3.0 Methodology

Research can be conceptualised as ‘systematic self-critical inquiry’ (Stenhouse, 1981, p. 103), and a large number of approaches to research have been proposed (Nisbet, 2005) but there remains no consensus on the most effective manner in which to investigate the social world (Baranov, 2004). Different approaches to inquiry arise as researchers necessarily make implicit or explicit assumptions (Kuhn, 1962) and hence no research can be considered to be free of assumptions (Golby, Martin, & Porter, 1995). Such assumptions can be classified as relating to the nature of entities which exist: ontological assumptions (Effingham, 2013; Sommers, 1963); assumptions regarding the nature of knowledge and its justification: epistemological assumptions (Dancy, 1985; Moser, 2002); and assumptions regarding values and ethics, axiological assumptions (Mertens, 2014; Weinberg, 1970). No particular combination of assumptions, sometimes labelled a paradigm (Lincoln & Guba, 2005), should be seen as superior to another, rather different suppositions are suitable for answering different types of research questions (Gawronski & De Houwer, 2014). A researcher has a duty to explicate and justify the assumptions made in their work (Caelli, Ray, & Mill, 2008; Creswell & Miller, 2000; Guba, 1981; Krauss, 2005), hence the importance of methodological justification, the examination of assumptions in a particular approach to research (Schwandt, 2007,). In particular a methodology should aim to develop a ‘coherent and consistent argument’ (Taber, 2007, p. 44) and ensure a good ‘match’ between the assumptions of the work and the phenomenon of interest (Krauss, 2005, p. 761).

Holloway and Todres (2003, p. 347) argue for consistency between the argument in different sections of a research paper, a concept which they describe variously as ‘goodness of fit,’ ‘logical staged linking’ or ‘how the whole thing “hangs together.”’ Failure to achieve this can lead to ‘method slurring’ (Baker, Wuest, & Stern, 1992) in which approaches with different philosophical assumptions are erroneously combined. The aims of research, its theoretical assumptions and the methods used must be justified as leading to a coherent argument as illustrated in Figure 3.0.

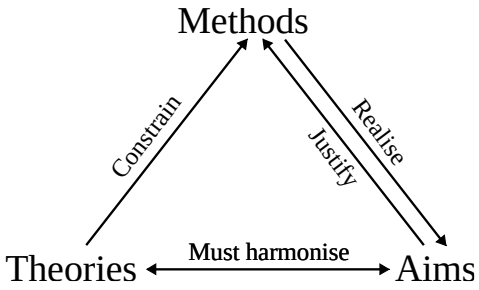

Figure 3.0: Relationship of methodology and methods seen in the triadic network of justification in Laudan (1986, p. 63).

The next sections will make the case that the assumptions of constructivism fit well with the aims and methods of this research.

3.1 Assumptions adopted in this work

The assumptions made in this thesis are outlined below in three categories: ontological, epistemological and axiological (Coe, 2012).

3.1.1 Ontological assumptions

Ontology is the study of what kinds of entities exist (Effingham, 2013). A range of different ontological assumptions is compatible with constructivism. Some writers have argued constructivism is agnostic over the existence of external reality (Staver, 1998). A similar observation was made by Quale:

> Thus, the theory does not deny the possibility of an objective reality, existing independently of all subjects; but it does assert that it is in principle not possible to obtain cognitive knowledge of such an entity, and hence it is irrelevant in the context of cognitive learning (Quale, 2007, p. 233)

Among several slightly different claims regarding ontology, von Glasersfeld argues that constructivism '… has has nothing to say about what may or may not exist' (von Glasersfeld, 1996, p. 113). It has been claimed that the proposition that knowledge is constructed by individuals or groups does not make any assumptions about the nature of reality (Noddings, 1990).

Other versions of constructivism, for example Kumar's realist constructivism (2011) and Cupchik's (2001) constructivist realism, adopt an unambiguous assumption that an external reality exists (Blackburn, 2005). Models such as these can be seen to be the source of Matthews' (1992) argument that constructivism, or some forms of it, are versions of empiricism and that '…talk of 'making sense' is quintessentially empiricist' (Matthews, 1992, p. 305). Empiricism, here, is taken to mean the development of knowledge through the acquisition of sense data about 'material objects' that are assumed to exist (Matthews, 1992, p. 302). Matthews (1992) suggest the difference in positions between, at least some versions of realism, empiricism and constructivism, may be relatively small. Finally, it has been observed that certain forms of constructivism, for example, von Glasersfeld's radial constructivism, incoherently adopt both a realist and solipsistic stance (Martínez‐Delgado, 2002).

It would seem that true solipsists, thinkers who believe only one's own experience exists (Blackburn, 2005, p. 343), are rare (Russman, 1987), in a survey of philosophers, only 4.8% of respondents expressed a position sceptical of an external world (Bourget & Chalmers, 2013). As Martínez-Delgado (2002) observes, even the radical constructivism of von Glasersfeld is not purely solipsistic: von Glasersfeld (1996, p. 118) implies that 'ontic reality' impinges on actions to some extent. It seems that, amongst constructivists in science education, there is general consensus that assumes an external reality impinges to some extent on awareness. Though at least one model of constructivism 'explicitly rejects... notions of absolute existence' (Quale, 2008, p. xv), the relativist ontological position is 'not representative of most work' in science education (Taber, 2009, p. 166). The existence of an 'external reality' will be assumed in this work, however, the extent to which it is possible to gain knowledge of such a reality is debated, as will be considered in the next section.

3.1.2 Epistemological assumptions

A central epistemological claim of constructivism is that access to reality is imperfect (Taber, 2009). Just as with the straw man of solipsism, critics of constructivism have exaggerated constructivists' arguments concerning the fallibility of the link to the external world. For example, Kitcher (2001, p. 156) argues that constructivists make use of an 'inaccessibility of reality argument,' that is they regard all objects as 'epistemically inaccessible'. However, arguing that there is no access to external

reality is by no means the same as a claim that access to an external reality is mediated or imperfect. Some philosophers and psychologists (Putnam, 1990; Reid, 1997; Searle, 2015) have proposed versions of direct realism, the claim that there are 'no entities mediating perception of objects' (Copenhaver, 2004, p. 62). Yet even realists such as Kitcher (2001, p. 167) argue that '[r]ealists should also acknowledge that our judgments of success are fallible' as they occur through our limited 'perceptual powers' (Kitcher, 2001, p. 191). Evidence from studies of perception suggest that direct (unmediated) and indirect perception form a continuum with no clear division between the two processes (Norman, 1983; Ulman, 1980). For example, 'seeing' is not simply a matter of perception but also of mental representation (Fodor & Pylyshyn, 1981). Models of direct perception struggle to explain how knowers can come to develop faulty representations (Fodor & Pylyshyn, 1981). The next sections consider a particular example of faulty representations, Gettier's (1963) cases, to develop a critique of the justified true belief model of knowledge that might seem to arise from direct realism.

The term knowledge is widely used in educational discourse (Taber, 2013b), for example, researchers refer to students' knowledge structures (Driver & Oldham, 1986; Novak, 1990; R. J. Osborne & Wittrock, 1983) or students' and teachers' knowledge of various concepts (Chinn & Brewer, 1993; Hogan, 2000; Justi & Gilbert, 2002; Van Driel & Verloop, 2002; Zohar & Nemet, 2002). However, the concept of knowing, and the related construct of knowledge, are problematic as they have been used with a range of different meanings (Aaron, 1971). For example, Price (1969, pp. 42–43) draws a distinction between possessing or having knowledge, 'a disposition' and the 'mental occurrence' of activating that knowledge at a particular time. Despite these different meanings, a model of knowledge, as justified, true belief, was taken for granted by the majority of philosophers until the middle of the twentieth century (BonJour, 2001).

3.1.2.1 The Platonic model of knowledge

It has been claimed that the Platonic definition of knowledge is 'standard' and 'widely accepted' (Boghossian, 2006, p. 15). Matthews (2002, p. 127) argues that the view of knowledge as justified true belief has been 'epistemological orthodoxy' since Plato proposed the definition. In the Theaetetus, Plato's Socrates is reported as arguing that

knowledge is distinct from belief because knowers have an 'account' of their true beliefs that believers do not possess (Plato, trans. 2004, p. 115). Plato proposed that justification tethers beliefs:

> For true opinions, as long as they remain, are a fine thing and all they do is good, but they are not willing to remain long and they escape from a man's mind, so that they are not worth much until one ties them down by (giving) an account of the reason why….After they are tied down, in the first place they become knowledge, and then they remain in place. (Plato, trans. 1981, p. 86)

Though it had become widely accepted, the justified true belief model of knowledge has encountered a number of challenges and it has been reported that '[m]ost philosophers' (Turri, 2010, p. 247) no longer accept the Platonic account of knowing.

3.1.2.2 Russell's challenge to the Platonic model

Though Gettier's (1963) thought experiments are seen as the most significant challenge to the justified true belief model of knowledge (Dew & Foreman, 2014), and are discussed in detail below, a number of commentators have noted that a case described by Russell prefigured Gettier's critique (Bigelow, 2006; Heathcote, 2012). Russell (1948, p. 170) argued that there is an 'inevitable vagueness and inexactitude' associated with the concept of knowledge and proposed a thought experiment concerning a clock:

> "Knowledge" is sometimes defined as "true belief", but this definition is too wide. If you look at a clock which you believe to be going, but which in fact has stopped, and you happen to look at it at a moment when it is right, you will acquire a true belief as to the time of day, but you cannot be correctly said to have knowledge. (Russell, 1948, p. 113)

Russell's example includes both the features of Gettier problems introduced below: luckiness and fallibility of justification (Hetherington, 2011). However the thought experiment was 'little noticed at the time' (Bigelow, 2006, p. 204) and it wasn't until

the second half of the twentieth century that epistemologists began to seriously question the justified true belief model of knowledge.

3.1.2.3 Gettier's critique

In 1963, Edmund Gettier published a three-page paper which has had an '[e]normous impact' (Foley, 2002, p. 178) on epistemology and demonstrated that the traditional model of knowledge was '…at the very least seriously incomplete and quite possibly even more badly mistaken' (BonJour, 2001, p. 40). The impact of the Gettier's paper was far-reaching and there is, as yet, no consensus amongst philosophers as to how to resolve the objections raised (Hetherington, 2011). Gettier (1963) proposed a thought experiment that considered two people, Smith and Jones, who have applied for a job at a company. The president of the company has told Smith that Jones will get the post, and Smith is also aware that Jones has ten coins in his pocket. Smith therefore holds the justified belief that the person who will get the job has ten coins in their pocket. However, it turns out that Smith eventually gets the job and, though he was unaware of it, he also had ten coins in his pocket. Gettier argued that Smith's belief that a person with ten coins in their pocket would get the job is both true and justified, and therefore might be considered knowledge. However, there is a 'virtual consensus' amongst philosophers that Smith's belief is not knowledge (Turri, 2013, pp. 1–2). Many different Gettier cases have been proposed but two features appear to be common to all the examples:

> (1) *Fallibility*. The justificatory support is *fallible*. It indicates strongly–without proving conclusively–that the belief is true.
> (2) *Luck.* Within each case, the well-but-fallibly justified belief is true. (Hetherington, 2011, p. 121, Italics in original)

Over the years since Gettier proposed his thought experiments, no consensus has emerged for how to overcome the challenge to the Platonic definition of knowledge (Bigelow, 2006). A range of different strategies to resolve the contradiction have been proposed, a small sample of which are summarised below:

> • Knowledge should be redefined to require *infallible* justifications for beliefs

• A belief should not be considered knowledge if the justification occurs through an accidental occurrence
• Knowledge may not be justified by a false belief
• A belief must be caused by appropriate evidence
• The intuition that Gettier cases do not represent knowledge should be discarded.
(Hetherington, 2011, pp. 122–128)

Despite these suggestions, contemporary epistemologists report there are still no ‘easy answers’ to Gettier’s challenge (Pritchard, 2016, p. 131).

3.1.2.4 Some Gettier cases in science education

Consider the cases below, which contain the two elements of Gettier cases, fallible justification and lucky truthfulness, in the context of students’ beliefs related to science education. In each case, though the student holds a justified true belief, it might be felt they do not possess knowledge.

Case 1

A student’s pre-formal experiences of the world have lead them to believe that all motion requires the action of a resultant force. A teacher asks the student if a resultant force acts on an accelerating rocket and they reply that a force does indeed act.

Case 2

A student’s parent assists them with a piece of homework on equilibrium related to a book that is at rest on a table. The parent tells the student that the reaction force and the book’s weight are equal and opposite as they form a Newton’s third law pair. In class, the teacher asks the student about the size of the reaction force and weight acting on a person standing on the ground and the student replies that their magnitudes are equal.

Case 3

A student has the belief that, in an ionic bond, an electron is transferred from one atom to another causing an attractive electromagnetic force between the particles. The student then encounters an exam question in which they are asked what force is

responsible for ionic bonding- the student responds that the electromagnetic force causes the bond.

3.1.2.5 Knowledge and belief in science education

The cases described above are doubtless contrived and are not common occurrences in the science classroom. However, they are significant for a number of reasons. Firstly, they highlight the problematic nature of the term knowledge. Matthews, writing with Southerland and Sinatra (2001, p. 349), had claimed: 'those that wish to make a strong distinction between knowledge and beliefs are on shaky ground from a psychological standpoint as no empirical distinction has been demonstrated' (Southerland et al., 2001, p. 349); he later critiqued constructivist thinkers for confusing belief with knowledge arguing that '…a psychological matter is confused with an epistemological one, and the consequence is educational havoc' (Matthews, 2002, p. 126). Gettier cases highlight that making a distinction between knowledge and belief may not be straightforward. Therefore, as Taber (2013b, p. 176) suggests, '…whilst the 'reasoned true belief' version of knowledge may be useful in philosophical discussions, it does not seem to 'do the job' in supporting research in science education.'

Secondly, there may be a class of beliefs that students possess which match accepted scientific understandings in some ways or under certain conditions, and for which students feel justifications exist (see the three cases above). As these kinds of beliefs contain elements that both match and contradict scientific models, they will be referred to as mixed beliefs (see Figure 3.1, below). For example, consider the belief that an object in motion experiences a resultant force (Viennot, 1979), as described in case one above. In the case of accelerating objects, this belief might be considered to be both justified and 'true' (here 'true' is taken to mean matches accepted scientific models), but in other cases, for example an object travelling at constant velocity, is not 'true', though a student may feel some form of justification for the belief (a discussion of sources of justification may be found below). The existence of justified 'true' belief in the case of accelerated motion is analogous to the belief in Russell's stopped clock example, the belief has a fallible justification and is 'lucky' in that it just happens to be correct in a particular situation.

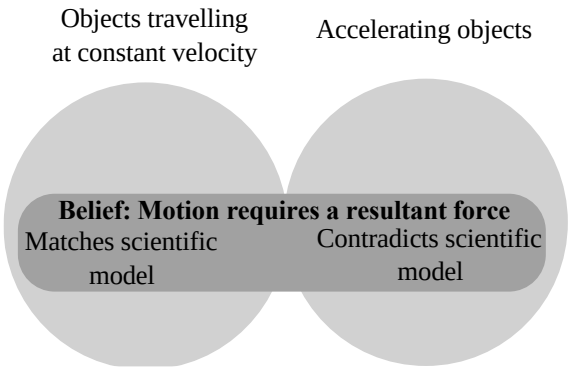

Figure 3.1: An illustration of a mixed belief: the belief that motion requires a resultant force may be a justified 'true' belief in the case of accelerating objects but a 'false' belief in the context of an object travelling at constant velocity.

The notion of a mixed belief suggests the knowledge status of a belief is dependent on the contexts to which it is applied. Consider the following thought experiment proposed by Wedgewood (2002), which supports this notion, imagine two possible worlds, w_1 and w_2, in which you have the same experiences and form the same beliefs:

> Now suppose that in w_1 you are bedeviled by an evil demon who ensures that many of your experiences are misleading, with the result that many of the beliefs that you hold in w_1 are false. In w_2, on the other hand, almost all your experiences are veridical, with the result that almost all the beliefs that you hold in w_2 are true. Intuitively, this makes no difference at all. Exactly the same beliefs are rational and irrational in both worlds (Wedgewood, 2002, p. 349)

Wedgewood argues that as the rationality of a belief depends only on 'internal facts' related to the thinker's mental states, justification might be considered to occur within the mind of the thinker, rather than through relation to the external world (Wedgewood, 2002, p. 350). The evil demon example is interesting as it echoes the experiences of a student inside and outside of the formal classroom. The belief that objects require a resultant force to be in motion may be a justified by a student's

experiences of motion outside of the classroom, however, within the boundaries of school science, the concept is a ‘false’ belief when considered in general.

Knowledge of the contexts to which a belief is applicable can also seemingly affect its knowledge status. Consider a mixed beleif in the case of knowledge of Ohm’s law. Ohm’s law has been described as a ceteris paribus law, that is, one which is a valid description only if some conditions are met (Cartwright, 1980). Imagine a student who believes that current is universally proportional to potential difference because this is what their teacher has implied and what the practicals they have carried out have justified. The student’s belief may be considered justified and ‘true’ in cases where temperature is constant but ‘false’ in other circumstances. Awareness of the temperature dependent nature of the law appears to change the belief about the relationship of current and potential difference from a mixed belief to a justified ‘true’ belief.

3.1.2.6 A psychological model of knowledge

The case made here is that the model of knowledge as justified true belief is not a useful one for science education (Taber, 2013b). The Gettier cases described above suggest that, at least in some cases, justified true beliefs seem intuitively to differ from instances of knowledge. Though Matthews (2002) has criticised constructivist models of cognition for conflating knowledge and belief, it is difficult to understand how a distinction between these two types of entity is sustainable. Gettier cases challenge the notion that justification can act as a ‘tether’(Plato, trans. 1981, p. 86) which distinguishes knowledge from mere belief. Indeed, a difficulty of science education arises because some beliefs may be justified and, in certain circumstances, true, whilst in general being thought of as alternative conceptions (see Figure 3.1).

The psychological construct of the concept would appear to be a useful way to model a learner’s constructions related to science. As Quine has argued ‘[e]pistemology, or something like it, simply falls into place as a chapter of psychology’ (Quine, 2000, p. 297). Claims about students’ views on science are all claims about psychological states and therefore it seems unsustainable that ‘knowledge’ of Newton’s first law, for example, should be accorded different epistemological status from a belief that motion requires a force. The fact that one concept more closely resembles the

accepted scientific model does not change the nature of the belief. There is no evidence to suggest that there is any difference in representation between conceptual constructs with differing levels of epistemological warrant (Southerland et al., 2001). This argument is not intended to imply that the two concepts are equally desirable in educational terms, rather it is important to acknowledge both are beliefs about the physical world which are supported by some form of justification. As Taber (2009) has argued claims for the pedagogic importance of students' beliefs should be conflated with claims for their scientific appropriateness. Some philosophers have argued, since the proposition of the Gettier cases that they '…face the unpleasant reality that we simply have no use for a definition of propositional knowledge' (Kaplan, 1985, p. 363). Though it may be time for researchers in science education to abandon the term knowledge, as it is widely used in the literature, the term will be used in this thesis but will refer to a psychological construct with varying degrees of justification and no assumption of a 'truth' criterion.

3.1.3 Axiological assumptions

It has been suggested that research is never value free (Boyd, 2000) and that even an assumption of value-neutrality is a value claim (Greenbank, 2003). Researchers must address axiology, that is, the manner in which values are ascribed (Blackburn, 2005), as a researcher's values may affect the decisions they make (Flynn, 1995; Greenbank, 2003) and therefore a clear statement of values is an important form of methodological clarification. A number of different classification systems for values have been proposed (Rokeach, 1973; Schwartz, 1994) which cover a range of topics including those related to relationships and pleasure. As the focus of this work is on developing a model of students' learning, the most significant issue will the manner in which value has been attached to different models of learning.

The seemingly theoretical debate over the nature of learning has recently become a political debate in the United Kingdom, with the former Secretary of State for Education arguing for reforms premised on the importance of 'knowledge acquisition' (Gove, 2013). This speech prompted a hundred education academics to sign a letter that appeared in a national newspaper arguing changes to the curriculum would lead to 'rote learning without understanding' (Bassey, 2013). The then Schools Minister,

Nick Gibb, in a recent speech, claimed there exists an: '…anti-knowledge - and, I would argue, anti-evidence - position in education debates' (Gibb, 2016).

This debate has existed from some time in the United States, with proponents of constructivist education arguing that:

> To us, rote learning and the conformity it engenders may be likened in some respects to a form of intellectual slavery. In contrast, we value and respect individual human minds and believe that, in a democracy, learners deserve an educational system that encourages, supports, and rewards divergent and creative thinking; deep understanding; and novel ways of problem solving. Further we believe that such a system is ultimately in our best political, social, and economic interests collectively. (Mintzes & Wandersee, 1998a, p. xix)

A recent movement has argued that rote learning and drill-like practice have a place in learning (Willingham, 2009) and approaches that are perceived as neglecting knowledge have been criticised:

> This supposed liberation from "mere" information and rote learning is one of the most precious principles of American educational thought, and lies at its very core. Its proponents disparage those who favor a definite, cumulative course of study for children as "traditional," "hidebound," and "reactionary," to mention only the more polite terms. (Hirsch, 2006, p. 40)

This argument seems to be misconceived through the exaggerated characterisations of the differences between the positions adopted by the two sides in the debate. For example, Hirsch (2000), accepts that pre-existing knowledge structures enable the acquisition of novel ideas, a central claim of constructivists (Mintzes & Wandersee, 1998b). This debate has surfaced recently in the context of the perceived learning styles of Asian students. Marton and colleagues (2005) describe the apparent 'paradox' that though Chinese students' approach to learning was interpreted as

relying on rote learning, the students often acquired good understandings of topics. They report that the students saw memorisation and understanding as two parts of the same learning process and therefore the meaning of terms such as memorisation and understanding may be culturally contingent (Marton, Watkins, & Tang, 1997). A simple dichotomy between memorisation and understanding may be misleading (Entwistle & Entwistle, 2003) as for Chinese students at least '…having an understanding of something implies memory, just as (meaningful) memory implies understanding' (Marton, Watkins, & Tang, 1997, p. 32). As Kosso (2002) has argued knowledge without understanding is undesirable but understanding requires a base of knowledge. Similarly, Toulmin (1961, p. 108) asserted: 'The business of science involves more than the mere assembly of facts: it demands also intellectual architecture and construction.' Valuing epistemological outcomes such as understanding and making sense should not be seen as diminishing the importance of the acquisition of propositions about the world. However, a number of authors (de Regt, Leonelli, & Eigner, 2009; Elgin, 1996; Martínez, 2013) have argued that understanding, not simply propositional knowledge, should be the goal of scientific education. Therefore, the assumption adopted in this work is that there is something epistemologically valuable in the process of 'making sense.'

3.1.2 Summary of the assumptions made in this work

Following the discussion above, the assumptions in Table 3.1 are adopted in this work:

Table 3.1: Assumptions adopted in the thesis.

Ontological assumption	• An external reality exists
Epistemological assumptions	• Knowledge of external reality is partial and personally constructed
Axiological assumptions	• Both knowledge and understanding are valuable epistemological goals in science education

Given the assumptions shown in Table 3.1, constructivism would appear to be a good fit with the axioms of the research (see section 3.5 for a fuller analysis of the

coherence of constructivism to this research). The next section considers different forms of constructivism and their potential coherence with this work.

3.2 The nature of constructivism

Constructivism is often linked to the notion of meaning-making (Bodner, Klobuchar, & Geelan, 2001; Crotty, 1998; Mintzes & Chiu, 2004) and so might be considered a good fit for the research questions being studied. The notion of constructivism has been associated with a number of meanings (Bickhard, 1997; Geelan, 1997; Taber, 2009) and the different models will be considered in the next sections.

3.2.1 The epistemological focus of various constructivism

The term constructivism has different connotations in different contexts (Taber, 2009). Irzik (2000) differentiates between cognitive and epistemic constructivism and a similar distinction is suggested by both Colliver (2002) and Taber (2009) who separate constructivism as a theory of learning in science education and other fields from its application to an epistemological position (See Table 3.2).

Table 3.2: Different epistemological foci of constructivism.

Philosophical constructivism	**Psychological constructivism**
Assumptions of philosophical constructivism (Doolittle & Hicks, 2003, p. 6)	The 'Hard Core' assumptions of constructivism in science education (Taber, 2009, p. 124)
• Knowledge is not passively accumulated, but rather, is the result of active cognizing by the individual. • Cognition is an adaptive process that functions to make an individual's cognition and behavior more viable given a particular environment or goal. • Cognition organizes and makes sense of one's experience, and is not a process to render an accurate representation of an external reality. • Knowing has its roots in both	• Learning science is an active process of constructing personal knowledge • Learners come to science learning with existing ideas about many natural phenomena • The learner's existing ideas have consequences for the learning of science • It is possible to teach science more effectively if account is taken of the learner's existing ideas • Knowledge is represented in the brain as a conceptual structure

biological/neurological construction and in social, cultural, and language-based interactions.	• Learners' conceptual structures exhibit both commonalities and idiosyncratic features • It is possible to meaningfully model learners' conceptual structures

Notice that in philosophical constructivism, the focus is on cognition and knowing, whereas the theory within science education focuses on the learning experiences of individual learners. It has been argued these two positions are independent of each other: one may adopt a constructivist view of learning (knowledge is constructed by the individual learner) and yet not adopt constructivism as a philosophical position (Colburn, 2000).

Tobin and Tippins (1993) present an alternative differentiation between constructivism as a method and as a referent. They argue some authors have used constructivism to refer to a method of teaching (Tobin & Tippins, 1993) and elsewhere, Tobin (1993) has described constructivism as 'a paradigm for the practice of science education'. Other researchers have described constructivism as an 'approach to teaching and learning' (Parson, 2013, p. 71) and a 'method' (J. F. Osborne, 1996, p. 63). Alternatively, Phillips (1995) distinguishes between constructivism as applied to individual psychology or as a public discipline. Colliver (2002) and Taber's (2009) two-category taxonomies of constructivism might therefore be extended to include an additional category of constructivism as a description of classroom practice (see Figure 3.2).

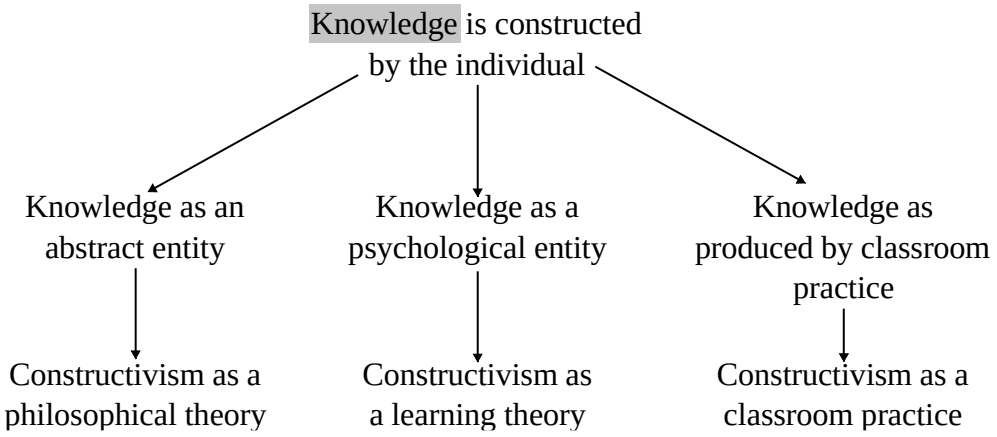

Figure 3.2: A taxonomy of constructivisms.

The three branches of the taxonomy in Figure 3.2 should not be seen as entirely distinct as each is based on assumptions about the nature of knowledge. The next section examines how different versions of constructivism establish knowledge claims.

3.2.2 Knowledge claims in variations of philosophical constructivism

In a 1993 editorial, Good (1993) noted the existence of at least 15 varieties of constructivism. One axis over which such models of constructivism might be differentiated contrasts the justification of constructions in the models and runs from theories which see knowledge as largely constrained by the external world to conceptions in which knowledge is determined by knowers (Phillips, 1995). A variety of these positions, and the criteria they propose for judging claims, are discussed in the sections below.

3.2.2.1 Relativist constructivism

Relativism has been defined as the epistemology that argues that there can be no evaluation of beliefs against an external reality, and therefore that no framework exists for measuring the truth, rationality or reality of claims (Bernstein, 1983; Hollis, 1993). A number of authors have claimed that constructivism, or at least some varieties of constructivism, are underpinned by a relativist epistemology (Irzik, 2000; Matthews, 1992, 2002; Nola, 1997).

The targets of accusations of relativistic constructivism are in some cases poorly defined. For example, the work of members the Strong Programme, such as Bloor (1991) and Collins (1981) have been critiqued for their relativistic positions (Irzik, 2000) but do not link their arguments to constructivism. A second source of claims of relativism in constructivism arises from pedagogic models which have been interpreted as implying that an exam question may have multiple acceptable answers (Scerri, 2003). However, Taber (2009) has pointed out this view is not one typically held by constructivists and has clarified the difference between pedagogical and scientific significance of student's alternative ideas (Taber, 2009). An analogous argument might be made in regard to constructivists approach to modelling learning. For example, Geelan (1997, p. 16) has described how a profusion of perspectives is 'both more flexible and more powerful' than a single model and describes the tension

between two opposing views as ‘a source of creativity and productivity’ (Geelan, 1997, p. 22). Geelan’s views do not propose that multiple models are simultaneously ‘true’ but rather that for complex systems such as learning and thinking a variety of different models may provide the richest representation (Taber, 2013a).

It has been claimed that in radical constructivism, criteria for comparing models do not exist, as would be expected of relativism, however a more nuanced connection between knowledge and reality is actually reported. Though von Glaserfeld has been accused of relativism (Matthews, 1994, 2002), he is careful to avoid claims that criteria for judging claims do not exist:

> Constructivism, as I explained earlier, has nothing to say about what may or may not exist. It is intended as a theory of knowing not as a theory of being. Nevertheless it does not maintain that we can successfully construct anything we want (von Glasersfeld, 1996, p. 113)

Indeed elsewhere, Matthews (1992) has argued that constructivism is no more than a version of empiricism. Quale (2008, p. 239) who has adopted an explicitly relativist approach to constructivism, nonetheless admits that is ‘perfectly permissible… to assign truth values to propositions’ though those evaluations are seen as personal and contextual. It would seem that it is challenging to find genuine relativist epistemologies of constructivism (i.e. those that argue there are no criteria for comparing knowledge claims (Bernstein, 1983; Hollis, 1993)) but rather a range of different constructions of ‘truth’ criteria exist.

3.2.2.2 Pragmatic constructivism

Unlike relativism, which posits no truth criteria, the pragmatic models of knowledge conceptualise theories as instrumental i.e. ‘they become true and they are true to different degrees based on how well they currently work’ (Johnson & Onwuegbuzie, 2004, p. 18). It has been suggested that von Glasersfeld’s radical constructivism is a type of pragmatic constructivism (Bickhard, 1997) as von Glasersfeld’s (1996) truth criteria of viability is a measure of the extent to which a concept can make accurate predictions about the outcome of events. Von Glasersfeld (1996) however, aligns

radical constructivism with a coherence construction of truth (discussed below). Another example of pragmatic constructivism is found in Kelly's (1955) personal construct theory. Kelly argues constructs should be tested to determine their 'usefulness' for anticipating events. Pragmatic epistemologies were critiqued by Russell (1946/1996) who observed that the fact that a concept is useful does not make it true. For example pragmatic models of constructivism may struggle to assist students in the early stages of learning about science when their alternative conceptions of the world seem more useful and therefore more 'true' than accepted models. An additional critique highlights that pragmatic notions of 'usefulness' are subjective and challenging to define (Hartwig, 2007, p. 486).

3.2.2.3 Coherence dependent constructivism

An alternative to a pragmatic judgements, are those based on assessments of coherence. Von Glasersfeld (1996, p. 68) argued that his radical constructivism was a coherentist theory and the 'validity' of concepts was not determined by their usefulness but rather '…their non-contradictory fit into the largest possible conceptual network.' One interpretation of constructivism is that the model is founded on a coherentist understanding of truth, rather than on correspondence to an external reality (Staver, 1998). However, coherence models of 'truth' have long been criticised on the basis that simply because a set of ideas are coherent does not make them true (Russell, 1907). Defining the nature of coherence is challenging (Garnham, 1997), and, as interpretations of coherence may be subjective (Hoey, 1991), learners may develop highly coherent networks of ideas that differ from accepted scientific models (Driver, Guesne, & Tiberghien, 1985; Wertheim, 2011). Given the critiques of relativist, pragmatic and coherentist constructivism this work will instead adopt a realist constructivism epistemology which fits with the ontological assumptions discussed above.

3.2.2.4 Realist constructivism

At the heart of realism lies the assumption that an external world exists that is independent of our thoughts and feelings (Boyd, 1983). Putnam (1975, p. 73) remarked realism 'is the only philosophy that does not make the success of science a miracle' because it involves an alignment with an external reality. Realist interpretations of constructivism are implied in the works of a number of writers: Driver and Oldham (1986); Reddish (2004); and Bodner (1986). Others, for example

Kumar (2011, p. 529), have proposed, explicit models of 'realist constructivism' in which a 'knowledge-reality correspondence' is accepted. Realist varieties of constructivism accept a link between knowledge and the external world, though typically argue the link is mediated in some manner, for example through personal or social experience (Khagram et al., 2010). Cupchik's (2001) model of constructivist realism proposes that 'real' phenomena will be constructed and interpreted by different individuals and communities in different manners. A particularly developed realist model of constructivism is found in Gilbert and Swift's (1985) Lakatosian research program for studying alternative conceptions. This model asserts that the world is real, but all observations of that reality are inherently theory laden. Realist models of constructivism face the challenge of describing how knowledge develops through the twin constraints of a single external reality and multiple personal perceptions. A useful analogy that addresses this issue is Bodner's (1986) description of locks and keys. He suggests that just as many versions of a key may fit the same lock, many different conceptualisations may have a sufficient 'fit' with reality (for example, the different models of learning shown in Figure 1.1).

3.3 Criticisms of constructivism

In order to defend the adoption of realist constructivism outlined in the previous section, several common critiques of constructivism will be considered and addressed in the following sections. The critiques are divided into those that address philosophical and psychological constructivism. Though a number of critiques of pedagogic constructivism have been proposed (for example, that its practices are culturally imperialist (Bowers, 2007)), as the focus of the thesis is on a model of learning, such criticisms will not be addressed in detail here.

3.3.1 Philosophical constructivisms

3.3.1.1 Knowledge claims and the charge of solipsism

Perhaps the commonest, and most serious charge, against philosophical constructivism is the accusation of solipsism levelled by a number of writers (Fox, 2001, p. 27; Martínez‐Delgado, 2002). Solipsism is the belief that only ones own experience exists and no link to any external referent may be established (Blackburn, 2005). Solipsism has been described as 'existentially irrelevant' as to reject the assumption that we share our experiential world with other people would be '…a sign

of mental aberration' (Quale, 2007, pp. 242–243). Whilst the critique of solipsism may be valid for relativist models of constructivism, it does not apply to the realist version assumed in this thesis as it assumes knowledge claims are to some extent constrained by an existing external reality.

3.3.1.2 The blurring of knowledge and belief

Matthews (2002) has criticised constructivist philosophies for not adequately distinguishing between knowledge and belief (see Section 3.1.2). He argues a psychological matter (belief) is confused with an epistemological one (knowledge); Matthews suggests that if the term knowledge in constructivist accounts were replaced with the word belief, the claims would become sustainable. This critique is premised on the Platonic model of knowledge (Matthews, 2002), and as discussed above, has been shown to be insufficient (Gettier, 1963). Matthews' charge is not without justification, there has been a period in which terms related to learning have been used ambiguously in the constructivist literature (Taber, 2013a). Lax usage, however, does not undermine the philosophical premises of constructivism. Taber (2009) argues that the term knowledge is inappropriate in a constructivst framework that has rejected a direct link to the external world and the concept of beliefs underemphasises the justifications students possess for their notions and therefore proposes conception as a suitable intermediate construct (see discussion of a psychological model of knowledge in section 3.1.2.6, above).

3.3.1.3 The charge of 'anything goes'

Another common criticism of constructivism is the claim that, as truth criteria are poorly defined, all constructions are equally valid (Nola, 1997; Scerri, 2003). However, again this charge may be valid of explicitly relativist models of constructivism, but as can be seen in realist, pragmatic and coherentist models of constructivism, care has been taken to formulate constructs that constrain the acceptability of statements, indeed even Matthews (1992) implies that constructivism is closer to empiricism than to relativism.

3.3.2 Psychological constructivism

Though the critiques of philosophical constructivism are generally aimed at the straw man of relativist constructivism, some of the critiques of psychological constructivism present greater challenges.

3.3.2.1 The impossibility of personal knowledge

A key claim of constructivism is that individuals develop personal and idiosyncratic understandings of the world (Brooks & Brooks, 1993; Taber, 2009, von Glasersfeld, 1996). However, a number of critiques of personal understanding seem to dispute this axiom. Wittgenstein (1953§243) argued the words of an individual's private language would refer to entirely personal entities such as feelings and moods and could therefore not be understood by another individual. Without private language, it is argued, there can be no personal concepts (Heller, 2009) However, as constructs are 'woven into relational context' and therefore 'it does not serve us to suppose that they are internalized into individual minds' (Wortham, 1996, pp. 81–82). Though individuals may possess personal frameworks, translating from one system to another might sometimes be difficult, but rarely impossible (Popper, 1970). The claim of constructivists is that an individual's concepts are unique, not that they are unintelligible to others; individual constructs may vary but be explicable in a common language.

3.3.2.2 The origin of concepts

The problem of concept acquisition presents another possible threat to psychological constructivism. Plato (trans. 2002) first proposed an apparent paradox inherent in learning: if one is aware of what one is trying to learn, then no learning is necessary; if one is unaware of the target information, no learning is possible. The problem has since been restated by Jerry Fodor (1983), who pointed out that learning a concept involves the manipulation of a concept that has yet to be acquired. This apparent paradox can be resolved as it is observed that the acquisition of a novel concepts tends not to happen in a single step and may be achieved by the development of existing conceptual resources (Margolis & Laurence, 2011). Carey (2009) has provided support for this argument by suggesting that certain innate representational primitives exist which participate in a process of bootstrapping more complex concepts from simpler elements.

3.4 An appropriate theoretical framework

This section makes a case for the close alignment between the assumptions of realist constructivism and the constructions of learning developed in this project. In this work the existence of an external reality is assumed, but, it is argued, access to that reality is imperfect and hence knowledge is constructed rather than directly

'discovered'. In Table 3.3, below, the major assumptions of constructivism in science education (Taber, 2009) are shown to fit closely with the model of making sense proposed in this thesis.

Table 3.3: The fit between assumptions of constructivism and the model of making sense presented in this thesis.

The 'Hard Core' assumptions of constructivism in science education (Taber, 2009, p. 124)	**Assumptions of the making sense model of learning**
• Learning science is an active process of constructing personal knowledge.	• Making sense is seen as both an idiosyncratic and an active process.
• Learners come to science learning with existing ideas about many natural phenomena.	• The conceptual compounds developed in the making sense process are expected to include ideas that both match and differ from accepted scientific models.
• The learner's existing ideas have consequences for the learning of science.	• Background knowledge and epistemological assumptions are assumed to guide the manner in which new coherences are formed.
• It is possible to teach science more effectively if account is taken of the learner's existing ideas.	• It is not a necessary assumption for the work that an understanding of learner's ideas will lead to more effective teaching though it is hoped that the model of the development of conceptual will lead to novel pedagogical approaches (see Section 6.4).
• Knowledge is represented in the brain as a conceptual structure.	• Though it has been emphasised that conceptual structure is a model of learning, and therefore, like all models, is to some extent an imperfect reflection (Box & Draper, 1987, p. 424), it is never-the-less accepted as useful model. The model of making sense is premised on the construction and modification of conceptual compounds.
• It is possible to meaningfully model learners' conceptual structures.	• Though it has been argued that researchers should avoid developing models of mental processes to which they have no direct access (Skinner, 1977),

	it has been observed that the constructivist research programme has 'achieved a good deal, and continues to suggest potentially fruitful directions for further research' (Taber, 2009, p. 356).
• Learners' conceptual structures exhibit both commonalities and idiosyncratic features.	• The making sense model assumes that learners' conceptual compounds will share both common elements and idiosyncratic features. The multiple-case design (Yin, 2009, p. 53) adopted in this research allows both the distinctive and shared features of learners' thinking to be discussed.

3.4.1 The nature of knowledge constructed in this research

Different forms of research produce different kinds of knowledge claims (DePoy & Gitlin, 2016) and researchers should attempt to explicate the nature of knowledge produced by their research (Fenstermacher, 2002). The conceptualisation of knowledge produced in this work is constructed to cohere with the model of learners' knowledge, described above. Therefore, knowledge produced in research is seen as a 'construction' arising out of a process of 'conscious, systematic, and disciplined sense-making' (Lincoln & Guba, 2013, p. 62). The knowledge constructed in educational research might be conceptualised as representations of researcher's personal mental models (Taber, 2013b). In constructivism, different researchers might be expected to develop different interpretations of data related to complex phenomena (Guzzetti & Hynd, 1998) and the existence of a plurality of models is seen as productive (Geelan, 1997). Acknowledging that multiple constructions of data are possible does not imply that all models are equally useful (Colliver, 1999), rather in realist constructivism, interpretations are, partially, constrained by the nature of reality (Kumar, 2011). In particular, the interpretations of data produced are conceptualised as embedded in the contexts in which they were produced (Flyvbjerg, 2006) and hence claims about the generalisability of the knowledge produced are limited to cases which researchers perceive are related (Taber, 2000a).

3.5 Fitting methods to assumptions

It is assumed that there should be a coherence between the theoretical assumptions, aims and methods of a piece of research (Laudan, 1986). It is argued that, once

researchers have stated their ontological and epistemlogical assumptions, they have a duty to adopt research methods that fit with their methodology (Boote, 2008). This does not necessarily mean that certain approaches to data collection are forbidden within certain philosophical approaches (Niaz, 2008), rather a clear case must be made the methods construct data in a manner that fits the assumptions of the research.

The methods will be described in detail in the next section, however the assumption that learning is an idiosyncratic process (Taber, 2009) suggests an approach that is sensitive to individual variation would be suitable. The case study approach is described as being sensitive to such idiosyncrasy (Yin, 1981) and in general qualitative methods are seen as useful in the early stage of theorising a concept (Johnson & Onwuegbuzie, 2004). For example, Taber (2008, p. 191) argues enquiry into conceptual integration, a process that may resemble making-sense, requires the use of qualitative approaches 'require more sophisticated qualitative 'based on in-depth study of particular teaching and learning contexts' in order to explore 'the nuances of thinking of individual learners.'

Secondly, making sense is a process that might be expected to occur over an extended period of time, however, research in science education has often used 'one shot' approaches to data collection giving relatively impoverished data (Taber, 2000b, p. 402). Similarly, diSessa (2008, p. 45) has argued that 'deep learning takes time' yet 'stunningly little process data is taken into account in conceptual change research. By and large, the paradigm has employed before and after 'snapshots' (diSessa, 2002, p. 37). An approach that can study processes and capture change requires a high density of observations. The microgenetic method focus on 'details of subjects' behavior in specific contexts' means it 'is the only approach that makes it possible to derive the kind of fine-grained information essential for grasping change processes' (Calais, 2008, p. 3). To gain insight into the extended process of learning one off observations will not do rather 'the learner must be followed for a significant period of time so that shifts in the landscape of cognitive structure may be detected. An in-depth case study approach is required' (Taber, 2001, p. 735). Hence this thesis adopts a microgenetic case study approach that sampled data over an extended period of time.

In addition to the fit of the research methods and assumptions in research, the processes of analysis should also be coherent with the methodology of a work (Van den Bergh, 2015). Analysis has been described as both developing understanding (Fossey, Harvey, Mcdermott, & Davidson, 2002; Stenhouse, 1981) and making sense of data (Miles & Huberman, 1994; Sullivan, 2009), processes which, in this research, are seen as personal and subjective and fit well with the constructivist view of knowledge adopted. The quantitative criterion of replicability is not expected in qualitative data analysis (Merriam, 1995) and in some constructivists expect and celebrate the development of multiple interpretations of data (Geelan, 1997). As will be discussed in the section on generalisability (Section 4.7.3), the analysis produced is seen as a reasoned interpretation developed by the researcher, with sufficient data reported and clear descriptions of the processes of generation of analysis outlined, to allow other researchers to engage critically with the ideas generated (Taber, 2000a).

3.6 The relationship of the researcher to the research

In a constructivist model of research, data are imagined to be constructions of the research process involving the interaction of the researcher and the participants (Kvale, 2007). Therefore, there is an onus on the qualitative researcher to provide sufficient information for a reader to make reasoned judgements about the manner in which the interactions between the researcher and participants may have channelled the data (Atkins & Wallace, 2012; Etherington, 2004; Fine, Weis, Weseen, & Wong, 2000). The term positional reflexivity refers to the relationships between the researcher and participants that shape the analytical activity (Macbeth, 2001).

One significant issue that occurs in this research is that during the collection of data I acted both as a part-time teacher and a researcher at the school the participants attended (see also, Section 4.8 for a consideration of ethical implications). I had taught all of the students at some time during their time at the school but was not a class teacher for any of the participants during the process. Wong (1995) has argued that a tension exists between the role of researcher and teacher, in particular, the roles have conflicting aims: the researcher wants to understand learning, the teacher to support it. However, Wilson (1995) has critiqued Wong's position arguing that there is not a clear distinction between the roles as both have a concern with understanding

students' learning. I saw my role as primarily that of a researcher, but understood that the interview process the students would cause changes in students' understanding (Brock & Taber, 2017). In that sense the process can be thought of as a form of dynamic assessment (Sternberg & Grigorenko, 2002) in which the learners receive feedback on their comments and the researcher is seen as an active participant in the process. As one-to-one interactions between a teacher and a student focused on making sense of a particular context do occur in the normal course of school activities the interviews could be constructed as quasi-naturalistic interactions (Lincoln & Guba, 1985). Though the interventions in the sessions and my role as a teacher known to the students doubtless had some effects on the data constructed, it is difficult to describe the precise nature of such influences.

References

Aaron, R. I. (1971). *Knowing and the function of reason*. Oxford: Oxford University Press.

Atkins, L., & Wallace, S. (2012). *Qualitative Research in Education*. London: SAGE Publications Ltd.

Baker, C., Wuest, J., & Stern, P. N. (1992). Method slurring: the grounded theory/phenomenology example. *Journal of Advanced Nursing*, *17*(11), 1355–1360.

Baranov, D. (2004). *Conceptual Foundations of Social Research Methods*. Boulder, CO: Paradigm.

Bassey, M. and colleagues. (2013, March 20). Letters: Gove will bury pupils in facts and rules. *The Independent*.

Bernstein, R. (1983). *Beyond Objectivism and Relativism: Science, Hermeneutics, and Praxis*. Philadelphia, PA: University of Pennsylvania Press.

Bickhard, M. H. (1997). Constructivisms and relativisms: A shopper's guide. *Science & Education*, *6*(1), 29–42.

Bigelow, J. (2006). Gettier's Theorem. In S. Hetherington (Ed.), *Aspects of Knowing: Epistemological Essays* (pp. 203–218). Oxford: Elsevier Ltd.

Blackburn, S. (2005). *The Oxford dictionary of philosophy* (2nd ed.). Oxford: Oxford University Press.

Bloor, D. (1991). *Knowledge and Social Imagery*. Chicago, IL: University of Chicago Press.

Bodner, G. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education*, *63*(10), 873–878.

Bodner, G., Klobuchar, M., & Geelan, D. (2001). The many forms of constructivism. *Journal of Chemical Education*, *78*(8), 1107.

Boghossian, P. (2006). *Fear of Knowledge*. Oxford: Clarendon Press.

BonJour, L. (2001). *Epistemology: Classical Problems and Contemporary Responses*. Lanham, MA: Rowman & Littlefield Publishers.

Boote, D. (2008). Notes Toward a Naturalistic Study of Education Research Methodology. *Interchange*, *39*, 303–325.

Bourget, D., & Chalmers, D. J. (2013). What do philosophers believe? *Philosophical Studies*, *170*(3), 465–500.

Bowers, C. A. (2007). *The false promise of constructivist theories of learning*. New York, NY: Peter Lang Publishing Inc.

Box, G. E. P., & Draper, N. R. (1987). *Empirical model-building and response surfaces*. New York, NY: Wiley.

Boyd, R. N. (1983). On the Current Status of the Issue of Scientific Realism. In C. G. Hempel, H. Putnam, & W. K. Essler (Eds.), *Methodology, Epistemology, and Philosophy of Science* (pp. 45–90). Dordrecht: Springer Netherlands.

Boyd, W. L. (2000). Editorial: What counts as educational research? *British Journal of Educational Studies*, *48*, 347–351.

Brock, R., & Taber, K. S. (2017). The application of the microgenetic method to studies of learning in science education: characteristics of published studies, methodological issues and recommendations for future research. *Studies in Science Education (Forthcoming)*.

Brooks, J. G., & Brooks, M. G. (1993). *In search of understanding. The case for constructivist classrooms*. Alexandria, VA: Association for Supervision and Curriculum Development.

Caelli, K., Ray, L., & Mill, J. (2008, December 9). "Clear as Mud": Toward Greater Clarity in Generic Qualitative Research. *International Journal of Qualitative Methods*.

Calais, G. J. (2008). Microgenetic analysis of learning: Measuring change as it occurs. In *National Forum of Applied Educational Research Journal. 21(3) 1-7.*

Carey, S. (2009). *The origin of concepts*. Oxford: Oxford University Press.

Cartwright, N. (1980). The Truth Doesn't Explain Much. *American Philosophical Quarterly*, *17*(2), 159–163.

Chinn, C. A., & Brewer, W. F. (1993). The Role of Anomalous Data in Knowledge Acquisition: A Theoretical Framework and Implications for Science Instruction. *Review of Educational Research*, *63*(1), 1–49.

Coe, R. J. (2012). The nature of educational research. In J. Arthur, M. Waring, R. Coe, & L. V Hedges (Eds.), *Research Methods and Methodologies in Education* (pp. 5–14). Thousand Oaks, CA: SAGE Publications Inc.

Colburn, A. (2000). Constructivism: Science Education's" Grand Unifying Theory." *Clearing House*, *74*(1), 9–12.

Collins, H. M. (1981). Introduction: Stages in the Empirical Programme of Relativism. *Social Studies of Science*, *11*(1), 3–10.

Colliver, J. (1999). Constructivism with a dose of pragmatism: a cure for what ails educational research. *Advances in Health Sciences Education*, *4*(2), 187–190.

Colliver, J. (2002). Constructivism: The View of Knowledge That Ended Philosophy or a Theory of Learning and Instruction? *Teaching and Learning in Medicine*, *14*(1), 49–51.

Copenhaver, R. (2004). A realism for Reid: mediated but direct. *British Journal for the History of Philosophy*, *21*(1), 61–74.

Creswell, J. W., & Miller, D. L. (2000). Determining Validity in Qualitative Inquiry. *Theory Into Practice*, *39*(3), 124–130.

Crotty, M. (1998). *The foundations of social research*. London: Sage publications.

Cupchik, G. (2001, February 28). Constructivist Realism: An Ontology That Encompasses Positivist and Constructivist Approaches to the Social Sciences. *Forum: Qualitative Social Research*.

Dancy, J. (1985). *An introduction to contemporary epistemology*. Oxford: Blackwell.

de Regt, H. W., Leonelli, S., & Eigner, K. (2009). Focsuing on Scientific Understanding. In H. W. de Regt, S. Leonelli, & K. Eigner (Eds.), *Scientific Understanding: Philosophical Perspectives* (pp. 1–17). Pittsburgh, PA: University of Pittsburgh Press.

DePoy, E., & Gitlin, L. N. (2016). *Introduction to Research: Understanding and Applying Multiple Strategies*. St Louis, MO: Elsevier.

Dew, J. K. J., & Foreman, M. W. (2014). *How Do We Know? An Inroduction to Epistemology*. Downers Grove, IL: InterVarsity Press.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29–60). Dordrecht, Boston, London: Kluwer.

diSessa, A. A. (2008). A bird's-eye view of the "pieces" vs."coherence" controversy (from the "pieces" side of the fence). In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (1st ed., pp. 35–60). New York, NY: Routledge.

Doolittle, P. E., & Hicks, D. (2003). Constructivism as a theoretical foundation for the use of technology in social studies. *Theory & Research in Social Education*, *31*(1), 72–104.

Driver, R., Guesne, E., & Tiberghien, A. (1985). *Children's ideas in science*. Milton Keynes, Bucks: Open University Press.

Driver, R., & Oldham, V. (1986). A constructivist approach to curriculum development in science. *Studies in Science Education*, (13), 105–122.

Effingham, N. (2013). *An introduction to ontology*. Cambridge: Polity Press.

Elgin, C. Z. (1996). *Considered Judgement*. Princeton, NJ: Princeton University Press.

Elgin, C. Z. (2009). Is Understanding Factive? In D. Pritchard & A. Miller (Eds.), *Epsitemic Value* (pp. 322–330). Oxford: Oxford University Press.

Entwistle, N., & Entwistle, D. (2003). Preparing for examinations: The interplay of memorising and understanding, and the development of knowledge objects. *Higher Education Research and Development*, *22*(1), 19–41.

Etherington, K. (2004). *Becoming a Reflexive Researcher - Using Our Selves in Research*. London: Jessica Kingsley Publishers.

Fenstermacher, G. D. (2002). The Knower and the Known: The Nature of Knowledge in Research on Teaching. In *Social Policy and Society* (Vol. 1, pp. 225–236). Sage PublicationsSage CA: Thousand Oaks, CA.

Feynman, R. P., Leighton, R. B., & Sands, M. L. (1963). *The Feynman Lectures on Physics* (Vol. 1). Reading, MA: Addison-Wesley Publishing Company.

Fine, M., Weis, L., Weseen, S., & Wong, L. (2000). For Whom? Qualitiative research, representations and social responsibilities. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (2nd Ed, pp. 107–131). Thousand Oaks, CA: SAGE Publications Inc.

Flynn, E. A. (1995). Feminism and Scientism. *College Composition and Communication*, *46*(3), 353–368.

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*, *12*(2), 219–245.

Fodor, J. A. (1983). On the impossibility of acquiring "more powerful" structures. In M. Piattelli-Palmarini (Ed.), *Language and learning: The debate between Jean Piaget and Noam Chomsky* (pp. 142–163). London: Routledge & Kegan Paul Ltd.

Fodor, J. A., & Pylyshyn, Z. W. (1981). How direct is visual perception?: Some reflections on Gibson's "ecological approach." *Cognition*, *9*, 139–196.

Foley, R. (2002). Conceptual Diversity in Epistemology. In P. K. Moser (Ed.), *The Oxford handbook of epistemology* (pp. 177–203). Oxford: Open University Press.

Fossey, E., Harvey, C., Mcdermott, F., & Davidson, L. (2002). Understanding and evaluating qualitative research*. *Australian and New Zealand Journal of Psychiatry*, *36*(6), 717–732.

Fox, R. (2001). Constructivism examined. *Oxford Review of Education*, *27*(1), 23–35.

Garnham. (1997). Mental Models. In M. A. Conway (Ed.), *Cognitive models of memory* (pp. 147–172). Cambridge MA: MIT Press.

Gawronski, B., & De Houwer, J. (2014). Implicit measures in social and personality psychology. In H. T. Reis & C. M. Judd (Eds.), *Handbook of research methods in social and personality psychology (2nd edition)* (2nd ed., pp. 283–310). New York, NY: Cambridge University Press.

Geelan, D. (1997). Epistemological anarchy and the many forms of constructivism. *Science & Education*, *6*(1), 15–28.

Gettier, E. L. (1963). Is Justified True Belief Knowledge? *Analysis*, *23*(6), 121–123.

Gibb, N. (2016). What is a good education in the 21st Century? (Speech). Hild Bede College, Durham University.

Gilbert, J. K., & Swift, D. J. (1985). Towards a Lakatosian analysis of the Piagetian and alternative conceptions research programs. *Science Education*, *69*(5), 681–696.

Golby, M., Martin, A., & Porter, M. (1995). Some researchers' understanding of primary teaching: comments on Mant and Summers' "Some primary-school teachers" understanding of the Earth's place in the universe'. *Research Papers in Education*, *10*(3 297-302).

Good, R. (1993). Editorial. The many forms of constructivism. *Journal of Research in Science Teaching*, *30*(9), 1015–1015.

Gove, M. (2013). Speech to the Social Market Foundation, 5th February 2013. Accessed 16th Feb 2013. Available at.

Greenbank, P. (2003). The role of values in educational research: the case for reflexivity. *British Educational Research Journal*, *29*(6), 791–801.

Guba, E. G. (1981). Criteria for assessing the trustworthiness of naturalistic inquiries. *Educational Communication and Technology Journal*, *29*(2), 75–91.

Guzzetti, B., & Hynd, C. (1998). *Perspectives on Conceptual Change*. Mahwah, NJ: Lawrence Erlbaum Associates.

Hartwig, M. (2007). *Dictionary of Critical Realism*. Abingdon, Oxon: Routledge.

Heathcote, A. (2012). Gettier and the stopped clock. *Analysis*, *72*(2), 309–314.

Heller, A. (2009). *A theory of feelings*. Plymouth: Lexington Books.

Hetherington, S. (2011). The Gettier Problem. In *The Routledge Companion to Epistemology* (pp. 119–130). New York, NY: Routledge.

Hirsch, E. D. (2000). You can always look it up—or can you. *American Educator*, *24*(1), 4–9.

Hirsch, E. D. (2006). *The knowledge deficit*. Boston: Houghton Mifflin Company.

Hoey, M. (1991). *Patterns of Lexis in Text*. Oxford: Oxford University Press.

Hogan, K. (2000). Exploring a process view of students' knowledge about the nature of science. *Science Education*, *84*(1), 51–70.

Hollis, M. (1993). Relativism. In W. Outhwaite & T. Bottomore (Eds.), *The Blackwell dictionary of Twentieth Century social thought* (pp. 554–555). Oxford: Blackwell.

Holloway, I., & Todres, L. (2003). The Status of Method: Flexibility, Consistency and Coherence. *Qualitative Research*, *3*(3), 345–357.

Irzik, G. (2000). Back to Basics A Philosophical Critique of Constructivism. *Science & Education*, *9*(6), 621–639.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, *33*(7), 14–26.

Justi, R. S., & Gilbert, J. K. (2002). Science teachers' knowledge about and attitudes

towards the use of models and modelling in learning science. *International Journal of Science Education*, *24*(12), 1273–1292.

Kaplan, M. (1985). It's not what you know that counts. *The Journal of Philosophy*, *82*(7), 350–363.

Kelly, G. A. (1955). *The psychology of personal constructs*. New York, NY: Norton.

Khagram, S., Nicholas, K. A., MacMynowski Bever, D., Warren, J., Richards, E. H., Oleson, K., … Brauman, K. A. (2010). Thinking about knowing: conceptual foundations for interdisciplinary environmental research. *Environmental Conservation*, *37*(4), 388–397.

Kitcher, P. (2001). Real Realism: The Galilean Strategy. *The Philosophical Review*, *110*(2), 151–197.

Kosso, P. (2002). The Omniscienter: Beauty and scientific understanding. *International Studies in the Philosophy of Science*, *16*(1), 39–48.

Krauss, S. E. (2005). Research paradigms and meaning making: A primer. *The Qualitative Report*, *10*(4), 758–770.

Kuhn, T. S. (1962). *The structure of scientific revolutions*. London: University of Chicago Press.

Kumar, A. (2011). Towards Realist Constructivism: Implications for Teaching & Training. *Indian Journal of Industrial Relations*, *46*(3), 523–535.

Kvale, S. (2007). *Doing interviews*. Thousand Oaks, CA: Sage.

Laudan, L. (1986). *Science and Values: The Aims of Science and Their Role in Scientific Debate*. Berkley, CA: University of California Press.

Lincoln, Y. S., & Guba, E. (1985). *Naturalistic inquiry*. New York, NY: Sage.

Lincoln, Y. S., & Guba, E. (2005). Paradigmatic controversies, contradictions, and emerging confluence. In N. K. Denzin & Y. S. Lincoln (Eds.), *The Sage handbook of qualitative research* (3rd ed., pp. 191–215). Thousand Oaks, CA: Sage.

Lincoln, Y. S., & Guba, E. G. (2013). *The constructivist Credo*. Walnut Creek, CA: Left Coast Press, Inc.

Macbeth, D. (2001). On "Reflexivity" in Qualitative Research: Two Readings, and a Third. *Qualitative Inquiry*, *7*(1), 35–68.

Margolis, E., & Laurence, S. (2011). Learning Matters: The Role of Learning in Concept Acquisition. *Mind & Language*, *26*(5), 507–539.

Martínez-Delgado, A. (2002). Radical constructivism: Between realism and solipsism. *Science Education*, *86*(6), 840–855.

Martínez, S. F. (2013). The scientific undercurrents of philosophical naturalism. In J. I. Galparsoro & A. Cordero (Eds.), *Reflections on Naturalism* (pp. 105–127). Rotterdam: Sense Publishers.

Marton, F., Watkins, D., & Tang, C. (1997). Discontinuities and continuities in the experience of learning: An interview study of high-school students in Hong Kong. *Learning and Instruction*, *7*(1), 21–48.

Marton, F., Wen, Q., & Wong, K. C. (2005). “Read a hundred times and the meaning will appear...”Changes in Chinese University students’ views of the temporal structure of learning. *Higher Education*, *49*(3), 291–318.

Matthews, M. R. (1992). Constructivism and empiricism: an incomplete divorce. *Research in Science Education*, *22*(1), 299–307.

Matthews, M. R. (1994). *Science teaching: the role of history and philosophy of science*. New York, NY: Routledge.

Matthews, M. R. (2002). Constructivism and science education: A further appraisal. *Journal of Science Education and Technology*, *11*(2), 121–134.

Merriam, S. (1995). What Can You Tell From An N of 1?: Issues of Validity and Reliability in Qualitative Research. *PAACE Journal of Lifelong Learning*, *4*, 50–60.

Mertens, D. M. (2014). *Research and Evaluation in Education and Psychology* (4th ed.). Thousand Oaks, CA: SAGE Publications.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. Thousand Oaks, CA: Sage Publications, Incorporated.

Mintzes, J. J., & Chiu, M. H. (2004). Understanding and conceptual change in science and mathematics: An international agenda within a constructivist framework. *International Journal of Science and Mathematics Education*, *2*(2), 111–114.

Mintzes, J. J., & Wandersee, J. H. (1998a). Reform and Innovation in Science Teaching: A Human Constructivist View. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Teaching science for understanding: A human constructivist view* (pp. 29–58). San Diego: Academic Press.

Mintzes, J. J., & Wandersee, J. H. (1998b). Research in science teaching and learning: A human constructivist view. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Teaching science for understanding: A human constructivist view* (pp. 59–92). San Diego, CA: Academic Press.

Moser, P. K. (2002). Introduction. In P. K. Moser (Ed.), *The Oxford handbook of epistemology*. Oxford: Open University Press.

Niaz, M. (2008). A Rationale for Mixed Methods (Integrative) Research Programmes in Education. *Journal of the Philosophy of Education Society of Great Britain*, *42*(2), 287–305.

Nisbet, J. (2005). What is educational research? Changing perspectives through the 20th century. *Research Papers in Education*, *20*(1), 25–44.

Noddings, N. (1990). Constructivism in Mathematics Education. *Journal for Research in Mathematics Education*, *4*, 7–18.

Nola, R. (1997). Constructivism in science and science education: a philosophical critique. *Science & Education*, *6*(1), 55–83.

Norman, J. (1983). Are the direct and indirect theories of perception incompatible? *The Behavioral and Brain Sciences*, *6*, 729–731.

Novak, J. D. (1990). Concept mapping: A useful tool for science education. *Journal of Research in Science Teaching*, *27*(10), 937–949.

Osborne, J. F. (1996). Beyond constructivism. *Science Education*, *80*(1), 53–82.

Osborne, R. J., & Wittrock, M. C. (1983). Learning science: A generative process. *Science Education*, *67*(4), 489–508.

Parson, S. (2013). *Transforming Schools Into Community Learning Centers*. New York: Routledge.

Phillips, D. C. (1995). The Good, the Bad, and the Ugly: The Many Faces of Constructivism. *Educational Researcher*, *24*(7), 5–12.

Plato. (1981). *Five Dialogues*. (G. M. A. Grube, Trans.). Indianapolis, IN: Hackett Publishing Company.

Plato. (2002). *Five Dialogues: Euthyphro, Apology, Crito, Meno, Phaedo*. (G. M. A. Grube, Trans.) (2nd ed.). Indianapolis, IN: Hackett Publishing Company.

Plato. (2004). *Theaetetus*. (R. Waterfield, Trans.). London: Penguin.

Popper, K. (1970). Normal Science and its Dangers. In I. Lakatos & A. Musgrove (Eds.), *Criticism and the Growth of Knowledge.* (pp. 51–58). Cambridge: Cambridge University Press.

Price, H. H. (1969). *Belief*. Woking: Unwin Brothers Limited.

Pritchard, D. (2016). Part IV: Epistemology. In D. Pritchard (Ed.), *What is this Thing Called Philosophy?* (pp. 121–158). Abbingdon, Oxon: Routledge.

Putnam, H. (1975). *Mathematics, matter and method*. Cambridge: Cambridge University Press.

Putnam, H. (1990). *Realism with a Human Face*. Cambridge, MA: Harvard University Press.

Quale, A. (2007). Radical constructivism, and the sin of relativism. *Science & Education*, *16*(3), 231–266.

Quale, A. (2008). *Radical Constructivism. A Relativist Epistemic Approach to Science Education*. Rotterdam: Sense Publishers.

Quine, W. V. (2000). Empistemology Naturalized. In E. Sosa & J. Kim (Eds.), *Epsitemology. An Anthology.* (pp. 289–300). Malden, MA.

Reddish, E. F. (2004). A theoretical framework for physics education research: Modelling student thinking. In E. F. Reddish & M. Vicentini (Eds.), *Research on physics education* (pp. 1–63). Bologna: Italian Physical Society/IOS Press.

Reid, T. (1997). *An Inquiry into the Human Mind*. Edinburgh: Edinburgh University Press.

Rokeach, M. (1973). *The Nature of Human Values*. New York, NY: Free Press.

Russell, B. (1907). The Nature of Truth. *Proceedings of the Arisotelian Society*, *7*, 228–249.

Russell, B. (1946). *History of Western Philosophy*. London: Routledge.

Russell, B. (1948). *Human Knowledge*. New York: Simon and Schuster.

Russman, T. A. (1987). *A Prospectus for the Triumph of Realism*. Macon, GA:

Mercer University Press.

Scerri, E. (2003). Philosophical confusion in chemical education research. *Journal of Chemical Education*, *80*(5), 468–494.

Schwandt, T. A. (2007). *The Sage Dictionary of Qualitative Inquiry*. Thousand Oaks, CA: Sage.

Schwartz, S. H. (1994). Are there universal aspects in the structure and contents of human values? *Journal of Social Issues*, *50*(4), 19–46.

Searle, J. R. (2015). *Seeing Things as They Are; A Theory of Perception*. Oxford: Oxford University Press.

Skinner, B. F. (1977). Why I am not a cognitive psychologist. *Behaviorism*, *5*(2), 1–10.

Sommers, F. (1963). Types and ontology. *Philosophical Review*, *72*, 327–363.

Southerland, S. A., Sinatra, G. M., & Matthews, M. R. (2001). Belief, Knowledge, and Science Education. *Educational Psychology Review*, *13*(4), 325–351.

Staver, J. R. (1998). Constructivism: Sound theory for explicating the practice of science and science teaching. *Journal of Research in Science Teaching*, *35*(5 SRC-GoogleScholar FG-0), 501–520.

Stenhouse, L. (1981). What counts as research? *British Journal of Educational Studies*, *29*(2), 103–114.

Sternberg, R. J., & Grigorenko, E. L. (2002). *Dynamic Testing: The Nature and Measurement of Learning Potential*. Cambridge: Cambridge University Press.

Sullivan, G. (2009). Making space: The purpose and place of practice-led research. In H. Smith & R. T. Dean (Eds.), *Practice-led Research, Research-led Practice in the Creative Arts* (pp. 41–65). Edinburgh: Edinburgh University Press.

Taber, K. S. (2000a). Case studies and generalizability: grounded theory and research in science education. *International Journal of Science Education*, *22*(5), 469–487.

Taber, K. S. (2000b). Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science Education*, *22*(4), 399–417.

Taber, K. S. (2001). Shifting sands: a case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education*, *23*(7), 731–753.

Taber, K. S. (2007). *Classroom-based research and evidence-based practice: a guide for teachers*. London: Sage Publications Limited.

Taber, K. S. (2008). Exploring conceptual integration in student thinking: Evidence from a case study. *International Journal of Science Education*, *30*(14), 1915–1943.

Taber, K. S. (2009). *Progressing science education: constructing the scientific research programme into the contingent nature of learning science.* Dordrecht: Springer.

Taber, K. S. (2013a). *Modeling Learners and Learning in Science Education*. Dordrecht: Springer.

Taber, K. S. (2013b). *Modelling Learners and Learning in Science Education: Developing representations of concepts, conceptual structure and conceptual change to inform teaching and research*. Dordrecht: Springer.

Tan, P. L. (2010). Towards a Culturally Sensitive and Deeper Understanding of "Rote Learning" and Memorisation of Adult Learners. *Journal of Studies in International Education*, *15*(2), 124–145.

Tobin, K. G. (1993). Preface. Constructivism: A paradigm for the practice of science education. In K. G. Tobin (Ed.), *The practice of constructivism in Science Education* (pp. ix–xvi). New York, NY: Routledge.

Tobin, K. G., & Tippins, D. (1993). Constructivism as a referent for teaching and learning. In K. G. Tobin (Ed.), *The Practice of Constructivism in Science Education* (pp. 3–21). New York, NY: Routledge.

Toulmin, S. (1961). *Foresight and Understanding*. New York, NY: Harper & Row.

Turri, J. (2010). Is knowledge justified true belief? *Synthese*, *184*(3), 247–259.

Turri, J. (2013). A conspicuous art: putting Gettier to the test. *Philosophers' Imprint*, *13*(10), 1–6.

Ulman, S. (1980). Against direct perception. *Behavioral and Brain Sciences*, *3*, 373–81.

Van den Bergh, H. (2015). Theory on different levels. In V. Donche, S. De Maeyer, D. Gijbels, & H. Van den Bergh (Eds.), *Methodological challenges in research on student learning* (pp. 173–178). Antwerp: Garant Publishers.

Van Driel, J. H., & Verloop, N. (2002). Experienced teachers' knowledge of teaching and learning of models and modelling in science education. *International Journal of Science Education*, *24*(12), 1255–1272.

Viennot, L. (1979). Spontaneous Reasoning in Elementary Dynamics. *European Journal of Science Education*, *1*(2), 205–221.

von Glasersfeld, E. V. (1996). *Radical constructivism: A way of knowing and learning*. London: Routledge Falmer.

Wedgewood, R. (2002). Internalism Explained. *Philosophy and Phenomenological Research*, *65*(2), 349–369.

Weinberg, A. M. (1970). Views: The Axiology of Science: The urgent question of scientific priorities has helped to promote a growing concern with value in science. *American Scientist*, *58*(6), 612–617.

Wertheim, M. (2011). *Physics on the Fringe: Smoke Rings, Circlons, and Alternative Theories of Everything*. New York, NY: Walker Publishing Company.

Willingham, D. T. (2009). *Why don't students like school?* San Francisco, CA: Jossey-Bass.

Wilson, S. M. (1995). Not tension but intention: A response to Wong's analysis of the researcher/teacher. *Educational Researcher*, *24*(8), 19–22.

Wittgenstein, L. (1953). *Philosophical Investigations*. (G. E. M. Anscombe, Trans.) (3rd ed.). Malden, MA: Blackwell.

Wong, E. D. (1995). Challenges confronting the researcher/teacher: Conflicts of purpose and conduct. *Educational Researcher, 24*(3), 22–28.

Wortham, S. (1996). Are constructs personal? *Theory Psychology, 6*(1), 79–84.

Yin, R. K. (1981). The case study crisis: Some answers. *Administrative Science Quarterly, 26*(1), 58–65.

Yin, R. K. (2009). *Case study research: Design and methods*. Thousand Oaks, CA: Sage Publications Incorporated.

Zohar, A., & Nemet, F. (2002). Fostering students' knowledge and argumentation skills through dilemmas in human genetics. *Journal of Research in Science Teaching, 39*(1), 35–62.