12-2005

Beyond Constructivism: An Introduction to Critical Realism in Science Education

Clinton Douglas Jackson
Avondale College, cjackson@bac.qld.edu.au

BEYOND CONSTRUCTIVISM: AN INTRODUCTION TO CRITICAL REALISM IN SCIENCE EDUCATION

Clinton Douglas Jackson

A thesis submitted to the
Faculty of Education,
Avondale College
in partial fulfilment of the requirements
for the award of the degree
Bachelor of Science / Bachelor of Teaching (Honours)

3rd November, 2005

I hereby certify that the work embodied in this thesis

is the result of original research

and has not been submitted for a higher degree

to any other University or Institution

Clinton Douglas Jackson

DEDICATION

To my father

1 Corinthians 13:12

ACKNOWLEDGMENTS

I would like to thank Dr John Watts for his assistance, patience, and guidance as principal supervisor of this project. Dr Watts' thoroughness and scholarship transformed this project. Special thanks also goes to Dr Brad Shipway for his invaluable assistance as associate supervisor. Dr Shipway's insights regarding philosophy gave this project its life.

I would also like to thank Mr Malcolm Coulson for overseeing the commencement of this project and Dr Cedric Greive for his hours of conversation that have lead to important conceptual clarifications.

Thanks also to all my science lecturers. In particular, Dr Lynden Rogers for overseeing my undergraduate science work and Dr Kevin de Berg for his help in locating numerous articles.

I also want to thank all my classmates, friends, and family who have endured endless conversations while I developed my own conceptual understanding. Their support throughout this project has been noticed and has been greatly appreciated.

CONTENTS

LIST OF FIGURES

ABSTRACT

In the context of social and philosophical debates concerning the nature of science, this thesis provides an introductory investigation of the application of critical realism to science education. It moves beyond the current impasse within constructivist science education and, in particular, philosophical debates that fail to represent science education as a whole. The current dominance of anti-realist positions in science education is treated as problematic. The thesis explores selected current and potential uses of critical realism in an endeavour to move beyond the perceived inadequacies of constructivism as the current paradigm of science education. The approach used is one of philosophical reflection engaging with literature that addressed representative positions in science education concerning epistemology, critical realism, the nature of science, and constructivism.

A preliminary explanatory framework for science education is developed. Features of this critical realist framework include epistemic humility, judgmental rationality, recognition of the transitive and intransitive domains, a stratified ontology, and the distinction between open and closed systems. A central core of the framework is the insistence that epistemology models ontology. The framework provides a philosophy that reflects the working epistemology of practising scientists and provides a robust stratified ontology. The framework also possesses greater theoretical and explanatory power than that of constructivism.

CHAPTER 1

INTRODUCTION

In this thesis, the possibility of critical realism as a philosophy of and for the field of science education, is explored. It is suggested that critical realism effectively describes a tacit position held by many science educators and that the explicit, intelligent adoption and understanding of critical realism would help to clarify existing problems faced by science educators, provide beneficial insights into science education, and impart new and fruitful research directions.

Background to Study

Science education is affected by societal and philosophical debates regarding the nature of science[1]. Major shifts in the debate are well documented (Kuhn, 1970) and science itself continues to debate the fundamental nature of science, especially in fields such as quantum mechanics (Eisberg & Resnick, 1985). Teachers are necessarily affected by the social and philosophical debates concerning the nature of science (Matthews, 1998). It is in the context of these continuing "science wars", that this thesis treats as problematic the current dominance of anti-realist positions in science education, such as the dominant anti-realist constructivist learning theories. For example, most current science syllabi are based on constructivist learning theories (Brooks &

[1] See, for example, Slezak (2000) for a discussion of the so-called science wars, culminating in the famous "Sokal Hoax" (Sokal & Bricmont, 1998)

Brooks, 1999; Good & Shymansky, 2001). In contrast, this thesis provides an introductory investigation of the application of a realist position, namely critical realism, to science education and examines its potential to address some of the problems encountered by anti-realist constructivist science education[2].

Purpose of this Thesis

The purpose of this thesis is to provide an introductory investigation concerning the application of critical realism to science education. It intends to move beyond the impasse within constructivist science education, particularly of philosophical debates that fail to represent science education as a whole and also the lack of a theoretical framework for practitioners. The thesis explores current and potential uses of critical realism in an endeavour to move beyond the perceived inadaquecies of constructivism as the current paradigm of science education.

Critical realist thought may be found in a number of traditions so labelled. This thesis will describe two contemporary forms of critical realism, Theological Critical Realism (ThCR) and "Bhaskarian" Critical Realism, as explored in the International Association of Critical Realism (IACR). ThCR and IACR were chosen as they represent two active international research communities. Both communities are engaged in active dialogue within their communities and are considered leaders in the field of critical realism. This thesis appropriates the strengths of both communities to engage with the field of science education.

Significance of this Thesis

This thesis contributes to a philosophy for science educators that intends to improve the reflexivity of science education practitioners and researchers. The philosophy offered contributes

[2] In one sense this thesis is a selective and focused extension of the work of Shipway (2002) into the field of science education. Shipway's contribution was to establish critical realism as a feasible philosophy for education.

to a more comprehensive frame of reference to inform and improve science education. Critical realism is of value for science educators, since it clarifies the current state of science education, and it is able to appropriate the strengths of anti-realist perspectives, specifically an awareness of epistemological relativism, while avoiding their mistakes. Of particular significance, critical realism provides a philosophically sound justification for the current emphasis on experientially rich science classrooms that develop students deep conceptual understanding.

Given the continuing discussion on constructivism, and its significant impact on education policy statements[3], the current study is timely. To this end the ontological presuppositions and resultant conclusions of two critical realist communities are proffered as a contemporary and sound philosophical "under-labourer" (Collier, 1994) for science education.

Theoretical Framework

This thesis is based on the premise that scientific realism continues to be the dominant paradigm used for natural scientific enquiry and practice. Consequently, it is reasonable to suggest that a significant goal of *science* education is to induct students into the realist scientific community. This study commenced out of concern for the lack of comment and seeming disregard for the necessity of a realist ontology in science education exhibited by constructivist science education.

Critical realism, by virtue of its open systems ontology[4], provides the framework for this study. Critical realism under-labours the closed systems ontology of scientific realism and the open systems ontology of some realist approaches to the social sciences. Thus, critical realism is ideally suited for use in science education.

[3]See (Department of Education and Training, 2003) especially "Problematic Knowledge"

[4]See Chapter 2 for an explanation of open systems ontology. The glossary also contains a definition.

Methodology

The methodology employed throughout this thesis is one of philosophical reflection, similar to the fine doctoral work of Shipway (2002). Given the centrality of critical realism to this thesis, the methodology adopted is compatible with a critical realist approach. Although critical realism is poised to comment on and critique methodology, it does not prescribe a methodology. The lack of prescription reflects the meta-theoretical "under-labouring" role of critical realism. That is, critical realism provides tools from which to build theories and methodologies, but no methodology is wholly endorsed or rejected by critical realism[5].

Literature reviews are now considered to be a research methodology in their own right (Evans & Kowanko, 2000)[6]. The recommendations for a literature review are to be thorough, careful, and maintain integrity (Hart, 1998; Evans & Kowanko, 2000). This thesis moves from and beyond literature reviews which overview the current state of the literature to investigate a case for critical realism in science education.

A significant complexity in the field of science education is the volume of literature[7]. This thesis appropriates a reflective philosophical approach by extracting major representative perspectives from the literature relating to the purposes of this study. Articles that addressed representative positions in science education concerning epistemology, nature of science, and constructivism were selected from the literature. Initially, articles were selected from the journal

[5] At the 2005 pre-conference workshop of the International Association of Critical Realism 9^{th} Annual Conference a considerable amount of discussion was devoted to methodology. Many of the young researchers at the workshop expressed frustration in regard to the selection of a methodology. This frustration was also felt through out the conference proper. The lack of prescription can lead to lack of agreement, for example, at one stage of the workshop two prominent critical realist researchers indicated that grounded theory could not be used if trying to do critical realist research. However, one of the PhD students cited examples of researchers using grounded theory from a critical realist perspective. The only area of fairly strong agreement is the caution when using statistics, one of the same established researchers dismissed the use of regressions completely at the workshop. The author refers the reader to Archer et al. (1999) and Porpora (2001) for discussions of the possible use of regressions in a critical realist framework.

[6] Note that the Australian Qualifications Framework (2002) for doctoral studies states that "substantial and original contribution to knowledge may take the form of a comprehensive and searching review of the literature".

[7] By the mid 1990s in excess of 4000 papers had been published relating to science education (Brown, 2005).

Science & Education, then the search was extended to other journals in the field of science education. Anthologies relating to constructivism were also selected, in particular Phillips (2000) and Fensham, Gunstone and White (1994), for their focus on constructivist science education.

Critical realism acknowledges and affirms the problematic nature of text and an approach to literary analysis consonant with a critical realist view was adopted for the current exploratory investigation. Appropriate weight was given to each of the contributing factors to textual analysis. These factors are the reader's perspective, the textual form, and the author's intent (Reynaud, 2000). A critical realist framework maintains that the author's intent is knowable, albeit mediated through the lenses of both the textual form and the reader's own perspective. A critical realist considers the influences of author's intent, textual form, and reader's perspective to be causally efficacious. That is, the author's intent, textual form, and reader's perspective all have causal power on the ultimate meaning taken from the text.

For the purpose of this thesis, texts were divided into three categories in reference to authors' comments on a given issue. The first category consisted of statements when the author makes an explicit comment directed at an issue. These statements are considered to be definitive descriptions of the author's perspective. The second category was implicit statements inferred to be made by the author while talking about an issue. These statements are considered to be important but need to be tempered by the reader's own perspective. The final category was statements that the reader considers the author to be inadvertently making. These statements are of interest, but must be used with a degree of caution.

Thesis Outline

Chapter One has briefly overviewed the background, purpose, and significance of this study. It further has provided a working theoretical framework and described the methodology employed in this thesis.

Chapter Two introduces critical realism. Critical realism has not been widely used in science education or in education in general. Two contemporary communities of critical realism are described, one being associated with the work of Roy Bhaskar and the International Association of Critical Realism, and the other being associated with a "theological" critical realism. Following this brief description, selected core tenets of the two movements are outlined.

Chapter Three considers constructivism in the field of science education. Psychological constructivism and social constructivism are described as philosophies that are inadequate for the purposes of science education. In terms of the philosophy of constructivist science education, there is reasonable evidence to suggest that (i) those who advocate constructivism often do so by incorrectly attacking a naïve realist straw man and (ii) those who attack constructivism often target radical constructivism or the sociology of scientific knowledge (SSK) while ignoring the tacit philosophy of science education. The chapter concludes by presenting a preliminary case for constructivist pedagogy as found in science education to be useful without the philosophical impedimenta of constructivism.

Chapter Four considers the current state of critical realism in the field of science education. Several key implications of critical realism for science education are examined. In particular the ability of critical realism to provide a justification for existing practices in science education from within a realist framework. Applications of critical realism in science education are developed for science education researchers and practitioners.

Chapter Five provides a summary of the thesis, then moves towards a critical realist framework for science education, and a conclusion. Readers are also referred to the glossary found at the end of this thesis. The glossary provides working definitions of terms as they are used throughout this thesis.

CHAPTER 2

AN INTRODUCTION TO CRITICAL REALISM

Critical realism (CR) is a philosophical position concerning the nature of human knowledge and its relation to the world external to the human. It refers to any philosophy of knowledge that affirms the existence of a mind-independent objective reality which is accessed through the mediated layers of perception. Critical realism asserts that "something is out there" that may be known, but what is actually known about it is altered by the multi-layered process of perception. Shipway (2002) states "...at its broadest level the term critical realism has been used to indicate the general idea of belief in a mind-independent reality, and that perception of this reality is not direct, but is rather mediated by means of our perception" (p. 12).

Contemporary Critical Realism

Explicit critical realist thought is found in two contemporary communities, which are explored in this chapter. Critical realism, as a movement, has not been used extensively within education. Critical realism in science education is discussed in Chapter 4. The purpose of this chapter is to (i) describe the two contemporary communities of critical realism[1] and thus con-

[1] There was a movement in the 1920s associated with a school of literary criticism, that is described as American Critical Realism. This movement does not impact on this thesis. A full history has been given by Shipway (2002) and Verstegen (2000).

tribute to the ongoing dialogue between the theological and secular strands of critical realism[2], (ii) provide an introduction to critical realism for the benefit of science education, and (iii) provide the background for the ensuing critique of constructivist science education.

The Community of Theological Critical Realism

Theological Critical Realism (ThCR) refers to the philosophy of a group of scholars working in the interface between science and theology. Shipway (2000, 2002) correctly points out this community does not call itself "theological critical realists". Rather, it is used to distinguish this community from other critical realist communities.

ThCR is used as an operational framework for a number of authors considering the interface between science and theology, and more particularly Christian theology. ThCR commenced with the work of authors such as Ian Barbour (1966, 2000), John Polkinghorne (1984, 1986, 1989, 1991, 1995, 1996), and Arthur Peacocke (1984, 1993). Each of these authors have qualifications and experience in the natural sciences, but subsequently has turned his scientific training to theology. The themes of these authors have been picked up by a wider range of authors, many of whom now come from a theological background (e.g. Moltmann, 2003). ThCR argues that the essential methodology and language of scientific inquiry is the same as theological inquiry and this provides an avenue through which dialogue may occur. Members of ThCR and their antagonists frequently publish in the journal *Zygon*.

Theological critical realism is included in this thesis as it consists of people who are *scientists* working in theology and who have found this approach useful. The secular community was

[2]This study confines itself to the elementary stages of these two movements. The theological strand has proponents who advocate a post-foundational move in critical realism (van Huyssteen, 1998; Shipway, 2000). The secular strand of critical realism has a dialectical development represented through Bhaskar's (1994) *Dialectic: The Pulse of Freedom.* This study has confined itself to only the elementary stages as needed for the engagement with science education (a move endorsed by Bhaskar who describes CR has a train journey, you disembark at the station that is useful to you). Science education needs to embark on the metaphorical CR train. This thesis contributes towards commencing that journey. The present author expects that future stages of critical realism will be found to be profitable to science education.

selected as it provides a more rigorous philosophical framework (Shipway, 2000). A brief description of two leading thinkers in the field of theological critical realism is provided to indicate the expertise and credibility of these authors as scientists. A description of the secular strand of critical realism follows. Chapter Four returns to the theme of science and religion dialogue in the classroom.

John Polkinghorne took a PhD under the renowned quantum physicist, Paul Dirac, as he was interested in the way in which mathematics could be applied to the natural world. After establishing himself in physics, he moved into the Anglican priesthood around the age of 40 years. He began contributing to the interaction between science and theology, for which he was awarded the Templeton prize in 2002.

Alister McGrath is one of the most respected and well known figures in the evangelical theological tradition. His publications include many works on Christian theology and historical theology. McGrath is currently Professor of Historical Theology at Oxford University, and Principal of Wycliffe Hall. McGrath originally trained as a research scientist, specialising in molecular biophysics, later taking degrees in theology and receiving ordination as a priest in the Church of England. He has recently published a three volume trilogy, *A Scientific Theology*, of which the second volume (2002) engages both ThCR and the secular strand now discussed.

The Community of Bhaskarian Critical Realism

Another community of critical realists today is centred around the philosophy of Roy Bhaskar, namely the International Association of Critical Realism. This form of critical realism, referred to in this thesis as IACR, is increasingly being used in the social sciences, especially in sociology and economics. Current interests of this community include attempting to define what, if anything, can be known about social structures, the nature of social structures, and how to measure social structures. Paralleling the interests of this thesis of applying critical realism to science education, applications of critical realism are being developed in fields such as archeology and health informatics.

The philosophy of IACR has developed as a result of its interest in social science. For example, an open systems ontology (discussed below in this chapter) reflects IACRs concern with social structures and social agency. Roy Bhaskar developed the first stages of his philosophy whilst working as a PhD student under Rom Harré, in response to problems he perceived in the philosophy of science.

Selected Tenets of Critical Realism

The following selected key characteristics are addressed to provide a framework for the viewing of constructivism in science education in Chapter 3. In brief, critical realism is ontologically realist, epistemologically relativist, judgmentally rationalist, maintains a distinction between open systems and closed systems, incorporates transitive and intransitive domains, and recognises reality to be vertically stratified.

Ontologically Realist

Critical realism is ontologically realist in perspective. That is, critical realism maintains that objects, structures, and events exist independently of human cognitive activity. A CR assertion is that these objects, structures, and events exist if they act as causes (New & Fleetwood, 2005). This assertion is defended by deploying the transcendental question: *Given X, what must have been the conditions for X to occur?* Bhaskar first used this approach to argue for the necessity of a realist ontology by using a modified form of Kant's transcendental method of argument[3]. This is what he means by "the possibility of an *ontology*" (Bhaskar, 1989, p. 13). Bhaskar goes on to describe the *epistemic fallacy* as the belief of post-Humean philosophers that all that can

[3]The use of a transcendental argument has subjected Bhaskar to criticism. Transcendental argument was first used by Kant. Since Kant was an idealist, it was incorrectly assumed that Bhaskar was an idealist (New & Fleetwood, 2005).

be discussed is the knowledge of some experience, not actually what that knowledge is describing (Bhaskar, 1989). ThCR shares IACR's ontological realism, but tends to view ontological realism as a presupposition that is argued from rather than towards (Shipway, 2002). However, Alister McGrath (2002) prefers an *a posteriori* engagement with reality which shares similarities with the transcendental approach. Both ThCR and IACR share a metaphysical and epistemological commitment to realism. The metaphysical component maintains that reality exists, the epistemological component that reality is knowable (Shipway, 2002).

Epistemologically Relativist

Critical realism recognises and insists on the fallibility of knowledge. The recognition by Kuhn (1970) of the historical and social factors in the development of science has been acknowledged by realist philosophers of science[4]. ThCR acknowledges the limits of human knowledge with terms such as *epistemic humility* or *epistemic modesty* (McGrath, 2002). In brief, both ThCR and IACR insist on the referentiality of knowledge to reality, which is poignantly encapsulated in Polkinghorne's phrase "epistemology models ontology."

Judgmentally Rationalist

While being epistemologically relativist, CR is judgmentally rationalist. For critical realists, this is a crucial difference from several anti-realist philosophies (e.g., postmodernism) as it enables CR to select and prioritise between competing theories. To distinguish between theories, critical realism employs strategies such as the transcendental approach already outlined and appeals to elegance and simplicity as expressed in Occam's razor (New & Fleetwood, 2005). Polkinghorne (1991) refers to the concept of verisimilitude, that is, knowledge which is the *most*

[4]These criticisms have been described by Bhaskar as T*he Copernican Revolution* in the philosophy of science. The present author considers that this label unnecessarily confuses readers concerning the revolution that involved Copernicus and the revolution instigated by Kuhn.

likely explanation for particular phenomena. Critical realism maintains that if a causal mechanism can be isolated - a task which itself is quite difficult to achieve - then the very ability to discern and describe such a causal mechanism indicates that the explanation of the phenomena is tenable.

Open and Closed Systems

Critical realism makes a distinction between open and closed systems. Closed systems are those in which all variables are controlled, with the exception of the target variable which is varied. For example, to analyse the relationship between pressure and volume, $PV = nRT$, the volume, V, and the quantity of gas, n, are held constant to determine the effect of temperature change, ΔT, on pressure, P. Bhaskar (1998) states that these closed systems are a feature of the natural sciences, where such variables can be controlled through laboratory conditions. According to critical realism, the same control is not available[5] in the social sciences, where one must deal with open systems, such as economies or classrooms. Consequently, critical realists typically are skeptical of the use of inferential statistics in open environments (Archer et al., 1999; New & Fleetwood, 2005).

Intransitive and Transitive Domains

The intransitive domain represents enduring objects and structures. Ideas about those structures reside in the intransitive domain (New & Fleetwood, 2005). For example, gravitation as a force exists in the intransitive domain. By contrast, the understandings of gravitation as expressed by Aristotelean mechanics, Newtonian mechanics, and Einsteinian mechanics, are found in the transitive domain. A complexity is that, since these theories about gravitation take on causal power, they also move into and reside in the intransitive domain. For example, the way

[5]This does not preclude, however, the possibility of a social science (Bhaskar, 1998).

in which gravitation is taught is affected by which theory of gravity is held, that is, the theory of gravitation causes an instructional sequence. In this way, a theory that is posited in the transitive dimension, and that is later shown to be valid, can, in some sense, be transferred to the intransitive dimension in the sense that it describes an aspect of the domain of the real, which is described below.

An Emergent, Vertically Stratified Reality

Critical realism views reality as being vertically stratified. Bhaskar identifies three strata, the empirical (what we observe), the actual (what we think is the case), and the real (the explanation of causes), as illustrated in Figure 2.1. The phrase *domain of the real* may be incorrectly understood as being the only domain that exists. All of the domains, however, possess an ontology, and, as such, the domain of the real may be considered to be the domain of the deep (McGrath, 2002, New & Fleetwood, 2005). Each stratum is emergent from but not reducible to the stratum below. For example, chemical properties are emergent from, but not entirely reducible to physics. Likewise, biological systems are emergent from but not reducible to chemistry. Further, human consciousness is an emergent property of the physiological function of the brain, but cannot be explained solely in terms of biology. The stratification may be further explained through an example. The observation that women are being discriminated in the workplace occurs in the domain of the empirical. After reflection and further observation, discussion among peers, and other approaches, it is decided that women are indeed discriminated against in the work place. This is the domain of the actual. The explanation for why women are discriminated against in the workplace, or the *causes*, occurs in the domain of the real or deep (New & Fleetwood, 2005).

A Comparison of Bhaskar's and Harré's Ontology

It is valuable for the purposes of this thesis to consider briefly the differences and similarities between Harré's triadic theory of science and Roy Bhaskar's stratified ontology. Roy Bhaskar

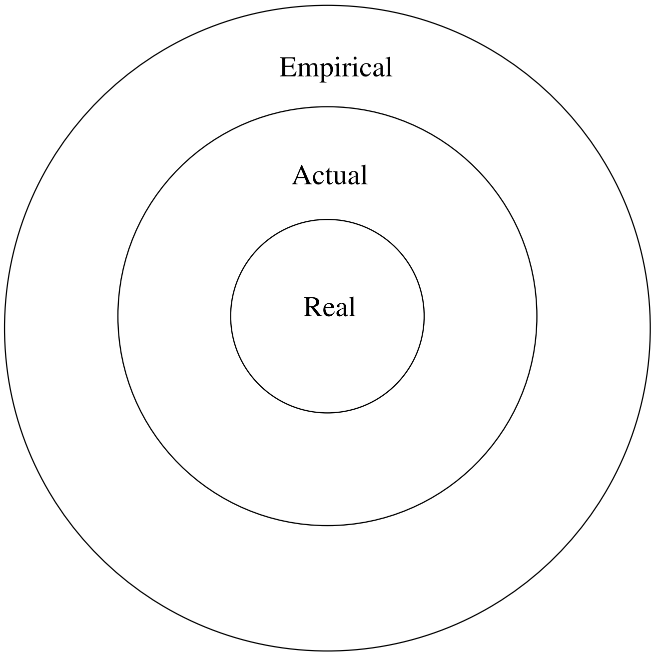

Figure 2.1: Bhaskar's stratified reality

was Harré's student so it is not very surprising then that their views share some similarities. Like Bhaskar, Harré has three *realms.* For Harré realm one contains "actual or possible objects of experience", these are the objects that can actually be observed, for example, tables, tongues, and the Grand Canyon. Realm two contains objects that require something to observe them. For example, a microscope is required to view bacteria and an ammeter is required to measure current. Realm three contains abstract unobservables, such as quantum states and fundamental particles. The objects are often mathematical entities and are usually described through mathematics (Outhwaite, 2001; Osborne, 1996). The main difference between the two approaches is that Bhaskar has a vertical stratification. Harré's approach suffers from ambiguities as to when the objects move between the realms, which they apparently can and may do. Harré's approach resembles many of the elements of Hacking's (1984) entity realism. The problem with Hacking and Harré is that theoretical entities have a more dubious ontological status, yet over time their ontology becomes more firm, which almost suggests that human activity is required for them to exist. Bhaskar's stratification enables an understanding of the fact that causes have and always will exist. It is the ideas about these phenomena that change.

Conclusion

This chapter has introduced critical realism. Critical realism is a philosophical position that acknowledges the provisional and transitory nature of knowledge, and insists that such knowledge represents an observer-independent reality. The following chapters build on the insights of critical realism by applying them to the field of science education. Chapter Three considers constructivism in the field of science education from a critical realist perspective.

CHAPTER 3

CONSTRUCTIVISM IN SCIENCE EDUCATION

Constructivism and science education are closely associated. This chapter treats science education as a field, of which the label constructivism is a defining feature. It discusses what is meant by the term constructivism. The chapter concludes that even for science education practitioners who have no clear explicit philosophical commitment, or any wish to address philosophical issues, it is possible to espouse a workable pedagogy that may be practised without any philosophical commitment on their part. Further, to constructivist practitioners, this pedagogy constitutes a distinct form of pedagogy. Throughout this chapter the tenets of critical realism outlined in the previous chapter are used to highlight problematic aspects of constructivist science education.

The Field of Science Education

Science education may be considered to be a field in its own right (Jenkins, 2001). As a field, science education is primarily concerned with how best to teach science. Jenkins (2001) has argued that, in order to sharpen thinking about science education, this primary concern should be expanded to include anything affecting science education, such as the history of science education and its relation to other fields. Though acknowledging Jenkins observation concerning the dominant pedagogical focus, the literature does display such diversity, ranging from theoretical philosophical debates (Nola, 2003) to demonstrations based on historical experiments (de Berg

& Greive, 1999).

The discourse of the field of science education is conducted in journals such as *Science Education*, *Science & Education*, *Journal of Research in Science and Technology Education, School Science Review, Journal of Research in Science Teaching,* and many others which are the domain of this field. The field has also produced many textbooks and collections, a notable example being the two volume *International Handbook of Science Education* (Fraser & Tobin, 1998).

Constructivism as the Paradigm that Defines Science Education

Broadly speaking, constructivism is a philosophical position that asserts knowledge is primarily the result of psychological factors or social factors or some combination of the two. Constructivism may or may not have a realist ontology. In the context of philosophy, however, the term constructivist normally denotes an anti-realist position (Kukla, 2000).

Discussion of the field of science education is currently incomplete without mention of constructivism. Any cursory look at the aforementioned journals will result in the recognition of the importance of constructivism to contemporary science education. Within education, this philosophy has been used as a benchmark to inform teachers how students learn, and the best ways to facilitate this learning. Constructivist science educators place high importance on helping students function as scientists[1]. Although constructivism is often employed for merely its utilitarian value, its philosophical nature is acknowledged (Simpson, 2002; Clements, 1997). In Kuhnian terms, the theory of constructivism can be argued to be the paradigm that most aptly describes science education. Constructivism is the theory by which data are interpreted and presented, and the theory to which newcomers to the field are inducted (Gil-Peréz et al., 2002; Jenkins, 2001; Tobin, 2000; Howe & Berv, 2000; Kuhn, 1970).

Although the link between constructivism and science education is acknowledged, the preva-

[1] As indicated by Driver's (1983) choice of title, *The Pupil as Scientist.*

lence of articles such as *Beyond Constructivism* (Osborne, 1996), *Dare I oppose constructivist theory?* (Simpson, 2002), and *Constructivism in school science education: Powerful model or the most dangerous intellectual tendency?* (Jenkins, 2000) begs the question whether constructivism represents the major consensus. A closer examination reveals numerous forms of constructivism (Geelan, 1997). In this context, Niaz et al. (2003) question whether constructivism is indeed the paradigm that defines science education. Phillips (2000) quotes the following excerpt from Latour which neatly summarises the issue.

> "Radical," "progressivist," "conservative," "reactionary," "golden mean"... A radical is someone who claims that knowledge is entirely constructed "out of" social relations; a progressivist is someone who would say that it is "partially" constructed out of social relations but that nature somehow "leaks in" at the the end. At the other end of this tug-of-war, a reactionary is someone who would claim science becomes really scientific only when it sheds any trace of social construction; while a conservative would say that although science escapes from society there are still factors from society that "leak in" and influence its development. In the middle, would be the marsh of wishy-washy scholars who add a little bit of nature to a little bit of society and shun the two extremes. (Latour, 1992, as cited in Phillips, 2000, p. 10).

Phillips locates himself among the wishy-washy middle. It is probable that such a position represents the consensus position of many researchers in science education, and that critiques of constructivism and supporters of constructivism fail to recognise the common ground. The recognition that the majority of science educators occupy a centre-position is not new (Gil-Peréz et al., 2002). In this chapter, it is argued that the centre, "wishy-washy", position possesses a tacit critical realism, for which the adoption of an explicit critical realism may bring benefits to the field of science education. Essentially, the adoption of an explicit critical realist ontology grounds the "wishy-washy" centre and moves it into the realm of a respectable theoretical framework for science education.

Psychological and Social Constructivism

Constructivism can be represented by two main approaches, psychological constructivism and social constructivism. A psychological constructivist is one who considers the various components of cognition to create knowledge and that, typically, knowledge resides in the individual. A social constructivist is one who considers that various social forces create knowledge and that, typically, knowledge is held in and by societies. Constructivists may combine elements of both of these views (Phillips, 1995).

A well known writer in psychological constructivism is Ernst von Glasersfeld who labels his variety of psychological constructivism, radical constructivism. Von Glasersfeld (1993) is a psychologist, strongly influenced by Piaget, who considers that "truth is an act of faith" (p. 27). Von Glasersfeld does not see the need for an external reality and refuses to be drawn on its existence. By his admission and from his own experience, von Glasersfeld has observed that physics teachers "have little sympathy for constructivism" preferring to talk "as though they were describing an absolute reality" (p. 27). Andrew Collier (1994), a prominent critical realist author, likewise comments that practitioners are unlikely to question the existence of an object. For example, a practising doctor normally would not question the existence of the disease that she is treating. In a similar manner, physicists, who actually deal with the entities they describe, would rarely question their ontological status. Consequently, psychological constructivism provides an inadequate framework for science educators.

Thomas Kuhn's *The Structure of Scientific Revolutions* (1962; 1970) is frequently cited as having a seminal influence on social constructivist views of science. Among other positions developed from Kuhn's work, one of the strongest programmes was the study of sociology of scientific knowledge (SSK). There are a number of reasons that suggest SSK and Kuhn provide an inadequate justification for social constructivism as practised in science education, and three of the more relevant reasons are now delineated.

First, SSK fails to represent science adaquately. For example, in *Laboratory Life,* a key SSK text, Latour and Woolgar (1979) sat in a laboratory listening to the conversations of scientists. They concluded from their observations that scientific knowledge was generated from the social activities of the scientists and not the scientists engagement with reality[2]. Second, SSK employs circular arguments. For example, André Kukla (2000) provides an insightful critique of SSK, during which, among other critiques, he demonstrates that SSK assumes constructivism to be true in the process of proving that constructivism is true. Kukla cites Latour's (1987) presupposition: "Rule 3: Since the settlement of a controversy is the *cause* of Nature's representation, not its consequence, we can never use this consequence, Nature, to explain how and why a controversy has been settled" (p. 45). Kukla argues that "Rule 3 amounts to no less than the claim that constructivism is true and that realism is false" (p. 45) which is supposed to be Latour's conclusion. Third, Kuhn himself does not agree with SSK. It is possible to demonstrate that Kuhn's relationship to SSK is problematic as he has, on occasion, distanced himself from the strong programme (Nola, 2000). In addition, Kuhn's work displays a more nuanced position than SSK as he emphasises the social and historical processes inherent in the work scientists do to uncover the natural world (Nola, 2000). Consequently, although science educators have frequently invoked Kuhn, often with some misunderstanding (Loving & Cobern, 2000; Matthews, 2004), to support social constructivism, social constructivism as a philosophical position remains inadequate.

The Debate Concerning Constructivism in Science Education

As noted, there is considerable debate over constructivism in science education, since there are many perspectives to be considered. In this section it is argued that in the ongoing debate,

[2]In this case it happened to be the work that led to the biochemist Roger Guillemin's Nobel prize which is recognised by scientists as highly valid descriptions of reality.

it is common practice to critique constructivism by attacking a radical constructivist or strong social constructivist, for example SSK, view of the nature of science, or alternatively, to defend constructivism by attacking a direct or naïve realist or objectivist view of the nature of science. Neither position represents the typical view of the nature of science held by many who label themselves as constructivist science educators. Examples of this tendency to attack non-representative straw men[3] are now highlighted from both perspectives. The pro-constructivist Driver (1988) and Carr et al. (1994) are considered first, followed by the anti-constructivist writers Slezak (2000) and Suchting (1992).

The late Rosalind Driver was a key figure in establishing the constructivist view of science education. A rather lengthy quote from Driver follows to clearly portray the argumentation noted above:

> In science education in particular we have a dominant perspective of a view of knowledge as objective and unproblematic. Textbook presentations and teaching methods in school and higher education reinforce this view. Even discovery approaches in science teaching give implicit support to this perspective in that they tend to assume that the empirical method (observing, classifying, interpreting, etc.) can be undertaken objectively without reference to an observer's way of seeing the world.
>
> Current perspectives on the philosophy of science, on the other hand, tend to reject the idea of an 'objective' base of observations against which theories of the world can be checked. Instead a dominant view is that science as public knowledge is not so much a 'discovery' as a carefully checked 'construction'. In attempting to represent the world scientists construct theoretical entities (magnetic fields, genes, electron orbitals ...) which in turn take on a 'reality'. Rather than viewing these observations as the base on which knowledge is built, there is a sense in which it is

[3] The *straw man* fallacy is explained in the glossary.

> these constructions of the world which are ‘real’. It is through them that we observe, interpret and reinterpret our experience. (Driver, 1988, p. 136)

The creation of a straw man is evident in the first paragraph. Few scientists would claim that science is purely objective and unproblematic. Indeed, the scientific process reflexively aims to continuously evaluate itself, first, by attaching confidence or error values to any measurements and, second, by following an intense process of peer review which incorporates the importance of the replicability of results.

In the second paragraph, Driver fallaciously contends that since this naïve, objectivist account of science is false, constructivism must be true. As noted above, while scientists are aware of the problematic nature of science, they do not abandon the belief that they are describing the world. From a critical realist perspective, Driver displays Humean type views of experience which contain the epistemic fallacy of equating statements of knowledge with statements of being. This epistemic fallacy has no place in a science education aiming to induct students into realist natural science.

Carr et al. (1994) argue that a traditional viewpoint of science considers “scientific *knowledge”* as “unproblematic”, science provides *“right answers”,* and *“truths* in science are *discovered* by observing and experimenting” (p. 147, emphasis in original). As previously mentioned, it is difficult to argue that such a viewpoint is held by scientists and may be regarded as a further example of a straw man. Scientists are acutely aware of the provisional nature of their scientific theories and are constantly trying to improve their theories or discredit the theories of others. A further fallacy in argument is evident when they say, “we construct meaning for the world around us from our prior attempts to make sense of it” (p. 149) in order to make the assertion that “the alternative constructivist paradigm is less clinical and more human” (p. 149). To prefer constructivism because it is “more human” is not a very compelling argument.

Carr et al. (1994) then pose a question to support their case for science being a constructed activity: “Does nature contain a definition of floating and sinking, energy, and photosynthesis which can be uncovered through appropriate experiences" (p. 151)? It is accepted that flotation, photosynthesis, and energy are problematic concepts. Having said that, this does not warrant acceptance of constructivism solely on the problematic nature of certain concepts. Flotation is a description of phenomena occurring in nature. It is true that nature has not taught the concept of flotation. Flotation is a human creation to describe nature. However, it is a description of *something* occurring in nature, that is, knowledge is reflecting reality, or in critical realist terms, epistemology models ontology. The notion of flotation may be further clarified using Bhaskar's stratified reality. There is some causal property in nature (the domain of the real) that causes flotation, what is thought about that reality (the domain of the actual) is experienced by us as, for instance, we float on the ocean (the domain of the empirical). Further, the fact that our ideas are subject to change about flotation (they are part of the transitive domain) does not mean that there is no underlying *intransitive* reality. Carr et al. place energy into the same problematic category, but do not explain this further. Energy is visited in the next chapter when a realist engagement with the concept is given.

Suchting's (1992) paper addresses the constructivism of Ernst von Glasersfeld. According to the paper "constructivism denies the 'existence of knowledge that corresponds to an observer-independent world-in-itself'" (p. 226). Suchting suggests, therefore, that constructivism must affirm "the existence of knowledge" of a "world that is *not* observer-independent, that is, it must be knowledge of an observer-dependent world" (p. 226). His argumentation leads him to draw the conclusion that constructivism is little more "than a sloganistic presentation" (p. 230). He further contends that the "metaphysical dialectic" employed by constructivism "could be spun out indefinitely and should be postponed till constructivism has succeeded in assigning some intelligible meaning to the notion of reality being the result of a subjective construction of or in experience" (p. 230). Suchting concludes his paper by noting that "far from being what it is claimed to be, namely, the New Age in philosophy of science, an even slightly perceptive ear can detect the familiar voice of a really quite primitive, traditional subjectivist empiricism with some overtones of diverse provenance like Piaget and Kuhn" (p. 247). Slezak (2000) provides a similar detailed critique of the strong programme in the sociology of scientific knowledge arriving at conclusions similar to those of Suchting.

Although both of these papers are valuable contributions to the debate concerning *philosophical* constructivism, it is contended they represent a subtle form of the straw man in regard to constructivism in the context of science education. Although the critiques are sophisticated and sound critiques of the positions that they engage, and the critiques are published in the context of science education (Suchting's paper in *Science & Education* and Slezak's paper in the collection *Constructivism in Education*), no explicit link to the field of science education seems to be made. There is a failure to demonstrate how radical constructivism or SSK may be seen in the constructivist science education literature. Thus, the critiques offered are of only indirect value when engaging science education.

It should be noted, however, that there are researchers (both pro-constructivist and anti-constructivist) who have attempted to avoid extreme positions and seek middle ground. For example, Kragh (1998) considers the "modern sociology of scientific knowledge" as needing to "be wholly rejected and has nothing to offer the science teacher" (p. 242), yet concludes by saying that the science teacher does not have to choose between the "two extremes" of positivist science and relativist constructivism. Science educators can recognise the useful contributions of both perspectives to the understanding of science, particularly in the socio-cultural context of knowledge construction. Hardy and Taylor (1997), in exploring von Glasersfeld's radical constructivism, also avoid taking an extreme position. They conclude their paper by suggesting that there is a "need to explore the socio-cultural context of knowledge construction and to incorporate a moral imperative for altering teaching practices if it is to serve as a viable referent for transforming the pedagogies of teachers of science and mathematics" (p. 147).

The recognition of the straw man phenomena in constructivism is not novel. For example, Burbules (2000) argues that opponents and supporters of constructivism often misrepresent each other. Anti-constructivists exaggerate features of constructivism, often avoiding the recognition of common ground. Likewise, pro-constructivist authors tend to characterise opposition to constructivism as naïve realism.

Matthews (2000b) neatly summarises these sentiments as follows:

> For instance most realists are sophisticated about science and its history. They recognize that science is a human creation, that it is bound by historical circumstances, that it changes over time, that its theories are under determined by empirical evidence, that its knowledge claims are not absolute, that its methods and methodology change over time, that it necessarily deals in abstraction and idealizations, that it involves certain metaphysical positions, that its research agendas are affected by social interests and ideology, that its learning requires that children be attentive and intellectually engaged, and so on. These are shared positions that both sides can happily agree about, and can encourage students to appreciate. If these positions collectively amount to constructivism, the we are all constructivist - although, as Ernst von Glasersfeld remarked on one occasion, this is *trivial* constructivism. (p. 329)

Matthews notion of shared positions reflects the concept of the "wishy-washy" middle introduced at the commencement of this chapter. Critiquing the centre position is difficult as the proponents of this position are rarely explicit about their epistemological commitments, owing, in part, to their focus on improving classroom practice. Gil-Peréz et al. (2002), however, argue for the necessity of engaging the centre position with a view to developing a philosophy for the centre position. They distance themselves from von Glasersfeld, as it is not the constructivism found in science education, and according to these authors, to correctly address the issue one must look specifically at science education.

In summary, for science education to benefit from an understanding of constructivism, there is a need to carefully eschew the straw man fallacy sometimes found in the literature, that is, criticism of constructivism which is overly extreme, and work with and beyond a more moderate and balanced view of constructivism that will benefit teaching in science education. This point is now further elaborated.

Constructivism in Science Education: What then can we say?

Constructivism has positively contributed to science education. The wealth of research into student misconceptions is deemed to be one of the most valuable contributions. There are, however, a number of points of concern. Of particular concern is the prevalence of anti-realist epistemologies among key figures in science education. Rosalind Driver and several from the group at Leeds exemplify anti-realist epistemology in science education:

> Learning science involves socialization into a particular way of looking at the world. It is not a matter of discovering 'how the world really is"; the science view is simply not there to be 'seen' in the real world. This highlights a very important distinction between discovery learning and constructivist approaches to learning. Since the science view is itself socially constructed within the science community, learning science requires students to be socialized into a 'new way of seeing'; they need to be enculturated into the science community. (Scott, Asoko, Driver, & Emberton, 1994, p. 219)

The statement that "the science view is itself socially constructed" identifies the authors with constructivist philosophies of science. Such a view contains anti-realist sentiments that are of little value to science educators. The following statement from Driver clearly shows these anti-realist sentiments:

> There is an epistemological implication of this view of knowledge as constructed which has yet to be taken seriously by educators, and that is that to know something

> does not involve correspondence between our conceptual schemes and what they represent ‘out there’; we have no direct access to the ‘real world’. The emphasis in learning is not on the correspondence with an external authority but the construction by the learner of schemes which are coherent and useful to them. (Driver, 1988, p. 135)

It is hardly surprising that such a view has “yet to be taken seriously by educators”, especially science educators for whom realist epistemologies are important. The invitation to rely on notions of coherence and efficacy are not likely to be greeted with enthusiasm by science educators.

Statements such as those outlined above show how anti-realist constructivist epistemology is influential in science education. Numerous authors consider the embedded anti-realist elements of constructivism to be harmful to science (Leplin, 1984; Bhaskar, 1989; Polkinghorne, 1991 1995; Leplin, 1997; Kukla, 2000; Matthews, 2000a; Nola, 2003). Moreover, the embedded anti-realist elements of constructivism are dangerous to science education. Critical realism is able to redeem and strengthen the positive aspects of constructivism and more effectively deploy them from within a realist framework.

The question then has to be asked: Is it possible to have constructivist pedagogy with constructivist epistemology? That is, is it possible to “disentangle metaphysics from pedagogy” (Grandy, 1997)? Davson-Galle (1999) argues that the good elements of constructivist pedagogy can and should be separated from the dubious philosophical underpinnings of constructivism. In response to Niaz et al. (2003), who contend that constructivist pedagogy without constructivist epistemology is just learner centred pedagogy, the next section illustrates how the constructivist pedagogy found in science education may be viewed as distinct, albeit theoretically undernourished.

Pedagogy as Distinct but Atheoretical

By far the most common perception about constructivist pedagogy is that it is merely learner centred or some form of discovery learning, commonly with a reference to Dewey. At the base level, constructivist learning theory has to be more than just discovery learning as it has a specific focus, namely science education (Gunstone, 2000). Science educators have developed a pedagogy that reflects the specific research findings in the field of science education. Several examples of this type of constructivist pedagogy are now presented.

The first example is given by Treagust (1995). For Treagust, constructivist pedagogy starts with the premise that students are actively engaged in constructing their own knowledge by using existing knowledge, hence they "are able to view the world in ways that are coherent and useful to them" (p. 44-45). The ideas students have may differ significantly from the accepted ideas of science, and student ideas are "surprisingly resistant to change" through instruction. Applied to pedagogy, constructivism attempts to find approaches that will alter students' misconceptions. Treagust believes this is best achieved using analogies. After the concept to be learnt is introduced, students examine the analogous situation and compare it to the concept being learnt, resulting in conclusions about the target concept. Finally, the students reflect on the analogy and target concept and where it breaks down. This process is called *focus, action* and *reflection.*

The process that Treagust has described does not rely on a specific epistemology. The starting premise that students are actively engaged in developing their own understandings can be accepted by both realist and anti-realist philosophers. The notion that students develop knowledge that is coherent and useful to them cannot be contested. Allowing students free reign to develop ideas that are useful to them depends on the view of epistemology and ontology that is held. For instance, both solipsists and postmodernists may be willing to accept a plurality of ideas. However, there is agreement among science educators that students need to develop understandings that match the scientific viewpoint. The reasons for this are rarely, if ever, stated. A critical realist approach, through its judgmental rationality, considers that students need to be shown why one idea is to be preferred over others. Critical realism thus explains why science educators are correct to be selective and preferential about the content taught in the science classroom.

The second example is given by Vance and Miller (1995). Vance and Miller are two high school teachers who adopted constructivist pedagogy to improve the learning and teaching of science in their classrooms. Vance and Miller's constructivist classroom starts with the students' preexisting ideas and works from their ideas. Vance and Miller prepare materials for the first lesson to find out what ideas students possess. They then develop the rest of the unit targeting the misconceptions of students. To adopt this approach, a teacher has to be very confident and competent in a subject area as the students' ideas guide the direction the teacher will take. The overview of a constructivist unit follows a sequence of eliciting student views, restructuring student views in order to address student conceptions which are scientifically incorrect. Questioning techniques are a good way to address misconceptions.

Vance and Miller (1995) detail the advantages and disadvantages of the constructivist pedagogy. The advantages are that weaker students are more involved, meta-cognition is enhanced, communication skills are better developed, teamwork is encouraged, students respect the freedom given to choose directions, classrooms are more frequently on task, teachers regain interest in teaching, and there is a higher enjoyment for students. The disadvantages are that extended absence can make it difficult for a student to catch up, constructivist pedagogy does not suit highly structured teachers, the process can be very time-consuming, classes are noisier, teachers have to think on their feet, and sometimes it can be difficult to decide on the direction to take after initial student ideas are uncovered. Gunstone (1995) notes a further problem of students having preconceived ideas about how schools should run and what constitutes learning. Constructivist teaching can be resisted by students for these and other reasons. Niaz et al. (2003) question the wisdom of eliciting student responses if the only purpose is to destroy them. The process of elicitation may well serve to reinforce these ideas. Nevertheless, the advantages of constructivist pedagogy are clearly numerous and many of the disadvantages may be overcome through a process of refinement. For example, students will soon become used to a constructivist classroom.

The constructivist pedagogy in science education may be summarised as eliciting student responses and then seeking to address student misconceptions. Scott et al. (1994) state:

> There is no unique method or instructional route for teaching a particular topic from a constructivist perspective. We would argue, however, that a central focus of planning such instruction should be in comparing the students and the accepted science point of view, thus providing insights to the intellectual demand, for the learner, of developing the science view. (p. 218)

Thus, although multiple approaches may be employed, comparing student ideas to the accepted ideas of science is a feature of constructivist pedagogy. Although Scott et al. offer no reason as to why multiple approaches may be used, critical realism can address this issue, which is explained more fully in Chapter 4. In brief, the judgmental rationality of critical realism asserts that multiple approaches may be used but not all will be beneficial.

Given that the pedagogy espoused by constructivist science educators lacks a clear philosophy, why is it that constructivism is so prevalent? Hawkins (1994) addresses this question when he details three sources of constructivism; philosophical, on which Kant, von Glasersfeld and Dewey are strong influences, "the experience of reflective practitioners", and the "professional research community" (p. 9) which attempts to combine the first two sources. It has already been established that there are problems with philosophical constructivism, especially for realist scientists. It has also been shown the positive results of reflective practitioners, namely constructivist pedagogy. This pedagogy is essentially a description of what has been found to work. Such a pragmatic approach has merits, but it is unable to offer a rigorous explanation of what is occurring. In critical realist terms, it does not answer the transcendental question of why this is the case and, consequently, it is poorly positioned to solve new and existing problems within the practice of science teaching.

The fact that Hawkins believes the professional research community is trying to combine both philosophical and practical constructivism highlights the absence of an explicit theory for science education. In a way this is what Niaz et al. (2003) are referring to when they claim that science education does not have a paradigm. From the analysis above, attempts to combine philosophical constructivism will not work as (i) philosophical constructivism does not correctly reflect the nature of science itself, nor the philosophy employed by scientists; and (ii) philosophical constructivism is unable, through the absence of a judgemental rationality, to explain why one theory is to be preferred over another theory. On the one hand, it is true that constructivism may explain the processes by which theories are accepted, namely psychological and sociological processes. On the other hand, it is unable to explain the cause of why these theories are to be preferred. Critical realism, through its under-labouring role and its attention to both the natural and social sciences, is able to better serve the needs of science education.

Conclusion

This chapter has explored constructivism in the field of science education. Science education practitioners who have no clear explicit philosophical commitment, nor any wish to address philosophical issues, may practice a workable pedagogy without the need for any philosophical commitment on their part. Critical realism is able to provide a relevant theoretical framework that can support the development of this pedagogy and further clarify and solve new and existing problems. The next chapter addresses critical realism in science education.

CHAPTER 4

CRITICAL REALISM IN SCIENCE EDUCATION

This chapter moves beyond constructivism in science education by exploring the praxeological implications of critical realism. The current status of critical realism in science education is described and used as a platform to posit an elementary or preliminary explanatory framework for science education. The framework is preliminary because critical realism in science education is at an early or incipient phase, and the literature is rather limited in this area of investigation. A chapter overview is presented in Figure 4.1 to provide the reader with a visual guide to the interrelated components found in this chapter.

The Current Status of Critical Realism in Science Education

Critical realism has not featured prominently in science education. This is hardly surprising as critical realism has not featured prominently in the wider field of education (Shipway, 2002). However, there are a several examples of explicit critical realist thought in science education (Ogborn, 1995). This situation is being addressed in education by such authors as Maton (2001), who calls for more research in critical realism and education, and Moore (2000), who is covertly uncovering realist underpinnings in education. For the purposes of this thesis, an overt critical realism is one in which a reference is made, usually a citation, to a key figure in critical realism, such as Bhaskar, Collier, or, in the case of ThCR, figures such as Polkinghorne, Barbour, and

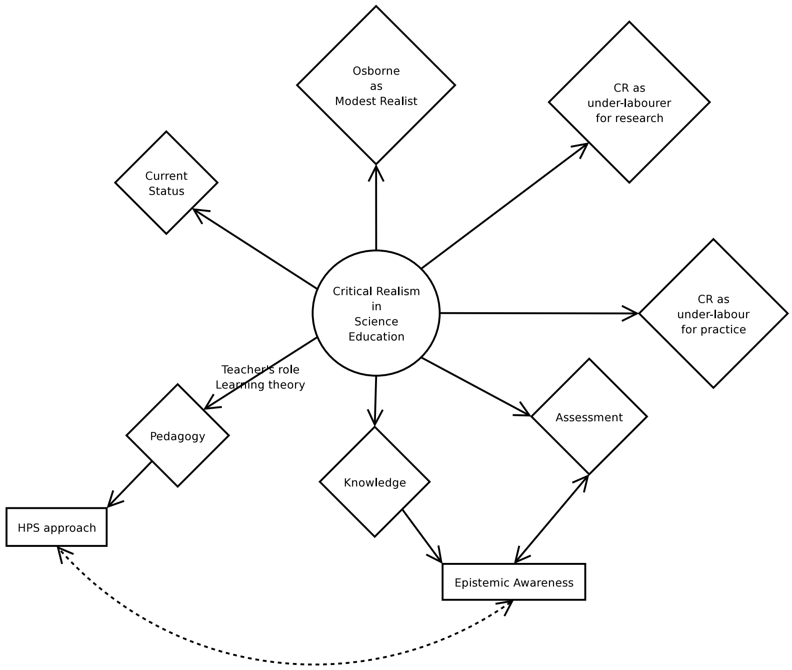

Figure 4.1: Chapter four diagrammatic overview

McGrath[1]. Two representative examples of high profile science education researchers who make explicit reference to critical realism are now given, Matthews and Ogborn[2].

Michael Matthews is foundation editor of the journal *Science & Education* and an associate professor in the school of education studies at the University of New South Wales, and is a significant figure in the field of science education. Critical realism has influenced Matthews'

[1]It is very rare, although not unknown, for a reference to critical realism to be made that does not seem to have any connection to the critical realist communities discussed in this thesis. Such an example is Watts (1994). He actually uses the phrase "critical realism - constructivism views knowledge as transitory and provisional. Knowledge of the world is constructed on the basis of the constraining influences of the nature of phenomena, personal context, language, predisposition, etc., and judged by such criteria as utility, plausibility and fruitfulness" (p. 52).

Another example is Taylor (2004) who refers to a "new critical realism" while defending radical constructivism.

[2]A few more explicit references to CR have been found:

(i) Cobern and Loving (2001), refer to Polkinghorne, and feature a dialogue between a critical realist and a "post-modern multiculturalist" in which the postmodernist insists that there is no way of determining whether knowledge is approximating reality yet concedes that it is highly unlikely that knowledge is diverging from a representation of reality.

(ii) Longbottom and Butler (1999) make positive reference to Bhaskar's social ontology.

(iii) Julian Cross (2001) completed a masters thesis in science education that made extensive use of Bhaskar. His supervisor, Rod Fawns, presented a paper (Fawns, Arkoudis, & Healy, 1999) at the 1999 Australasian Science Education Research Association (ASERA) conference and Cross and Fawns (2000) presented a paper at the 2000 ASERA conference that used Bhaskar's critical realism.

thought. In *The Marxist Theory of Schooling* (1980) he cites Bhaskar (1978), and, in the preface, acknowledges Bhaskar as one from whom "I have learnt much" (p. x). In *Challenging NZ Science Education* (1995), he cites Bhaskar (1975)[3] as an opponent of anti-realism. Apart from the influence in thinking Bhaskar seems to have had (Matthews is rarely complementary of constructivism, and the journal he edits is a good source of anti-constructivist papers), it is difficult to find further references to Bhaskar in papers by Matthews, and in the journal *Science & Education*[4]. Though clearly some influence of critical realism is evident in Matthews' thought, it seems that critical realism is used for little more than critiquing constructivism. In other words, Bhaskar is invoked when needing to critique anti-realist sentiment, however, the use of critical realism as an under-labouring theoretical framework for science education has not been realised.

Likewise, Ogborn (1995) used Bhaskar to critique SSK in a similar manner to that discussed in the previous chapter. Jon Ogborn was highly influential in developing the A-level physics course in the UK. It is worth noting that CR has been noticed by some influential figures in science education, yet its potential has not been realised. One reason that CR may not have been used to its potential in science education is that it seems to be only used as a vehicle to critique constructivism. This chapter seeks to move beyond the adversarial use of critical realism. The next section engages with Osborne whose modest realism approaches that of critical realism[5].

Osborne as Modest Realist

The paper *Beyond Constructivism* (1996) had a seminal influence on this thesis, providing some of the first insights into the philosophical issues relating to constructivism. Osborne presents a case for a modest realism, which is similar in many ways to critical realism, showing how realist descriptions of science education can improve pedagogy. Thus, Osborne is moving

[3]The fact that Matthews references the first edition of Bhaskar in his later book is a point of interest.

[4]Ogborn (1997) is a notable exception.

[5]Interestingly, Osborne references articles by Ogborn, and Osborne and Ogborn both spent time together at Kings College London (Ogborn did his PhD in 1994 at Kings College). It seems likely that Osborne may have been aware of critical realism.

towards critical realism for its praxeological implications in the classroom.

Epistemology in Science Education

Osborne argues that teachers and students need to be taught epistemology to aid understanding of why scientists' claims can be deemed to be rational. Osborne (1996) affirms the work of "Hacking [(1983)] and Harré [(1986)] [who] both present a clear argument for a realist epistemology based on an objective ontology" (p. 72). This statement reflects the critical realist tenet of epistemology modelling ontology. Consequently, Osborne believes that science takes its place in the school curriculum because it offers distinctive and preferential claims about some aspect of reality, namely the natural world. By teaching epistemology, students may gain an understanding of *why* the description of the natural world given by science is to be preferred over other descriptions.

Epistemic Humility

Osborne shares the epistemic humility found in critical realism: "this realist position is epistemologically modest and does not make 'incorrigible existential claims' about reality" (p. 70). Hence, Osborne is not a naïve realist and freely admits the provisionality of scientific knowledge. Epistemic humility is a desirable feature that has been identified by science educators and is in consonance with critical realism.

Judgmental Rationality

Osborne is committed to the judgmental rationality of science. Although he acknowledges scientific knowledge is problematic, he shares the belief held by critical realists that rational scientific knowledge is the best knowledge available and is the most likely representation of an objective reality. For instance, Osborne (1996) notes that "such knowledge is incomplete, curtailed, and limited but it grows through the creative efforts of individuals who continually strive to formulate new hypotheses about its nature and test these ideas experimentally" (p. 68). He also notes that "scientists' confidence in the objectivity of their descriptions is founded on the consensus of practice and ideas that emerge as the fruits of their work and actions on the world" (p. 68). It is evident that Osborne espouses realist ontology, recognises the problematic nature of scientific knowledge, and is committed to judgemental rationality. Osborne, then, is well positioned to critique the relativism of some science educators.

Osborne critiques Tobin, a noted radical constructivist in science education who argues that knowledge need only to fit with experience:

> First, it [radical constructivism] attaches itself to the bivalence principle, knowledge is either true or false, and since we can never know absolute truth, all knowledge is only subjective, provisional and uncertain. For the radical constructivist, there is no halfway house, no asymptotic approach to any zenith of human understanding and no admission that what we know improves and increases. The "unattainable best is used to drive out the attainable better" (Ogborn, 1994), and instead we are simply abandoned on the ocean of experience condemned to search for knowledge that is "viable". (Osborne, 1996, p. 57)

Essentially Osborne is pointing out that radical constructivism rejects a modest realist conception of truth which recognises the provisionality of scientific knowledge, yet is willing to reside in a "halfway house". When applied to science education, Osborne's modest realism suggests that students need to gain an understanding of how science distinguishes between theories:

> One of these is an understanding of how the processes deployed by scientists ensure their reliability and validity of their knowledge. Thus, concepts of fair testing, the identification and control of variables, the generation of sound hypotheses, the recognition and measurement of sources of error, the criteria by which any theory is distinguished from another, repetition of experimental determination, and the use of

> averaging are all essential ideas that enable scientific knowledge to be distinguished from pseudo-science. (Osborne, 1996, p. 56)

Critical realism's judgmental rationality provides a fitting framework for this praxeological application to science education.

Transitive and Intransitive Domains

Osborne does not explicate the need for the transitive and intransitive domains, yet he implicitly recognises their existence:

> Basically the confusion that occurs here [talking about Driver] is to conflate ideas and objects, that is, to fail to discriminate between the objects of the discourse with the statements of the discourse. The two are not the same, one exists and can be experienced, often with the aid of instrumentation, the other is a socially negotiated construct. (Osborne, 1996, p. 61)

And:

> Referential relations and our descriptive vocabulary can be revised but the basic ontological sketch is not in question. For instance, the heart and the circulatory system existed before Harvey first described them in 1628. (Osborne, 1996, p. 71)

Critical realism agrees with Osborne's observation that knowledge is based on an underlying reality. However, critical realism moves beyond descriptions of scientific understanding by providing further explanatory power to science education. Critical realism appropriates the ability of ideas to move from the transitive domain into the intransitive domain, and recognises how transitive ideas about intransitive phenomena can move into the intransitive domain as they *cause* the ideas to be taught in a particular way.

Stratified Reality

A departure from critical realist conceptions of reality is Osborne's use of Harré's *triadic theory of science*, which was introduced in Chapter 2. Osborne applies Harré's realism to pedagogy, in particular to the teaching of energy. Osborne argues that, since much of science occurs at Harré's realm three, there is a tendency to forget that realm one and realm two objects form the basis of speculation. Osborne considers as problematic, attempts to move the concept of energy from realm three to realm one, that is, attempts to treat energy as an entity capable of being directly experienced rather than a purely mathematical abstraction. Using this line of argument, it follows that energy should not be taught until students possess the cognitive ability to perform the requisite abstractions and possess the mathematical skills to treat these abstractions. Consequently, this approach implies that elementary science education should confine itself to realm one objects that are clearly able to be experienced. Middle science education is then able to examine realm two objects using, for example, experimental apparatus. Finally, concepts which are deemed to be mathematical abstractions (realm three), such as energy, are confined to higher levels of science education.

In contrast, Bhaskar's stratified ontology views the mathematical abstractions of the concept of energy as residing in the domain of the actual (See Figure 2.1 on page 14). These abstractions are based on some causal property that resides in the domain of the real. We experience these abstractions of energy in the domain of the empirical as, by way of example, waves at the beach, the shock from an electric fence, or the lack of energy when food has not been eaten recently. Although the approach commended by Osborne suggests energy should be precluded from early science curriculum, Bhaskar's ontology indicates that students should be given rich energy experiences from which to build an understanding of the subsequent mathematical abstraction in higher years. From a praxeological viewpoint, critical realism envisages a curriculum sequence that provides a rich experiential and conceptual learning environment for elementary science students, which then may be built on throughout the higher levels of schooling.

Critical realism provides a robust stratified ontology and a viable theoretical framework with greater explanatory power than the theoretically impoverished constructivist (with its disjoint philosophical referents) and postmodernist (often little more than rhetorical textual analysis) approaches. Constructivist approaches show what should be done, for example activity based learning to counter student misconceptions, but CR is better able to explain why rich experiential learning and conceptual learning should occur in classrooms. These insights constitute a significant and tangible example of how critical realism can contribute positive explanations and support to the field of science education.

Developing Applications of Critical Realism in Science Education

This section now develops applications of critical realism in science education to help address the rather limited use of critical realism by science education researchers and practitioners. This development is done with a view to improving praxeology in the field of science education.

Critical Realism as a Philosophy for Science Education Researchers

Science education as a field has no dominant methodological preference, rather, selection of methodology depends on the disciplinary framework and the problem that is being investigated (Keeves, 1998). Keeves acknowledges epistemology as being important in methodology. As in the wider field of education, science education has been dominated by research methodologies that are positivist in origin, without serious reflection on the theoretical assumptions inherent in these methodologies (Maton, 2005).

More recently, critical methodologies have been used in science education. Kincheloe (1998), writing in the *Handbook of Science Education*, describes critical research as (i) postpositivist, (ii) reflexively aware of value commitments, (iii) making explicit inherent political and social practices, (iv) concerned with emancipation, and (v) praxeological. These critical methodologies are primarily concerned with improving the world through emancipation. However, critical methodologies rarely have a realist ontology, and indeed, often consider realist ontology to be unnecessary. Critical realism appropriates all of the strengths of critical methodologies, yet retains an ontology. This retention of an ontology is important for science educators who usually have a background in the natural sciences where scientific realism is the dominant position (Boyd, 1984; Leplin, 1997). It should be noted that the *critical* aspect of critical realism is maintained as exemplified in point (iii) when Brown (2005), a critical realist curriculum theorist who is concerned about science education, acknowledges the sexist teacher attitudes, misconceptions that students develop about science, and other influences that form part of the hidden curriculum. In sum, the application of critical realism to science education research is an informed choice that provides the strengths of epistemic awareness, realist ontology, and critical research. A current example of the application of these strengths is the critical realist guided research of Christensen (2005).

As part of her doctoral studies, Christensen (2005) currently is investigating young peoples' accounts of what she terms uncertain science or contested science. Specifically, Christensen is investigating how young people (aged 18-26 years) respond to conflicting media reports about the reported health risks of using mobile phones. Critical realism was used to guide methodology selection and interpretation[6]. The selection of a critical realist methodology resolves a dilemma faced by many science education researchers, including Christensen. Christensen trained as a biochemist, and, like many in the sciences does "subscribe to a realist ontology" (p. 3). Most science education researchers trained initially in the natural sciences. When these researchers move to science education (a social science), they encounter philosophical issues for which they are not prepared. Christensen comments on this state of affairs in the following way:

[6]The methodology involved group interviews with seven groups of young people and follow-up interviews with Christensen. Some groups had a science training while others did not. The young people were shown a video containing a news report with conflicting reports of the risks of mobile phones. A semi-structured interview followed. In critical realist terms, the responses of the participants were interpreted in terms of "*causal tendencies* and *mechanisms*". The analytic tool was discourse analysis.

> Surprisingly, most science education researchers use qualitative methodologies, thus they appear to accept interpretive approaches, but they rarely engage in theoretical discussion which might clarify their positions. Much language and discourse in this field appears to be interpreted unproblematically and atheoretically, with little reference to issues of ontology or epistemology. Thus the science education literature does not initiate a novice researcher into any explicit theoretical territory. (Christensen, 2005, p. 3)

Christensen chose IACR because it offered a sophisticated philosophy of science, that is, more sophisticated philosophy "than is frequently applied in science education research" (p. 3). Critical realism provided a realist account of social science that was non-positivistic.

In summary, the paper by Christensen constitutes an example of the use of explicit critical realism in the field of science education. Christensen's study investigates a common concern in science education, namely student misconceptions, from a critical realist perspective. Science education researchers should consider adopting a similar approach because it is consistent with natural science and science education.

Critical Realism as a Philosophy for Science Education Practitioners

This section now engages with a critical realist orientation to education with a praxeological focus on science education. Brown's (2005) paper is used as a basis for engaging three key areas of education, namely those of knowledge, pedagogy, and assessment[7]. Before engaging these three areas, however, brief mention should be made of critical realist ontology in schools, as ontology has been dealt with fairly comprehensively in this thesis. Brown notes that "schools and classes are open systems despite assumptions and efforts to the contrary" and "ontology is

[7] Gordon Brown is a curriculum theorist at the University of Wollongong with a science education background whose doctoral thesis (1999) made use of critical realism in science education. Brown's paper does not directly engage with science education, but is adjunct to the concerns of science education. Brown's science education background may be seen in many of the examples that he gives.

logically prior to knowledge" (p. 6). As previously noted, critical realism considers knowledge to be based on ontology which provides a more authentic framework for practitioners in the field of science education. The critical realist view of the ontology of the classroom recognises that it is not an insular, closed environment. It is, rather, a dynamic, open environment in and on which many causes (some unrecognised) act.

Knowledge

Critical realism views knowledge as subject to change, but insists certain knowledges may be preferred. Given the centrality of epistemology to critical realism, this section moves towards a view of epistemic awareness in the science classroom. Brown summarises a critical realist view of knowledge in the context of schools as follows:

> Knowledge emerges from, or is given in, the ontology of the total learning environment of the student. Knowledge is dialectical; an interplay of individual and social constructions of meaning which are constrained by, or given in, natural and social realities. [Critical realism] sees knowledge as constructed through social interaction and individual cognition (and therefore contextually located and contingent or transitive), but there are rational criteria for making judgements between competing theories and ideas. That is, there is epistemic relativism but judgemental rationality. Not all claims to knowledge provide an equal grasp on reality. Thus there are grounds for specifying the knowledge content of the curriculum. One criterion must be a working knowledge of the Cultural System: propositions of the theories, beliefs, values and arguments of the culture. Knowledge can be emancipatory when it is of causal mechanisms and multiple dimensions. (Brown, 2005, p. 6)

How may this critical realist orientation to knowledge be applied to science education? Critical realism provides justification for science educators' preference for particular descriptions of the natural world, at the same time cautioning against epistemic dogmatism, and further provides a realist framework for understanding changing views of the natural world. It is noted that many current science syllabi in Australia exhibit these characteristics. Namely, science educators have indicated views of the natural world that are deemed to be preferential ways for students to view the natural world, yet contain sometimes lengthy sections outlining the provisional and contingent nature of science. Critical realism provides a sound theoretical framework that justifies and explains existing practice from a realist perspective.

The preferential selection of science content by curriculum designers and individual teachers, for example, is evidenced in the topical and lively discussions regarding the inclusion of the Intelligent Design hypothesis in the science classroom. The critical realist view of knowledge, in particular the insights of ThCR who specialise in questions relating to science and theology, can provide a basis for an intelligent engagement concerning this issue in the science classroom. ThCR, through its a posteriori engagement, considers natural science to be an engagement with the natural world, and theology an engagement with the supernatural world, both of which may be unified for theistic philosophers as they constitute different aspects of the same reality. It is noted that authors such as McGrath (2002) who deal extensively with science and religion do not acknowledge, let alone comment on, the intelligent design debate. For authors such as McGrath, science works as a maidservant to theology, enabling a greater unified understanding of theology. Christian educators may be able to use McGrath's viewpoint that states, since God has revealed Himself in many ways, natural scientific enquiry is the preferred method to explore God's revelation through the natural world. Other types of revelation, such as the Bible, spiritual experience, and social interaction, require different methods for understanding that revelation. Teachers, when confronted with opposition to natural scientific explanations of human origins, may say something like; "there is scientific knowledge and theological knowledge and science is only one way of knowing the world", "they can co-exist", and "scientific theories are tentative and the big bang is the current picture" (Nott & Wellington, 1998, p. 583). An example of the positive use of ThCR to engage science and religion in a secular science classroom has been given by Shipman, Brickhouse, and Dagher (2002).

Shipman et al. (2002) report on the introduction of a science and religion component to a general multi-disciplinary astronomy course in a secular university. Shipman et al. take their lead from a number of authors such as McGrath and Polkinghorne. One of the activities conducted in the class was an assignment question that "asked them to advise NASA whether research on the origin of life, or the ultimate origin of the Universe, was a legitimate NASA project or was in the realm of religion or philosophy" (p. 530). It is noteworthy that most of the students sought ways to integrate science and religion, and none of the students insisted on a confrontational approach to science and religion. Shipman et al. considered the trial to be successful.

In summary, it is emphasised that critical realism seems well able to provide a framework for intelligent engagement with these issues. Further, it is a refreshing change from such questions as whether or not radical constructivism permits the teaching of creationism (Kelly, 1997).

Pedagogy

Critical realism provides a realist foundation to examine pedagogy and to support pedagogy. This section comments on selected components of pedagogy from a critical realist perspective, and proceeds to develop an incipient view of epistemic awareness. The components are student learning role, learning theory, and the teacher's role. Student learning role and learning theory are combined for the purposes of exposition, and Brown (2005) is used as being representative of a critical realist view of pedagogy. Brown describes, from a critical realist viewpoint, the learning role of a student as follows:

> An active constructor of knowledge whose own skills, belief system and previous knowledge are causes that contribute to engagement with learning opportunities in the school and wider society. Students have different preferred learning styles or modes. (Brown, 2005, p. 7)

Brown describes learning theory in the following way:

> Realist-constructivist-interactionist model of the learner as a causal agent whose reasons are causes. Students construct meanings through psychological and sociological processes; they are part of a rich and stratified reality which is more than just the classroom. All strategies and claims to knowledge do not lead to an equal grasp of reality. (Brown, 2005, p. 7)

In the context of science education, these insights have several key implications. First, CR shares the belief of constructivism that students are "active constructors of knowledge", but unlike constructivism, CR considers the prior understanding of students to be causally efficacious. Critical realism considers these prior understandings may emanate from the "rich" reality beyond that of the classroom. Second, students have multiple preferred learning styles or modes, applications of which are currently being explored in the science education literature (e.g., Prain & Waldrip, 2003). Since the causes of student misconceptions often originate from outside the classroom, teachers need to identify these causes in order to alter these misconceptions. Brown's description of a critical realist view of the role of the teacher follows:

> Like all other actors in education, teachers are causal agents. The teacher's overall role is to be the agent in the students' experience whose primary concern is causing student learning. The teacher's own reasons, knowledge, skills and belief system are causes of teacher action and judgement, which in turn are contributing causes of student learning. Because classes are partly open systems, teachers are not the only causes of student learning: other mechanisms also operate and cause a mixture of effects. Thus part of the teacher's role will be to monitor student progress as events, postulate likely causal mechanisms and act to address those mechanisms. Teacher roles may vary for and between teachers, depending on their professional and collaborative decisions about the most desired learning outcomes. The teacher

> is an adaptive professional who is able to select from a variety of modes of teaching and interacting with students, colleagues and community. All strategies do not lead to an equal grasp of reality. (Brown, 2005, p. 8)

In contrast to the tendency of constructivist views of the classroom to relegate teachers to the role of a facilitator or project director, critical realism views the teacher as a causal agent whose role is to cause student learning by employing strategies of varying effect to alter and develop student conceptions. From a critical realist perspective, teachers need to possess deep knowledge and broad ranging skills grounded in science to be effective teachers of science. An approach to teaching science which follows the approach of constructivist pedagogy as outlined in Chapter 3 is now described. This approach may be causally effective in remedying student misconceptions and developing epistemic awareness among students. First, though, some cautionary remarks concerning overextending goals for epistemic awareness are offered.

Teaching students about the epistemology or nature of science is a laudable goal (Osborne, 1996). Educators, however, need to exercise restraint when setting goals for the teaching of epistemology (Matthews, 1998). Matthews warns of the dangers of philosophical indoctrination when teaching epistemology to students. In regard to philosophy in general, Matthews further states that "it is unrealistic to expect students or prospective teachers to become competent historians, sociologists, or philosophers of science" (p. 168). Matthews believes, correctly, that students first need to learn to ask elementary questions about knowledge, such as clarifying definitions and questions of how does one know. Such elementary questions need to be asked before developing more complex philosophical reasoning. Finally, "modesty does not entail vapid fence sitting, but it does entail the recognition that there are usually two, if not more, sides to most serious intellectual questions" (p. 170). With these considerations in mind, an approach to science education that involves teaching from the history and philosophy of science (HPS) approach is now introduced as a means to incorporate a critical realist approach to modestly (in the critical realist sense of the term) teach epistemology.

The constructivist pedagogy described in Chapter 3 featured the important initial step of eliciting students' prior misconceptions. A growing body of research indicates that the misconceptions of students often mirror early scientists' views of the world (de Berg, 1997; Bar & Zinn, 1998; Gauld, 1998; Seroglou, Koumaras, & Tselfes 1998; Villani & Arruda, 1998). It is reasoned that "the similarity between the ideas of young people today and those of early scientists suggests that a study of historical change might be a fruitful source of information for improving the teaching of scientific concepts" (Gauld, 1998, p. 7). Thus, after student ideas have been elicited, the HPS approach to pedagogy suggests that student misconceptions, at least in part, may be overcome by following the historical development of scientific ideas and experiments that have led to the current understanding of science.

This approach contains many aspects that a critical realist view of science education deems to be desirable. The HPS approach exemplifies (i) the demonstration of epistemological fallibility as students are shown clearly how ideas have been subject to change throughout history, (ii) the development of epistemic awareness by demonstrating *how* scientific knowledge is developed, and (iii) how the transitive and intransitive domains are included through changing ideas of science. Importantly, this model views teachers as causal agents who are responsible for guiding students through the historical development of a scientific idea. Finally, the historical development of a concept in science can be used as a guide for curriculum sequencing. As discussed under the heading *Stratified Reality* earlier in this chapter, early science learning should incorporate experientially rich activities that can form the basis of later engagements with the lower levels of the stratified reality of critical realism. Essentially, it is proposed that students should be exposed to, or undertake, the same types of activities that scientists themselves have undertaken in the development of a concept. Some assessment implications for science education practioners are now introduced as a result of a critical realist view.

Assessment

Assessment is an important component of any classroom and should not be overlooked. Assessment tasks, from a critical realist perspective, are viewed as causal mechanisms which are used in open systems. Brown explains this as follows:

> Assessment tasks and strategies are causal mechanisms used in open systems, and will therefore have multiple effects (e.g. ranking, diagnosis, control, motivation, demotivation). Therefore they are selected according to the explicit and negotiated goals judged to be likely from their causal effects. (Brown, 2005, pp. 8-9)

Critical realism provides a counter balance to the tendency of some science teachers to place undue confidence in the validity of their assessment tasks. Assessment of students occurs in the context of an open system and science educators cannot expect to find the same degree of certainty as may be found in closed systems, such as in the conduct of science experiments under controlled laboratory conditions.

It is important to consider several key assessment implications relating to epistemic awareness. There is no dispute that teaching students about the nature of science is important. Assessing, however, the efficacy of a strategy for teaching students about the nature of science has proven to be problematic. There is a long history of nature of science assessments (Rubba & Anderson, 1978; Cotham & Smith, 1981; Aikenhead & Ryan, 1992; Halloun & Hestenes, 1998). These assessments have been used to examine both student (Meyling, 1997; Tsai, 1998; Kichawen, Swain, & Monk, 2004) and teacher (Pomeroy, 1993; Mellado, 1997; Abd-El-Khalick, Bell, & Lederman, 1998; Nott & Wellington, 1998) understandings of the nature of science. Lederman, Wade, and Bell (1998) in their comprehensive review of the nature of science assessments, point out that many of the instruments used for assessment contain value laden interpretations or flawed methodologies. For example, Pomeroy (1993) actually argues that it is a good thing for elementary science teachers to undertake more non-science in-service programmes in preference to further science training. In fact, she even appears to believe that it is good for elementary science teachers to have little understanding of science, as, in her study, too much understanding of science was linked to traditional views of science, which, from her constructivist viewpoint, are not desirable. A realist science educator would not find Pomeroy's case compelling.

In summary, critical realism recognises assessments to be one of many causes in student learning and that assessments are used in open systems. The nature of science assessments mentioned may be able to be improved using the methodological insights of critical realism. Indeed, the assessment area may provide a rich source of research for future investigations. Further investigations are also needed to more fully understand the relationship between teacher epistemology and classroom practice (Alters, 1997; Tobin & McRobbie, 1997; Lederman et al., 1998).

Conclusion

Applications of critical realism in science education often have been limited to an adversarial use in the context of challenging anti-realist constructivism. The applications developed in this chapter move beyond the adversarial use of critical realism by demonstrating how critical realism may be used to support, enrich, and correct existing practice in science education. Several key findings are now summarised.

Critical realism, through its understanding of a vertically stratified reality, praxeologically supports a curriculum sequence that justifies and explains why a rich experiential and conceptual learning environment for elementary science students should be provided. The rich experiences provided in this learning environment may be viewed as providing the experiential basis to further explore the causes of experiences in later schooling.

Critical realism, as a philosophy, comments extensively on methodology. This interest in methodology and the ability of critical realism to under-labour scientific realism and modest realism in the social sciences, positions critical realism as a preferred theoretical framework for science education researchers.

In terms of classroom practice, critical realism views students as causal agents whose misconceptions are causes. The misconceptions often originate from outside the classroom. An approach has been suggested in this chapter that follows the historical development of a scientific concept. This approach is considered to be a fruitful means to correct student misconceptions, wherein the teacher acts as a causal agent by intentionally guiding students through the process of historical rediscovery.

It has also been shown how the critical realist view of knowledge provides a basis for an intelligent engagement with the interaction of science and theology. In particular, the insights of ThCR who specialise in questions relating to science and theology, are deemed to provide a substantive contribution towards an integrative view of science and theology. Critical realism, in this regard, is able to exercise its judgmental rationality and move beyond the relativism of some constructivist science educators who question the exclusion of material from the science classroom.

It is worth reiterating that critical realism provides a robust stratified ontology and a viable theoretical framework with greater explanatory power than the constructivist, postmodernist, and other similar approaches. A introductory critical realist framework with implications for science education is now developed in the following chapter.

CHAPTER 5

CONCLUSION

The purpose of this thesis was to provide an introductory investigation concerning the application of critical realism to science education. It intended to move beyond the impasse within constructivist science education, particularly of philosophical debates that fail to represent science education as a whole. Owing to the lack of a theoretical framework for practitioners, the current dominance of anti-realist positions in science education was treated as problematic. The thesis has explored selected current and potential uses of critical realism in an endeavour to move beyond the perceived inadequacies of constructivism as the current paradigm of science education. This chapter presents a summary of the thesis, followed by a proposed initial critical realist framework for science education, limitations, and then recommendations for future research.

Summary of Thesis

Chapter One briefly overviewed the background, purpose, and significance of this study. It further provided a working theoretical framework and described the methodology employed in the thesis.

In Chapter Two, the philosophy of critical realism was introduced. Two contemporary communities of critical realism were described, namely the International Association of Critical Realism and a community of "theological" critical realists. Selected core tenets as found in these two movements were outlined.

Constructivism in the field of science education was considered in Chapter 3. It was suggested that (i) those who advocate constructivism often do so by incorrectly attacking a naïve realist straw man and (ii) those who attack constructivism often target radical constructivism or the sociology of scientific knowledge (SSK) while ignoring the tacit philosophy of science education. The chapter concluded by presenting a preliminary case for the usefulness of constructivist pedagogy in science education, without the need for the philosophical components of constructivism.

The current status of critical realism in the field of science education was the focus of Chapter 4. It was noted that critical realism is able to provide a compelling justification for existing practices in science education from within a realist framework. Applications of critical realism in science education were developed for science education researchers and practitioners.

Towards a Critical Realist Framework for Science Education

Throughout the thesis, features of a critical realist framework applicable to science education have been enunciated in order to provide a preliminary explanatory framework for use in science education. A central core of this framework is the insistence that epistemology models ontology. The robust stratified ontology of critical realism features the strata of causes, events, and experiences, from which critical realism derives much of its explanatory power. Although critical realism acknowledges the transitory nature of ideas, its insistence on judgmental rationality ensures it does not descend into epistemic pluralism. As a consequence of these features, critical realism, in contrast to constructivism, is able to (i) provide a philosophy that correctly reflects the working epistemology of practising scientists, and (ii) explain the justificatory basis for preferential selection of theories in science.

When applied to science education, these features enable critical realism to position itself between the long-refuted naïve realist and the contemporary social and psychological constructivist accounts of science, both extremes being inadequate philosophies for science education. Science education practitioners are able to identify with critical realism, as critical realism provides a theoretical framework which explains and clarifies the “wishy washy” middle ground that encompasses much of science education today. In essence, the constructivist pedagogy of science education may be considered to be atheoretical. Critical realism is able to appropriate the strengths of, and soundly support, this pedagogy. The ability of critical realism to uncover causal mechanisms advantageously positions it to explain causally the current processes in science education, and also to solve new and existing problems within the practice of science teaching. Several praxeological implications emerging from this critical realist framework for science education are now outlined:

1. Judgmental rationality. Critical realism, while recognising the provisional and transitory nature of scientific knowledge and cautioning against epistemic dogmatism, affirms the rationality of preferential selection of theories. Consequently, science educators are justified in being selective and preferential about the inclusion of content in the science curriculum. Students also need to be shown the process by which science selects its theories.

2. Transitive and intransitive domains. Critical realism recognises how transitive ideas about intransitive causes can lead to intransitive causes in themselves. This insight establishes the link between scientific theory and pedagogical practice as the ideas in science are causally efficacious in the selection of a teaching approach.

3. Stratification of reality. The critical realist view of the stratification of reality suggests a curriculum sequence that emphasises rich experiential and conceptual learning in elementary science classrooms, which then provides a basis for the exploration of causal mechanisms in higher levels of schooling.

4. Causes. A critical realist examination of schools reveals several causes, two of the more

important being: (i) teachers are responsible for causing student learning, and (ii) students often have misconceptions resulting from causes outside of the classroom.

5. Open systems. The critical realist view of the ontology of the classroom recognises that it is not an insular, closed environment. It is, rather, a dynamic, open environment in and on which many causes (some unrecognised) act. Thus, processes such as student learning occur in the context of this rich open environment. Science teachers are cautioned against placing undue confidence in their assessments which also are used in open systems.

6. Relationship between other fields of knowledge. Critical realism considers that different fields of knowledge uncover aspects of the same reality. This insight positions critical realism, in particular ThCR, to develop an integrationist view of science and religion. Consequently, science educators are better able to benefit from the insights of critical realism when exploring the sensitive issues of science and religion in the classroom, particularly in the context of the perceived warfare between science and religion.

The approach to pedagogy that follows the historical development of a scientific concept contains many of the above features of a critical realist approach. Specifically, the HPS approach (i) highlights the rational selection of theories through history and how these theories have been subject to change; (ii) incorporates the demonstration of the transitive and intransitive domains as the changing ideas of science are featured; (iii) is able to suggest experiential activities from the history of science that have led to the current understanding of causal mechanisms; (iv) accepts that the teacher intentionally causes student learning by guiding them through the historical development of a concept; (v) recognises the complex social environment in which ideas were developed (or suppressed); and (vi) demonstrates the interplay between science and other fields, particularly that of religion.

In summary, critical realism not only critiques the anti-realist tendencies of many current constructivist theories, but, significantly, also provides a more robust and viable theoretical framework with greater explanatory powers for science education.

Limitations

A limitation imposed on the investigation was the difficulty of locating and obtaining relevant literature relating to critical realism in science education. It is expected that as interest in critical realism filters into the field of education, a corresponding increase in interest will be evidenced in the science education literature as well. Furthermore, there should be greater opportunity for access to relevant and current literature. In critical realist terms, it is hoped that this study will be one of many causal agents addressing this issue.

Recommendations

In developing the framework described in this thesis, several recommendations for future research have become evident. Several significant research areas are now identified.

Recommendations for critical realism research

1. There is an urgent need for an introductory guide to the philosophy of critical realism for the benefit of researchers and teachers wishing to use critical realism.

2. Adjunct to the above recommendation is the need for a guide to conduct empirical research from a critical realist perspective[1]. Further, there is a need for clear examples of how to apply critical realism to methodology in the context of empirical research. Through this guide, potential researchers will not have to engage in lengthy philosophical discussions prior to empirical work.

[1] The recent *SAGE Handbook of Qualitative Research* (Denzin & Lincoln, 2005) is critical of critical realism. MacLennan (2005) provides a detailed response to these criticisms.

Recommendations for science education research relating to critical realism

1. As noted in this thesis, though several key figures in science education may have been aware of critical realism, its potential was not realised. An investigation as to why critical realism was overlooked may be warranted.

2. Further exploration of the praxeological implications arising from the later dialectical forms of critical realism is needed for the field of science education.

3. The elementary engagement with Brown's model of curriculum in this study was deemed to be fruitful. A further sustained engagement with the components of his model that were not utilised in this investigation should yield further insights for science education.

4. The link between teacher epistemology and classroom practice needs to be further explored. Developing strategies for improving the link between teacher epistemology and classroom practice would also be a fruitful area of research. The results of this research would be of particular benefit to practitioners.

5. Teaching sequences based on the history and philosophy of science, particularly for junior and middle schools, should be developed and distributed.

Final Comments

To be true to the principles of critical realism as espoused in this investigation, this thesis necessarily has to apply these principles to itself. Namely, it exercises epistemic humility by not claiming to be the final or authoritative word. Further, the thesis is not a free construction. It has been constrained by the causal influences of time, the author's creativity, the supervisors' wisdom, and the requirements of writing in the current zeitgeist. Finally, it is hoped that this thesis will be causally efficacious in affecting change in the field of science education.

BIBLIOGRAPHY

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Make the unnatural natural. *Science Education*, *82*, 417–436.

Aikenhead, G. S., & Ryan, A. G. (1992). The development of a new instrument: "Views on science-technology-society" (VOSTS). *Science Education*, *76*(5), 477–491.

Alters, B. J. (1997). Whose nature of science? *Journal of Research in Science Teaching*, *34*(1), 39–55.

Archer, M., Sharp, R., Stones, R., & Woodiwiss, T. (1999). Critical realism and research methodology. *Alethia*, *2*(1), 12–16.

Australian Qualifications Framework (2002). *Doctoral degree*. Retrieved October 21, 2005, from http://www.aqf.edu/doctor.htm.

Bar, V., & Zinn, B. (1998). Similar frameworks of action-at-a-distance: Early scientists' and pupils' ideas. *Science & Education*, *7*, 471–491.

Barbour, I. G. (1966). *Issues in science and religion*. London: Prentice-Hall.

Barbour, I. G. (2000). *When science meets religion*. San Francisco: Harper.

Bhaskar, R. (1975). *A realist theory of science*. Leeds: Leeds Books.

Bhaskar, R. (1978). *A realist theory of science* (2nd Ed.). London: Harvester Press.

Bhaskar, R. (1989). *Reclaiming reality: A critical introduction to contemporary philosophy.* London: Verso.

Bhaskar, R. (1994). *Dialectic: The pulse of freedom*. London: Verso.

Bhaskar, R. (1998). *The possibility of naturalism* (3rd Ed.). London: Routledge.

Boyd, R. N. (1984). The current status of scientific realism. In J. Leplin (Ed.), *Scientific Realism* (pp. 41–82). Berkeley: University of California Press.

Brooks, M. G., & Brooks, J. G. (1999). The courage to be constructivist. *Educational Leadership*, *57*(3), 18–24.

Brown, G. (1999). *Towards a more authentic school science: Grounding school science in the metascientific literature*. Unpublished doctoral thesis, University of Wollongong, NSW, Australia.

Brown, G. (2005, July). *Towards the critical-realist school*. Paper presented at the 9th Annual Conference of the International Association for Critical Realism, Sydney, Australia.

Burbules, N. C. (2000). Moving beyond the impasse. In D. C. Phillips (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (pp. 308–330). Chicago: NSSE.

Carr, M., Barker, M., Bell, B., Biddulph, F., Jones, A., Kirkwood, V., Pearson, J., & Symington, D. (1994). The constructivist paradigm and some impications for science content and pedagogy. In P. J. Fensham, R. F. Gunstone, & R. T. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 147–160). London: The Falmer Press.

Christensen, C. (2005, July). *Waiting for certainty: young people's accounts of science-in-the-making*. Paper presented at the 9th Annual Conference of International Association for Critical Realism, Sydney, Australia.

Clements, D. (1997). (Mis?)Constructing constructivism. *Teaching Children Mathematics*, *4*, 198–200.

Cobern, W. W., & Loving, C. C. (2001). In defense of realism: It really is commonsense. Retrieved April 15, 2004, from http://www.wmich.edu/slcsp/slcsp162/realism_defended_slcsp162.pdf.

Collier, A. (1994). *Critical realism: An introduction to Roy Bhaskar's philosophy*. London: Verso.

Cotham, J. C., & Smith, E. L. (1981). Development and validation of the conceptions of scientific theories test. *Journal of Research in Science Teaching*, *18*(5), 387–396.

Cross, J., & Fawns, R. (2000, June). *Transformational model of social action, semiosis and purpose, an analysis of the science technology and society movement*. Paper presented at the 30th Annual Conference of the Australasian Science Education Research Association (ASERA), Rotura, New Zealand.

Cross, J. S. (2001). *Return to reality: A causal realist approach to re-construction in science teaching*. Unpublished master's thesis, University of Melbourne, Victoria, Australia.

Davson-Galle, P. (1999). Constructivism: 'A curate's egg'. *Educational Philosophy and Theory*, *31*(2), 205–219.

de Berg, K., & Greive, C. E. (1999). Understanding the siphon: An example of the development of pedagogical content knowledge using textbooks and the writings of early scientists. *Australian Science Teachers Journal*, *45*(4), 19–26.

de Berg, K. C. (1997). The development of the concept of work: A case where history can inform pedagogy. *Science & Education*, *6*, 511–527.

Denzin, N. K., & Lincoln, Y. S. (2005). *The SAGE handbook of qualitative research* (3rd Ed.). Thousand Oaks: SAGE.

Department of Education and Training (2003). *Quality teaching in NSW public schools*. Sydney: Author.

Driver, R. (1983). *The pupil as scientist?* Milton Keynes: Open University Press.

Driver, R. (1988). Theory into practice II: A constructivist approach to curriculum development. In P. Fensham (Ed.), *Development and Dilemmas in Science Education* (pp. 133–149). London: The Falmer Press.

Eisberg, R., & Resnick, R. (1985). *Quantum physics of atoms, moleculues, solids, nuclei, and particles* (2nd Ed.). New York: John Wiley & Sons.

Evans, D., & Kowanko, I. (2000). Literature reviews: Evolution of a research methodology. *Australian Journal of Advanced Nursing*, *18*(2), 33–38.

Fawns, R., Arkoudis, S., & Healy, G. (1999, July). *Signs, social ontology and critical realism in science education*. Paper presented at the 30th Annual Conference of the Australasian Science Education Research Association (ASERA), Rotorua, New Zealand.

Fensham, P. J., Gunstone, R. F., & White, R. T. (1994). *The content of science: A constructivist approach to its teaching and learning*. London: The Falmer Press.

Fraser, B. J., & Tobin, K. G. (Eds.) (1998). *International handbook of science education*. Dordrecht: Kluwer Academic Publishers.

Gauld, C. (1998). Solutions to the problem of impact in the 17th and 18th centuries and teaching Newton's Third Law today. *Science & Education*, *7*, 49–67.

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

Gil-Peréz, D., Guisásola, J., Moreno, A., Cachapuz, A., Pessoa de Carvalho, A. M., Martínez Torresgrose, J., Salinas, J., Valdés, P., González, E., Gené Duch, A., Dumas-Carré, A., Tricárico, H., & Gellego, R. (2002). Defending constructivism in science education. *Science & Education*, *11*, 557–571.

Good, R., & Shymansky, J. (2001). Nature-of-science literacy in benchmarks and standards: Post-modern/relativist or modern/realist? *Science & Education*, *10*, 173–185.

Grandy, R. E. (1997). Constructivisms and objectivity: Disentangling metaphysics from pedagogy. *Science & Education*, *6*, 43–53.

Gunstone, R. F. (1995). Constructivist learning and the teaching of science. In B. Hand & V. Prain (Eds.), *Teaching and learning in science: The constructivist classroom* (pp. 3–20). Sydney: Harcourt.

Gunstone, R. F. (2000). Constructivism and learning research in science education. In D. C. Phillips (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (pp. 254–280). Chicago: NSSE.

Hacking, I. (1983). *Representing and intervening*. Cambridge: Cambridge University Press.

Hacking, I. (1984). Experimentation and scientific realism. In J. Leplin (Ed.), *Scientific realism* (pp. 154–172). Berkeley: University of California Press.

Halloun, I., & Hestenes, D. (1998). Interpreting VASS dimensions and profiles for physics students. *Science & Education*, *7*, 553–577.

Hardy, M. D., & Taylor, P. C. (1997). Von Glasersfeld's radical constructivism: A critical review. *Science & Education*, *6*, 135–150.

Harré, R. (1986). *Varieties of realism: A rationale for the natural sciences.* Oxford: Basil Blackwell.

Hart, C. (1998). *Doing a literature review: Releasing the social science research imagination*. London: SAGE.

Hawkins, D. (1994). Part II. Constructivism: Some history. In P. J. Fensham, R. F. Gunstone, & R. T. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 9–13). London: The Falmer Press.

Howe, K. R., & Berv, J. (2000). Constructing constructivism, epistemological and pedagogical. In D. C. Phillips (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (pp. 19–40). Chicago: NSSE.

Jenkins, E. (2001). Science education as a field of research [Electronic version]. *Canadian Journal of Science, Mathematics & Technology Education*, *1*(1), 9–21.

Jenkins, E. W. (2000). Constructivism in school science education: Powerful model or the most dangerous intellectual tendency? *Science & Education*, *9*, 599–610.

Keeves, J. P. (1998). Methods and processes in research in science education. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 1127–1153). Dordrecht: Kluwer Academic Publishers.

Kelly, G. J. (1997). Research traditions in comparative context: A philosophical challenge to radical constructivism. *Science Education*, *81*, 355–375.

Kichawen, P., Swain, J., & Monk, M. (2004). Views on the philosophy of science among undergraduate science students and their tutors at the university of Papua New Guinea: Origins, progression, enculturation and destinations. *Research in Science & Technological Education*, *22*(1), 81–98.

Kincheloe, J. L. (1998). Critical research in science education. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 1191–1205). Dordrecht: Kluwer Academic Publishers.

Kragh, H. (1998). Social constructivism, the gospel of science, and the teaching of physics. *Science & Education*, *7*, 231–243.

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

Kuhn, T. S. (1970). *The structure of scientific revolutions* (2nd Ed.). Chicago: University of Chicago Press.

Kukla, A. (2000). *Social constructivism and the philosophy of science*. London: Routledge.

Latour, B. (1987). *Science in action: How to follow scientists and engineers through society*. Cambridge, MA: Harvard University Press.

Latour, B. (1992). One more turn after the social turn. In E. McMullin (Ed.), *The social dimensions of science* (pp. 272–294). Notre Dame, IN: University of Notre Dame Press.

Latour, B., & Woolgar, S. (1979). *Laboratory life: The social construction of scientific facts*. Los Angeles: SAGE.

Lederman, N. G., Wade, P. D., & Bell, R. L. (1998). Assessing the nature of science: What is the nature of our assessments? *Science and Education*, *7*, 595–615.

Leplin, J. (1984). *Scientific realism*. Berkeley: University of California Press.

Leplin, J. (1997). *A novel defense of scientific realism*. New York: Oxford University Press.

Longbottom, J. E., & Butler, P. H. (1999). Why teach science? Setting rational goals for science education. *Science Education*, *83*, 473–492.

Loving, C. C., & Cobern, W. W. (2000). Invoking Thomas Kuhn: What citation analysis reveals about science education. *Science & Education*, *9*, 187–206.

MacLennan, G. (2005, October). *CR according to the (2005) edition of the Sage handbook of qualitative research (Denzin and Lincoln)? [Msg 322].* Message posted to http://lists.econ.utah.edu/pipermail/critical-realism/2005-October/000322.html.

Maton, K. (2001). The critical and real need of educational research for critical realism [Review of the book *Realism and educational research: New perspectives and possibilities*]. *Journal of Critical Realism (Alethia)*, *4*(1), 56–59.

Maton, K. (2005, July). *What is to be done? Critical realism and the sociology of education.* Paper presented at the 9th Annual Conference of the International Association for Critical Realism, Sydney, Australia.

Matthews, M. (2004). Thomas Kuhn's impact on science education: What lessons can be learned? *Science Education*, *88*, 90–118.

Matthews, M. R. (1980). *The Marxist theory of schooling: A study of epistemology and education*. Brighton: Harvester Press.

Matthews, M. R. (1995). *Challenging NZ science education*. Palmerston North: The Dunmore Press.

Matthews, M. R. (1998). In defense of modest goals when teaching about the nature of science. *Journal of Research in Science Teaching*, *35*(2), 161–174.

Matthews, M. R. (2000a). Appraising constructivism in science education. In D. C. Phillips (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (pp. 161–192). Chicago: NSSE.

Matthews, M. R. (2000b). *Time for science education: How teaching the history and philosophy of pendulum motion can contribute to science literacy*. New York: Kluwer Academic.

McGrath, A. E. (2002). *A scientific theology volume one: Reality*. Edinburgh: T&T Clark.

Mellado, V. (1997). Preservice teachers' classroom practice and their conceptions of the nature of science. *Science & Education*, *6*, 331–354.

Meyling, H. (1997). How to change students' conceptions of the epistemology of science. *Science & Education*, *6*, 397–416.

Moltmann, J. (2003). *Science & wisdom*. Minneapolis: Fortress Press.

Moore, R. (2000). For knowledge: Tradition, progressivism and progress in education - reconstructing the curriculum debate. *Cambridge Journal of Education*, *30*(1), 17–36.

New, C., & Fleetwood, S. (2005, July). *Critical realism*. Paper presented at the pre-conference workshop of the 9th Annual Conference of the International Association for Critical Realism, Sydney, Australia.

Niaz, M., Abd-El-Khalick, F., Benarroch, A., Cardellini, L., Laburú, C. E., Marín, N., Montes, L. A., Nola, R., Orlik, Y., Scharmann, L. C., Tsai, C., & Tsaparlis, G. (2003). Constructivism: Defense or a continual critical appraisal - a response to Gil-Pérez et al. *Science & Education*, *12*, 787–797.

Nola, R. (2000). Saving Kuhn from the sociologists of science. *Science & Education*, *9*, 77–90.

Nola, R. (2003). 'Naked before reality; Skinless before the absolute': A critique of the inaccessibility of reality argument in constructivism. *Science & Education*, *12*, 131–166.

Nott, M., & Wellington, J. (1998). Elicting, interpreting and developing teachers' understandings of the nature of science. *Science & Education*, *7*, 579–594.

Ogborn, J. (1994). *Theoretical and empircal investigations of the nature of scientific and commonsense knowledge*. Unpublished doctoral thesis, King's College, London.

Ogborn, J. (1995). Recovering reality. *Studies in Science Education*, *25*, 3–38.

Ogborn, J. (1997). Constructivist metaphors of learning science. *Science & Education*, *6*, 121–133.

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

Outhwaite, W. (2001). In defence of social structure [Electronic version]. *Studies in Social and Political Thought*, *4*, 3–15.

Peacocke, A. (1993). *Theology for a scientific age: Being and becoming - natural, divine, and human*. Minneapolis: Fortress Press.

Peacocke, A. R. (1984). *Intimations of reality*. Notre Dame, Indiana: University of Notre Dame Press.

Phillips, D. C. (1995). The good, the bad, and the ugly: The many faces of constructivism. *Educational Researcher*, *24*(7), 5–12.

Phillips, D. C. (2000). *Constructivism in education: Opinions and second opinions on controversial issues*. Chicago: NSSE.

Polkinghorne, J. (1986). *One world: The interaction of science and theology*. Princeton, NJ: Princeton University Press.

Polkinghorne, J. (1989). *Science and providence: God's interaction with the world*. London: SPCK.

Polkinghorne, J. (1991). *Reason and reality: The relationship between science and theology*. London: SPCK.

Polkinghorne, J. (1995). *Serious talk: Science and religion in dialogue*. Valley Forge, Pennsylvania: Trinity Press International.

Polkinghorne, J. (1996). *The faith of a physicist: Reflections of a bottom-up thinker*. Minneapolis: Fortress Press.

Polkinghorne, J. C. (1984). *The quantum world*. Princeton, NJ: Princeton University Press.

Pomeroy, D. (1993). Implications of teachers' beliefs about the nature of science: Comparison of the beliefs of scientists, secondary science teachers, and elementary teachers. *Science Education*, *77*(3), 261–278.

Porpora, D. V. (2001). Do realists run regressions? In J. Lopez & G. Potter (Eds.), *After postmodernism: An introduction to critical realism* (pp. 260–266). London: The Athlone Press.

Prain, V., & Waldrip, B. G. (2003, July). *Using multi-modal representations of concepts in learning science*. Paper presented at the 34th Annual Conference of the Australasian Science Education Research Association (ASERA), Melbourne, Australia.

Reynaud, D. (2000). The bible and literary theory. *The Avondale Reader*, *2*(1).

Rubba, P. A., & Anderson, H. O. (1978). Development of an instrument to assess secondary school students' understanding of the nature of scientific knowledge. *Science Education*, *62*(4), 449–458.

Scott, P., Asoko, H., Driver, R., & Emberton, J. (1994). Working from children's ideas: Planning and teaching a chemistry topic from a constructivist perspective. In P. J. Fensham, R. F. Gunstone, & R. T. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 201–220). London: The Falmer Press.

Seroglou, F., Koumaras, P., & Tselfes, V. (1998). History of science and instructional design: The case of electromagnetism. *Science & Education*, *7*, 261–280.

Shipman, H. L., Brickhouse, N. W., Dagher, Z., & Letts IV, W. J. (2002). Changes in student views of religion and science in a college astronomy course. *Science Education*, *86*, 526–547.

Shipway, B. (2000). Critical realism and theological critical realism: Opportunites for dialogue? *Alethia*, *3*(2), 29–33.

Shipway, B. (2002). *Implications of a critical realist perspective in education*. Unpublished doctoral thesis, Southern Cross University, Lismore, NSW, Australia.

Simpson, T. L. (2002). Dare I oppose constructivist theory? *The Educational Forum*, *66*(4), 347–354.

Slezak, P. (2000). A critique of radical social constructivism. In D. C. Phillips (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (pp. 91–126). Chicago: NSSE.

Sokal, A., & Bricmont, J. (1998). *Fashionable nonsense: Postmodern intellectuals' abuse of science*. New York: Picador.

Suchting, W. A. (1992). Constructivism deconstructed. *Science & Education*, *1*, 223–254.

Taylor, P. C. (2004). [Review of the book *Radical constructivism in action: Building on the pioneering work of Ernst von Glasersfeld*]. *Science Education*, *88*(1), 149–152.

Tobin, K. (2000). Constructivism in science education: Moving on... In D. C. Phillips (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (pp. 227–253). Chicago: NSSE.

Tobin, K., & McRobbie, C. J. (1997). Beliefs about the nature of science and the enacted science curriculum. *Science & Education*, *6*, 355–371.

Treagust, D. F. (1995). Enhancing students' understanding of science using analogies. In B. Hand & V. Prain (Eds.), *Teaching and learning in science: The constructivist classroom* (pp. 44–62). Sydney: Harcourt.

Tsai, C. (1998). An analysis of scientific epistemological beliefs and learning orientations of Taiwanese eighth graders. *Science Education*, *82*, 473–489.

van Huyssteen, J. W. (1998). *Duet or duel? Theology and science in a postmodern world.* London: SCM Press.

Vance, K., & Miller, K. (1995). Setting up as constructivist teacher: Examples from a middle secondary ecology unit. In B. Hand & V. Prain (Eds.), *Teaching and learning in science: The constructivist classroom* (pp. 85–105). Sydney: Harcourt.

Verstegen, I. (2000). *Bhaskar and American critical realism.* Retrieved July 14, 2005, from the Critical Realism Archive Web site: http://www.raggedclaws.com/criticalrealism/archive/iverstegen_baacr.html.

Villani, A., & Arruda, S. M. (1998). Special theory of relativity, conceptual change, and history of science. *Science & Education*, *7*, 85–100.

von Glasersfeld, E. (1993). Questions and answers about radical constuctivism. In K. Tobin (Ed.), *The practice of constructivism in science education* (pp. 23–38). Washington, DC: AAAS Press.

Watts, M. (1994). Constructivism, re-constructivism and task-oriented problem solving. In P. J. Fensham, R. F. Gunstone, & R. T. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 39–58). London: The Falmer Press.

GLOSSARY OF TERMS

This glossary provides working definitions of terms as they are used and to be understood in this thesis. It is not meant, as such, to be either exhaustive or authoritative.

Anti-realism A philosophical position that either (i) asserts that a mind-independent reality (reality existing apart from the knower) does not exist or (ii) expresses doubt over the possibility of gaining access to a mind-independent reality.

Closed systems Systems where all the variables can be controlled.

Constructivism As a philosophy, the position that knowledge is constructed by various factors, usually some combination of psychological and social factors. Within education, it may refer to this philosophical assertion, but often refers to a pedagogy that places the emphasis on learner-centred activities.

Critical realism A philosophical position that acknowledges the provisional and transitory nature of knowledge, and insists that such knowledge represents an observer-independent reality.

Epistemic awareness The awareness of questions relating to epistemology. For example, how does one know.

Epistemic fallacy The tendency of post-Humean philosophers to reduce statements of knowledge to statements of being.

Epistemological relativism The recognition that knowledge is fallible and subject to change. This is also called *epistemic humility* or *epistemic modesty.* Epistemological relativism is a feature of anti-realist philosophies such as postmodernism, but is also recognised by critical realism.

Epistemology The branch of philosophy that deals with knowledge. Epistemology looks at the formation and limits of human knowledge. It asks questions such as: What are the limits of our knowledge? When used as an adjective, it may be taken to mean simply knowledge. For example, epistemic (or epistemological) humility means literally to be humble about knowledge. See also *ontology.*

Humean philosophy Philosophy that originated in the philosopher David Hume. It is characterised by the assertion that the only knowledge that may be considered derives from individual or collective experiences.

Intransitive domain A critical realist term for enduring objects and structures. See also *transitive domain*.

Judgmental rationality The critical realist recognition that, although knowledge is fallible, rational and preferential selection of a theory is possible.

Ontological realism A commitment to an objective mind-independent reality, that is, reality exists apart from an observer.

Ontology The branch of philosophy that deals with being. Ontology asks questions such as: What exists and what form does that existence take? For a critical realist, epistemology models ontology. See also *epistemology.*

Open systems Systems where all the variables cannot be controlled.

Paradigm The word paradigm indicates the values and theories that dictate how a particular academic community operates. The word came into use from the work of Thomas Kuhn (1970).

Pedagogy The science and art of classroom practice. It refers to the methods and approach used within the classroom that develop student learning.

Positivism A philosophical position that is characterised by direct or naïve realism, and the belief that quantification is possible in all situations. It is required for enquiry to be deemed scientific.

Postmodernism A philosophical position that is typically anti-realist and emphasises the provisional nature of knowledge.

Praxis Theory applied to action. The action then re-informs the theory which is able to improve the action and so the cycle continues.

Praxeological The adjectival form of *praxis.*

Psychological constructivism The philosophical position that knowledge construction is the result of predominantly psychological factors.

Scientific realism May be used in the sense of a realism that is scientific and a description of the realism used by scientists. The philosophy of science usually prefers the latter use.

Social constructivism The philosophical position that knowledge construction is the result of predominantly social factors.

Stratified reality The recognition by Bhaskar that reality is vertically stratified into levels that are emergent from, but not reducible to, the lower level.

Straw man The use of a set of arguments to irrelevantly represent a position that can be easily demolished. The arguments usually fail to properly recognise the actual position that should be subject to critique..

Transitive domain A critical realist term for ideas that are subject to change concerning objects in the *intransitive domain*.