code high 0, high 1, high 2 and high 3. The panel models a PICAXE 18M2 microcontroller, shown right. The benefits of the model include the virtual representation of the microcontroller's outputs on-screen.