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Beyond Constructivism: The Progressive Research Programme into Learning Science

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Abstract

Around 1980 research into learning in science underwent a significant shift, informed by consideration of the significance of studies exploring student ideas in a wide range of science topics. At this time a number of seminal studies appeared which reviewed the state of the field of research into learning and teaching in science, and set out a research agenda for future work. These studies, with a good many subsequent papers, have been described as constituting the basis of 'constructivism in science education' or the 'alternative conceptions movement'. Over the following two decades this 'movement' became considered as both the dominant paradigm and as a spent force in science education. The present review takes an intermediate view, and considers the seminal constructivist studies to have initiated a research programme, setting out both axiomatic commitments and fruitful directions for future work. This analysis makes it possible to evaluate the extent to which the initial research goals have been achieved, and also to see how a wide variety of work related to learning in science – some not normally considered to be 'constructivist' - can be seen to be part of the evolving agenda of the original programme. In particular, this analysis shows that shifts in the focus of research in the field can be understood as part of the expected progression within a progressive research programme - as accumulating empirical studies offer data to test key ideas, initial tenets come to seem commonplace, and new concepts are developed allowing research questions to be refined. The review highlights those areas where progress has been made, and offers heuristic guidance for researchers in the field.

Introduction

In 1994, *Studies in Science Education* published a review discussing 'the rise and fall of constructivism' (Solomon, 1994). This paper suggested that 'constructivism', which had become seen as the most significant perspective and indeed the dominant paradigm (cf. Kuhn 1996/1962), in science education for several decades, had outlived its usefulness, and that perhaps it was time for the science education community to 'move on'. Solomon's paper presented a strong case that constructivism was ceasing to act as a fertile stimulus to research, and worse, "If constructivism obscures other perspectives, either by its popularity or its blandness, that could be damaging" (Solomon, 1994: 17)

A decade further on, there is no clear evidence of a new 'paradigm' overthrowing the constructivist orthodoxy, despite problems with the notion of constructivism in science education that have been identified by many commentators (e.g., Matthews, 1992, 1993, 1994b; Millar, 1989; Solomon, 1993a; Johnstone, 2000; Scerri, 2003). Rather, studies into the learning of science continue to be informed by a range of perspectives (Erickson, 2000; Solomon, 2000 cf. Solomon, 1993b) some of which may be seen to develop from, or be consistent with, earlier 'constructivist' research to differing degrees.

The argument in this paper is that research into learning and teaching in science may be considered as an academic 'field', but one which is still pre-paradigmatic in the Kuhnian sense (just as it was characterised by Gilbert and Watts over twenty years ago in 1983). That is, there is not "a 'characteristic set of beliefs and preconceptions' … including instrumental, theoretical, and metaphysical commitments" (Kuhn, 1977: 294) "shared by [all] the members of a particular scientific community" (p.xix). Indeed there is such variety within published research, drawing upon a wide range of 'foundational' ideas (Matthews, 2004), that it could be argued that science education is an anarchic field, perhaps more closely aligned with the thinking of Feyerabend (1988) than Kuhn. Such a view would offer new researchers much flexibility in choosing ways to conceptualise their research foci, but provides little guidance in suggesting the most appropriate and potentially fruitful directions for enquiry. In this paper, however, it is suggested that whilst there are a variety of frames (Solomon, 1993b), or perspectives (Driver, Asoko, Leach, Mortimer & Scott, 1994), that guide research into learning science, a pre-paradigmatic field need not be a 'free-for-all'. Lakatos suggested that academic research fields were characterised by research programmes (RP), which offered heuristic guidance to researchers, and which sometimes, *but by no means always*, led to a dominant RP having the status of a Kuhnian paradigm.

It is argued in this review that Lakatos' approach is a useful way for identifying continuity in research traditions within a field such as science education. This review takes up a long-standing proposal (Gilbert & Swift, 1985) that research into learning in science that has been labelled as 'constructivism in science education' or the 'alternative conceptions movement', could be understood as a Lakatosian RP. It is argued here that

- key papers published around 1980 outlined a RP concerned with learning in science, based around 'constructivist' principles;
- the research agenda established then is still being addressed through much current research;
- considerable progress has been made in addressing some parts of the original research agenda, and shifts in the focus of studies may reflect the expected development in a progressive RP.

The Lakatosian model provides a means for demarcating a RP within the field, and for characterising it. Such characterisation is important because it provides a basis for considering and responding to key criticisms of constructivist work in science education and for 'taking stock' of the current state of the field. The key purpose of the present review is to evaluate what has been achieved within the RP, and to highlight fruitful avenues for further research.

There are three caveats that are offered to the reader at the outset. Firstly, the complex nature of the phenomena studied in education, learning and teaching (Pring, 2000) is such that it may be inappropriate to expect clear-cut disciplinary structures. The model presented here is *one possible characterisation* of a coherent RP, but alternative models could be offered that draw upon some of the same literature. The present review offers *a model* which may help new researchers conceptualise the field, and identify possible directions for enquiry, rather than claiming the definitive account that all those in the field should accept.

In particular, any model is likely to reflect the modeller's biases as well the target phenomena. The author recognises that he tends to be a 'lumper' rather than a 'splitter' (Lewin, 1989/1987). A focus on similarity and affinity rather than difference and distinction tends to lead to the development of an inclusive model that incorporates viewpoints that could also be construed as in some ways inconsistent. In a Lakatosian RP, differences between researchers stimulate the dialogue expected within a programme – *as long as the researchers share a common set of axiomatic assumptions*.

Finally, *the starting point* for characterising the RP is the notion of 'constructivist' research in science education. The term constructivism continues to be used in many ways, even within science education (see Section 1) and for some critics the term is largely associated with research limited to identifying learners' ideas. Some of the work cited here is not normally considered part of that mainstream 'constructivist' tradition, and certainly some of the studies referred to are not explicitly labelled constructivist by their authors. However, the purpose of this paper is not just to review *overtly* constructivist studies. Rather, this review aims to offer *an overview of a body of research concerned with learning in science that can be seen to form part of a continuing progressive research programme*. This RP certainly derives from and builds upon, but is not limited by, that body of work commonly identified in science education as constructivist. A Lakatosian RP, such as the one discussed here, has its own inherent demarcation criteria, in terms of its 'hard-core' commitments. Key 'constructivist' studies (e.g. Driver & Easley, 1978; Gilbert, Osborne & Fensham, 1982; Driver & Erickson, 1983; Gilbert & Watts, 1983; Osborne & Wittrock, 1983) are the starting point for the analysis: an analysis that leads to a model of a progressive RP that moves *beyond* constructivism as it was characterised at the start of the programme.

The structure of the review

The paper is organised into five main sections. The first introduces the field of study in which the work to be reviewed is located, and explains why it may be productive to identify within this field a 'Research Programme' in the sense that Lakatos (1970) used this term. This section concludes by presenting a simple model of a RP in terms of the 'hard core' commitments set out in seminal 'constructivist' studies. This model is then used as a framework for the next three sections of the paper which review (a) research into how learners come to hold wide ranging ideas about aspects of the natural world; (b) how researchers have attempted to model learner's knowledge structures; and (c) studies considering how classroom teaching should be informed by the RP.

Section 1: Identifying and characterising a research programme in learning science

This present paper suggests a way of conceptualising a substantial body of research into the learning and teaching of science, which could offer a fruitful way for researchers and those who are informed by science education research to approach the vast canon of work associated with the constructivist banner. This paper revisits a suggestion first tentatively proposed over twenty years ago (Gilbert & Swift, 1985), that research into the learning of science could be understood in terms of Scientific Research Programmes in the sense of the philosopher of science Imre Lakatos (1970, 1978). Although this idea was not then strongly developed, it does offer considerable potential for making sense of 'constructivist' research into the learning of science as *part of a developing, continuing tradition of enquiry* (e.g., Erickson, 2000). In other words, a Lakatosian analysis gives an option of considering the constructivist child as the parent of a new more mature stage of research activity (whereas a Kuhnian paradigm shift would seem to imply discarding the constructivist baby along with its now tainted bathwater!)

This convenient feature of a Lakatosian analysis does not *by itself* justify conceptualising a body of research in that way. This section of the paper will suggest why the Lakatosian notion of RP is applicable to research into learning science, and offer a model to show how principles underpinning 'constructivist' research in science education map against the key features of a Lakatosian RP. Such an analysis (a) clarifies some of the key debates around criticisms of the constructivist 'movement' in science education, and so provides a definitive 'position' from which such criticisms may be addressed (Taber, in press); and (b) offers useful guidance on appropriate future directions for research – a key concern of this present review.

Fields, domains, paradigms and research programmes

Science Education, as an academic study of aspects of the learning and teaching of science, has been identified as a 'field' (Fensham, 2004), and is a relatively young field (Jenkins, 2000). According to Duschl and Hamilton (1992), connected fields can be considered to make up a 'domain of inquiry', and they claim that Science Education is part of such a domain,

> Since the 1950s advances in philosophy of science, cognitive psychology, and science education have led to the development of a domain that, for lack of any specific label, seeks to understand the dynamics of the growth of scientific knowledge.
>
> (Duschl & Hamilton, 1992: 7)

Within this domain, science education is primarily concerned with the scientific learning of individuals (albeit often in the context of the social construction, or reconstruction, of knowledge in classrooms etc.), rather than with questions relating to the wider growth of human knowledge. For the purpose of this review, studies concerned with the learning and teaching of science will be considered to make up a research field, within which it may be possible to identify traditions with sufficient continuity and coherence to be considered as RPs.

Changes in many science curricula during the second half of the twentieth century, towards perspectives that emphasised process skills and conceptual development, led to considerations of

- whether learners had the conceptual apparatus in place to cope with the demands of the new curricula - largely explored in the context of Piagetian stage theory (e.g. Shayer and Adey, 1981);
- the implications of the existence of 'children's science' (Gilbert, Osborne & Fensham, 1982), i.e. learners' existing ideas about science topics for the learning of curricular science.

Fensham (2004) has suggested that within the field of science education, research into alternative conceptions and conceptual change can be identified as a discrete 'sub-area'. The rising interest in exploring children's science, and its possible consequences, dates from a period in the late 1970s and early 1980s when three seminal papers were published in *Studies in Science Education* (Driver & Easley, 1978; Driver & Erickson, 1983; Gilbert & Watts, 1983),

> somewhere during the five year period 1978-1983 the seeds were sown for constructivism to become a dominant way of making sense of mathematics and then science education
>
> (Tobin, 2000: 232)

Wide-scale research activity into "children's science" was stimulated. In particular, there was a flurry of empirical and theoretical papers from the Surrey 'Personal Construction of Knowledge' (PCK) group, and major research projects initiated in Waikato (the Learning in Science Project, LISP) and Leeds (the Children's Learning in Science Project, CLISP).

Driver and Easley (1978) focused on the learner's active role in constructing their personal knowledge - and the term 'constructivism' came into common use in Science Education, although this area of research was also labelled as the Alternative Conceptions Movement, ACM (Gilbert & Swift, 1985). A particular feature of work in this tradition was the significance assigned to learners' own ideas about the natural world,

> Now what had been commonplace and unremarkable became significant, and what was too well known to be thought worthy of comment, was suddenly the substance of illuminating research.
>
> (Solomon, 1994: 6)

Although the origins of the constructivist perspective are ancient - antecedents could include, at least, Plato and Socrates, Jesus, Vico, Rousseau, and Dewey (Clark, 1968; Evetts, 1973; Egan, 1984;

von Glasersfeld, 1989; Hyland, 1993) – the early 'constructivist' work in science education was primarily influenced by workers from psychology and closely related fields.

In their seminal paper, Driver and Easley (1978: 62) referred to the work of David Ausubel (e.g. Ausubel, 1961, 2000). However, the major 'constructivist' influence on Driver's thinking was the work of the developmental psychologist and 'genetic epistemologist' Jean Piaget. Piaget is best known for proposing his 'stage-theory' of development, (Beard, 1969; Crain, 1992), that has been summarised as "children of a given age are more likely to demonstrate similarity of [mental] structures than children of different ages" (Brown, 1977: 82). Piaget's epistemology has been characterised as "constructivist and relativist" (Pope and Gilbert, 1983: 195), and has been widely influential in Science Education (Bliss, 1995). Piaget demonstrated that children who have not undertaken formal instruction might still have constructed their own ideas about phenomena they experience in the world and their own meanings for words as they acquire language (e.g., Piaget, 1973/1929). Piaget wrote of the 'myth' of the sensory (or even perceptual) origins of scientific knowledge, and emphasised his view that the role of intelligence was to 'transform'. He believed that knowledge was formed through operating on perceptions with logico-mathematical frameworks (Piaget, 1972/1970).

Although Pope and Gilbert acknowledged the importance of Piaget's work, the Surrey based PCK group, tended to look elsewhere for the primary source of their constructivist thinking (Pope, 1982). This was the psychotherapist George Kelly's 'constructive alternativism' which proposed that individuals construct models of their environment, based on tentative hypotheses, which are then tested against experience and modified as required (Pope and Gilbert, 1983: 196-7). Kelly's 'personal construct theory' proposed that learning was on-going and central to personality (1963: 75), and his central metaphor of man-the-scientist (1963: 4), was also reflected in Driver's focus on the pupil-as-scientist (Driver and Erickson, 1983; Driver, 1983).

As Larochelle, Bednarz and Garrison point out, constructivism "is an umbrella term covering theorizations which are primarily centred on either the cognitive subject; the situated subject (or social actor); or the locus of knowledge, which…has now become the group" (1998: vii). Studies concerned with learning science have increasingly cited Vygotsky's (1934/1986; 1978) work as a key 'constructivist' influence (Bentley, 2003). Vygotsky was a Soviet contemporary of Piaget, who looked at learning from a 'sociohistorical' (Luria, 1976) or sociocultural perspective. Like Piaget, Vygostky saw conceptual learning as requiring active involvement of the learner,

> concepts do not simply represent a concatenation of associative connections assimilated by the memory of an automatic mental skill, but a complicated and real act of thinking which cannot be mastered by simple memorization
>
> (Vygotsky, 1934/1994: 356)

Work strongly influenced by Vygostsky is sometimes described as 'social constructivist' (or 'social constructionist', Schwandt, 2001) to contrast with the 'personal constructivist' focus deriving from the perspectives of Piaget and Kelly. Although there has been what Matthews (1992) colourfully described as "some skirmishing between main-stream Piagetian personal-constructivists and Vygotskian social-constructivists" it will be argued here (see the discussion of Tenet 1, in Section 2) that work in both traditions can be accommodated within the same RP, although having different foci (cf. Solomon, 1993b; Driver, Asoko, Leach, Mortimer & Scott, 1994).

In 1978, Driver and Easley were able to describe naturalistic studies based on clinical interviews as "usually small scale and scattered" (p.77). In 1982, Gilbert (UK), Fensham (Australia) and Osborne (NZ) published their influential paper considering 'children's science', and the various possible outcomes when the children concerned were subject to formal instruction in the topics where they already had established ideas:

- a 'unified scientific outcome', where the learned meanings closely matched that intended (pp. 630-1).
- a two perspectives outcome, where the pre-existing conceptions and the newly learnt material would co-exist (p.624).
- children's science largely undisturbed by 'teaching' (Pope and Gilbert, 1983: 201).
- a reinforced outcome where the material presented is (mis)understood to support the learner's existing ideas.
- partial learning of ideas, as only so much new material could be learnt at one time, so that ideas would not be fully integrated in cognitive structure, and could be contradictory.

In the following year, Driver's *The Pupil as Scientist?* (1983), was published as well as two of the key papers framing the outline of the constructivist position (Driver & Erickson, 1983; Gilbert & Watts, 1983), and a number of other related significant papers (e.g. Osborne & Wittrock, 1983; Osborne, Bell, & Gilbert, 1983). Driver's book was very influential in drawing attention to the significance of learners' ideas for their learning. Only two years later, an edited volume (Driver, Guesne & Tiberghien, 1985a), written by an international team from the UK, Canada, France, Australia and Israel, was able to present results from a range of core science topics. In the same year, the New

Zealand based LISP team produced their own edited volume discussing 'the implications of children's science' (Osborne & Freyberg, 1985).

Over a period of a few years, the study of learners' ideas about science topics had developed into a major international research activity. This produced a vast literature on learners' understanding of science (Gilbert, 1994). By the end of the decade over a thousand papers were catalogued (Carmichael et al., 1990; Duit, 1991: 71). Driver's group produced a popular book reviewing findings in topics taught at secondary school level (Driver, Squires, Rushworth & Wood-Robinson, 1994).

By the mid 1990s, constructivism had become an explicit referent for science teaching (Tobin, 1993a), so that major texts on teaching and learning science were branded as taking a 'constructivist approach' (Fensham, Gunstone & White, 1994) or a 'constructivist view' (Mintzes, Wandersee & Novak, 1998). Constructivism in science education was considered a worthy focus of books in its own right (Tobin, 1993b; Matthews, 1998). 'Constructivist' writing was seen as dominant (Erickson, 2000) and even an unavoidable orthodoxy (Jenkins, 2000) in the research literature, and became likened to a paradigm of 'Kuhnian normal science' (Matthews, 1993: 363).

Education is a social science, and although constructivism in science education has been described as a movement or paradigm, it is something of a diverse movement - certainly in terms of claimed philosophical underpinning (e.g. Good, Wandersee & St. Julien, 1993; Matthews, 1998; Phillips, 2000a, b). Indeed 'constructivism' is sometimes used as a label for the general methodological approach to social research also known as 'naturalistic enquiry' (Beld, 1994 – so, for example, Kvale, 1996:14, refers to the qualitative research interview as "a construction site for knowledge"). Although such an approach to enquiry may seem to be consistent with constructivist views of learning, the focus is somewhat different. In this review, no assumption is made that researchers having a constructivist perspective on student learning *would necessarily* subscribe to research methodologies that would be labelled as constructivist social research. Constructivism as a referent for Science Education is seen here as an ontological commitment (that what is studied, student learning of science, can be understood in terms of the active 'construction' of knowledge), but *not necessarily* as an epistemological commitment (that research findings themselves are constructed rather than discovered). Undoubtedly the authors of 'constructivist' science education research would take a variety of positions here.

It is probably not possible to make general (non-trivial) statements that would apply to all of the work in science education that *could* be identified as constructivist, and, indeed, without an accepted analysis there are no clear boundary criteria allowing definitive demarcation of the 'movement'. Despite these problems, the importance and long-lasting influence of the key ideas set out in the early constructivist papers make it a worthy topic for continuing attention. This present paper proposes a normative model of constructivist research in science education: that is by characterising constructivism in science education in terms of the establishment of a RP, here labelled the Active Construction of Knowledge in Science (ACKiS) RP, within the field of research into learning and teaching of science, it becomes possible to set out a model of what this programme of research is about; the range of issues and questions that included studies will be addressing; and some key assumptions that research in this programme would share.

Paradigms, revolutions, and research programmes in science

So although constructivism in science education has been described as a Kuhnian paradigm (Matthews, 1993; Solomon, 1994), it is considered to be more fruitful here to frame constructivism in terms of a RP. Watts and Pope suggested that this was a useful way to consider learners' personal construct systems as early as 1982, and a few years later Gilbert and Swift (1985) described how the new research movement had the characteristics of a Lakatosian RP. The CLISP group referred to "an active research programme…in the area of children's conceptual understanding in science" (Scott, Asoko & Driver, 1982: 310). More recently, Erickson (2000) has discussed constructivism as being one current RP in Science Education.

Kuhn's (socially focussed) description of science-proceeding-by-paradigm-shifts (1996) suggested that science progressed by a series of scientific revolutions providing transitions between discrete and mutually exclusive ('incommensurable') research traditions. The Lakatosian model suggests that it is more common for rival RP to coexist (cf. Gilbert & Swift, 1985), and for theory-change to occur *within* programmes of research.

A key point in Lakatos' model is that although some changes in commitment would not be possible within a RP, others are not only acceptable but to be welcomed: so evolutionary (cf. revolutionary) change is possible. For Lakatos, a RP continues to be viable (regardless of whether it coexists with parallel programmes), as long as it continues to be 'progressive', and it slowly fades away once it becomes 'degenerate' (terms expanded upon below). This feature of a RP does not make it immune to falsification – decisions over which commitments may be changed within the programme are not arbitrary ones. Indeed, identifying which elements of a programme make up core commitments, and which can be actively challenged, is central to a Lakatosian analysis, and forms an essential component of this present review.

So, if constructivism in science education is be understood as having initiated a RP, then it becomes possible to ask whether this ACKiS RP is a progressive RP which has the potential to continue to inform science education. Indeed, an effective Lakatosian analysis offers guidance ('the positive heuristic', discussed below) to researchers over how to proceed to develop the programme.

Can ACKiS be seen as a scientific research programme?

Lakatos initially proposed 'scientific research programmes' as a methodology for analysing the history of the 'growth' of knowledge in the natural sciences. However, he also suggested that "Marxism, Freudianism, are all research programmes" (1970: 5), and suggested that the 'methodology' of RP was suitable for application "to any normative knowledge, including even ethics and aesthetics" (Lakatos, 1978/1974: 152).

Research informed by constructivist principles has often focused on the ideas and learning *of individuals*, and has drawn heavily on the idiographic research tradition common in social sciences; but it has also sought to produce models of widespread applicability (e.g., Gilbert & Watts, 1983, Driver, 1989). The complexity of the phenomena studied (learning), and the practical and ethical issues concerned with working with students, have often required approaches that involve in-depth study of small samples of willing volunteers, by researchers who are intimately involved in the construction of data (e.g. Pope & Dencolo, 1986). Nevertheless, early seminal 'constructivist' studies established a programme that seeks to develop models that have utility in informing science teaching, and is therefore fundamentally a normative activity. Although there is often a significant gap between the conclusions of individual studies, and the level of guidance that usefully informs teachers, this is seen here as a methodological issue for the programme (i.e. how to move from the individual to the general, cf. Taber, 2000a) rather than a fundamental chasm.

Lakatos' model of scientific RP provides an analytical tool that allows judgments to be made about the continuing viability of research traditions. Framing the ACKiS RP through Lakatos' model provides a perspective for 'taking stock' of this body of research.

The structure of a RP

The main concepts Lakatos (1978) introduces to characterise a RP are the *hard core*, *protective belt*, and the *positive* and *negative heuristics*. The hard core is the set of assumptions that are accepted as fundamental to the research programme. The protective belt is the auxiliary theory that researchers construct to explain phenomena. These theories are open to critical review, but must be consistent with the hard core, which itself is sacrosanct within the research programme. The heuristics direct scientists by giving them 'methodological rules' to follow in carrying out their work: the negative heuristic protects the hard core (by indicating "what paths of research to avoid"), and the positive heuristic outlines the development of the protective belt (by indicating "what paths to pursue") (Lakatos, 1970: 132). For Lakatos, a key feature of a research programme is its heuristic power, such that "not only novel facts but, in an important sense, also novel auxiliary theories, are anticipated" as a PR has "right at the start, a general outline of how to build the protective belts" (Lakatos, 1970: 175).

Thus, if ACKiS qualifies as a RP then it should be possible to demonstrate that the initial establishment of the programme implied directions for the movement, i.e. that key aspects of the positive and negative heuristics were present from the establishment of the programme. This case will be made below, at the close of this section of the paper.

Theory Change and Research Programmes

The 'protective belt' of a RP comprises the various theory which grows up around the hard core ("the auxiliary hypotheses should be formed in accordance with the positive heuristic of a genuine research programme", Lakatos, 1970: 182), but which is itself in flux. So, for Lakatos, it is perfectly possible for theory to change within a RP, as a "series of theories are usually connected by a remarkable continuity which welds them into research programmes" (Lakatos, 1970: 132); provided that the developing theory remains true to the hard core of the programme, i.e. "the successive modifications of the protective belt must be in the spirit of the heuristic" (Lakatos, 1978: 179).

For Lakatos, the theory making up the protective belt of a programme was just part of a sequence of models, "the 'refutable variants' of the research-programme" (1970: 135), that was "bound to be replaced during the further development of the programme" (p.136). This review will identify some candidate 'refutable variants' within the ACKiS RP.

Progressive research programmes

Although the 'methodology' (analytical model) of RP can be applied to any normative activity, Lakatos draw a major distinction between progressive and degenerating research programmes. For Lakatos, a key characteristic of science is the way that it comprises of *progressive* research programmes (whereas a RP in what might be consider pseudoscience continue despite lacking the characteristics of a progressive programme). Although theory change is to be expected in a RP, this does not mean that it is acceptable just to change theory purely in response to difficulties suggested by new data. A progressive RP needs to move forward by developing its (auxiliary) theories, but not in a purely ad hoc manner. The test is whether adjustments to theory are merely to patch-up a match with new findings, or also to provide new predictions that can be corroborated empirically (1978: 179). A programme may be considered progressive if it leads to new facts, and degenerating if new theory is only provided to explain what is already known (Lakatos, 1981/1974). For the ACKiS RP to be judged as progressive it is necessary to show that the programme has moved the field of research into learning and teaching of science forward, and continues to do so, guided by the heuristics of the RP, and in ways that have increased our ability to explain learning, and inform teaching, in science.

For Lakatos, a RP is judged in hindsight, when it is overtaken by a more progressive alternative RP: "which explains the previous success of its rival and supersedes it by a further display of heuristic power" (Lakatos, 1970, p.155), i.e., predicting "all that its rival predicts and some more besides" (Lakatos, 1978, p.179). It is certainly possible to see

- how some research into cognitive development in the Piagetian tradition evolved into constructivist research in science education, and
- how work into learning difficulties in science topics that was already well under way in the 1970s can in retrospect be seen to be part of the corpus of work on 'alternative conceptions' that is now considered to fall under the constructivist banner.

This type of continuity is expected in Lakatos' model of science (1970), but ACKiS can only be considered an established RP once there is some explicit identification of core components that can provide heuristic guidance for researchers.

It is suggested here that the manifesto for the RP was in effect set out for the research community in the seminal papers by Driver & Easley (1978), Driver & Erickson (1983) and Gilbert and Watts (1983), and associated papers (e.g. Gilbert, Osborne and Fensham, 1982; Osborne & Wittrock, 1983). This allowed Gilbert and Swift to publish a paper in 1985 setting out "towards" (their term) a provisional Lakatosian analysis, comparing the Piagetian tradition and the ACM as parallel RPs. Fensham (2004) has suggested that there has been progression in what he identifies as the 'sub-area' of science education concerned with alternative conceptions and conceptual change. He has identified several phases of work in this sub-area (2004: 135):

- 1973 - rediscovery of students' views as an area of interest
- 1979 - studies of alternative conceptions
- 1982 - studies of conceptual change
- 1988 - studies of concepts and context
- 1990 - studies of social dimensions of conceptual change; and studies of the origins of alternative conceptions

Whilst some observers may primarily associate constructivism with the first two phases Fensham has identified, it was be argued here that *all of these themes sit comfortably in a progressive ACKiS RP based around the research agenda established by the early constructivist position papers*. Three decades on from the 'rediscovery' of informal ideas in science as a research focus; two decades on from the suggestion that this area of work may usefully be considered as a research programme; and a decade after the claim that constructivism has outlived its usefulness, it seems timely to revisit the constructivist agenda to consider what has been achieved in these three decades, and what remains to be done.

Hard Core assumptions	Broad research questions (informing the positive heuristic)
1. Knowledge is constructed by the learner, not received	A. How does knowledge construction (i.e. learning) take place?
2. Learners come to science learning with existing ideas about many natural	B. What ideas do learners' bring to science classes, and what is the nature
3. Each individual has a unique set of ideas	C. How much commonality is there between learners' ideas in science?
4. Knowledge is represented in the brain as a conceptual structure	D. How is knowledge organised in the brain?
5. It is possible to model learners' conceptual structures	E. What are the most appropriate models and representations?
6. The learners' existing ideas have consequences for the learning of	F. How do learners' ideas interact with teaching?
7. It is possible to teach science more effectively if account is taken of the	G. How should ['constructivist'] teachers teach science?

Table 1: Suggested Hard Core and Positive Heuristic for the ACKiS RP

A model of a RP

Table 1 is derived from the literature and presents an outline of the tenets of the ACKiS RP, the hard core of axiomatic assumptions which underpin the research programme, and gives an indication of the type of general research question that would be indicated by each assumption.

It will become clear in the analysis that follows that these elements of the programme are not discrete, as the issues are often highly inter-related. None-the-less, table 1 provides a useful starting point for reviewing this area of work. In the following sections these tenets, are used as a framework for exploring the achievements and status of the RP. These hard core assumptions have been identified as being key features of the ideas presented in early seminal papers:

1. Knowledge is constructed by the learner, not received (Driver & Easley, 1978: 62, 70; Gilbert, Osborne & Fensham, 1982: 624; Driver & Erickson, 1983: 39; Gilbert & Watts, 1983: 83; Osborne & Wittrock, 1983: 492);
2. Learners come to science learning with existing ideas about many natural phenomena (Driver & Easley, 1978: 67; Gilbert, Osborne & Fensham, 1982: 623; Driver & Erickson, 1983: 38; Gilbert & Watts, 1983: 72; Osborne & Wittrock, 1983: 489);
3. Each individual has a unique set of ideas (Driver & Easley, 1978: 74; Driver & Erickson, 1983: 42; Gilbert & Watts, 1983: 69);
4. Knowledge is represented in the brain as a conceptual structure (Gilbert, Osborne & Fensham, 1982: 623; Driver & Erickson, 1983: 39; Gilbert & Watts, 1983: 84; Osborne & Wittrock, 1983: 490);
5. It is possible to model learners' conceptual structures (Driver & Erickson, 1983: 40, 43; Gilbert & Watts, 1983: 69; Osborne & Wittrock, 1983: 503);
6. The learners' existing ideas have consequences for the learning of science (Driver & Easley, 1978: 78; Gilbert, Osborne & Fensham, 1982: 624, 628; Driver & Erickson, 1983: 39, 48; Gilbert & Watts, 1983: 71; Osborne & Wittrock, 1983: 490, 491);
7. It is possible to teach science more effectively if account is taken of the learner's existing ideas (Driver & Easley, 1978: 78; Gilbert, Osborne & Fensham, 1982: 625; Driver & Erickson, 1983: 39, 50; Gilbert & Watts, 1983: 83; Osborne & Wittrock, 1983: 492).

A difficulty with using RP as a framework, is the potential for tautology. Any set of statements proposed as the hard-core of a programme *defines* a corpus of studies which are underpinned by assumptions consistent with that programme, and excludes others from consideration as part of the RP. The present formulation is consistent with a wide and significant literature, as the discussion in Sections 2-4 will show. However, alternative sets of fundamental assumptions could be proposed demarcating a different set of studies as falling within 'the' RP. (For example, in reviewing the field back in 1994, Wandersee, Mintzes and Novak suggested a set of eight knowledge claims that characterise this area of research.) In using the RP model as an analytical framework for reviewing the field, Lakatos' notion that the hard core of a programme has to be evident from the beginning has been followed in identifying key ideas that feature strongly in seminal papers from the period that Tobin has identified as when "the seeds were sown" (2000: 232, see above). Some scholars in the field may not agree on the choice of hard core assumptions outlined here, and so may well apply different demarcation criteria to decide when to include or exclude studies from this canon of work. The present contribution will at the least provide a model for others to critique, and so to suggest alternative characterisations. Ultimately, the value of the framework depends upon its heuristic value in informing future work – a key purpose of this review and something that is very Lakatosian in spirit.

Section 2: Learners' ideas in science

This Section explores the first three Tenets of the ACKiS RP, and the associated research questions. In this Section, the core notion of an individual's construction of knowledge is considered, along with studies exploring the nature of the consequent 'constructions', including the extent to which different learners develop similar/distinct ideas about the natural world.

Tenet 1. Knowledge is constructed by the learner, not received

This is the essence of the constructivist position. At its core, constructivism - as adopted in Science Education (as opposed to wider interpretations of 'constructivism' in the social sciences, e.g. Beld, 1994; Potter, 1996; Gergen, 1999; Phillips, 2000b; Matthews, 2000) - is a perspective which views human learning as an active process, i.e. something done *by*, not *on* or *to*, the learner herself. Driver, Asoko, Leach, Mortimer & Scott(1994:5) suggested that "the core commitment of a constructivist position" is "that knowledge is not transmitted directly from one knower to another, but is actively built up by the learner". This perspective reflects Piagetian ideas about the way the individual learns through interaction with the environment taken here to include the social and cultural (including linguistic) environment as well as the physical environment.

So the learner is seen to be pro-active, rather than being the passive recipient of given knowledge (e.g., Driver & Bell, 1986: 448, Pope & Gilbert, 1983: 194). This fundamental perspective has been highlighted from the beginning of the RP. In their 1983 paper, Driver and Erickson present three 'empirical premises', the first of which is that

> Many students have constructed from previous physical and linguistic experience frameworks which can be used to interpret some of the natural phenomena which they study formally in school science classes
>
> (Driver & Erickson, 1983: 39)

Osborne and Wittrock described how "stored memories and information processing strategies of the brain interact with the sensory information received from the environment to actively select and attend to the information and to actively construct meaning" (Osborne & Wittrock, 1983: 492). This focus on active construction of knowledge has been adopted here in labelling the RP as the Active Construction of Knowledge in Science Research Programme.

Children's science: knowledge or belief?

There is a potential problem with the use of the term 'knowledge' in this context, as clearly much of the 'knowledge' constructed by learners does not match what authorities would regard as true. It might seem that reference to learners' *beliefs* about the natural world could avoid this problem, as this term is neutral with regard to the veracity of those beliefs: they may be truly held beliefs, but need not be true beliefs. The problem with using the term 'belief' is that it implies a commitment to an idea that is not always appropriate. Students may understand the curriculum models without believing in them (Chinn & Samarapungavan, 2001) and this can be significant for research with the ACKiS RP. Learners' ideas may vary along a range of dimensions – the degree to which they are alternative to target knowledge, and the degree to which they are considered feasible, likely or true being just two of them (Taber & Watts, 2000).

Whilst learners undoubtedly do have beliefs (i.e., strongly committed ideas) about some aspects of the natural world, an authentic science education should not be concerned with getting students to believe the models of the world presented in the curriculum, but rather to consider them as useful tools for thinking about aspects of the world. Being able to develop and explore ideas, and their consequences, without having to be committed to them is a key aspect of scientific thought (e.g., Thagard, 1992), and is essential for any kind of creative work in science. In this analysis, I will use the term 'knowledge' to stand for learners' ideas, but without implying either a truth-value of those ideas or even any assumption about whether it is meaningful to ascribe such a truth-value. One definition for knowledge is "representations of facts (including generalisations) and concepts organised for future use" (Gregory, 1987, p.410), which would seem to provide a wide enough meaning of the term for present purposes.

The distinction has some significance when one of the common criticisms made of constructivism in science education is that it supports a relativist view of knowledge, i.e. that all knowledge claims should be considered to have equal validity. The issue is important because the existence and nature of reality, and the extent to which any reality is knowable remain live issues in the philosophy of science (e.g., Chalmers, 1982; Losee, 1993). 'Constructivist' research has sometimes been identified as being relativist by those who see this as an inappropriate foundation for science education (e.g., Matthews, 1993; Cromer, 1997), or at least having a confused epistemological foundation (e.g., Suchting, 1992; Scerri, 2003). It is suggested that some researchers seem to present learners' alternative ideas in science as having as much validity and significance as the consensual models of science that they are alternatives to. However, this is by no means the default position in science education. Indeed, when Gilbert and Swift set out their (1985: 689) model of the RP they suggested six principles for a hard core, starting with:

1. The world is real
2. All observations are theory-laden…

In educational contexts, learning science is not about *doing* science, but about *learning about* the nature of, processes of and (perhaps too often almost exclusively) the products of science: "almost entirely a body of consensually agreed knowledge" (Millar, 1989: 588). Similarly, Driver and Easley had described a function of science instruction to be to "communicate the agreed conventions concerning useful ways of analysing and interpreting events" (1978: 76). So there is 'target knowledge', that is the officially sanctioned set of curriculum models that reflect the consensual models of science. School science is influenced by various political and pragmatic pressures and constraints (Kind & Taber, 2005), and provides curriculum models that are sometimes questionable representations of scientific ideas (e.g., Justi & Gilbert, 2000; Taber, 2003a) regardless of the status of scientific knowledge itself. Research within the ACKiS RP has been concerned with studying learners' ideas *in comparison with* the target knowledge. This approach is made explicit in Leach and Scott's (2002) notion of the 'learning demand', which, is about the difference between 'where the learners are' conceptually, and 'where' the teacher is supposed to get them, The criterion for working within ACKiS is a commitment (i.e. Tenet 1) to what has been variously labelled as 'cognitive' (or 'trivial' or 'psychological') constructivism, i.e. accepting that knowledge is constructed though cognitive processes within learners; and is independent of any wider epistemological beliefs about the nature and source of human knowledge (see Taber, in press, for a more detailed discussion on this point). So regardless of the veracity/validity of the curriculum models, and for that matter the status or verisimilitude of the scientific models that they are intended to reflect, institutionalised education offers a convenient placeholder that takes the role of Gilbert and Swift's real world: the version of science that is prescribed for learners. As Driver (1983) pointed out, 'discovery' learning needs to be guided carefully if we want learners to 'discover' the accepted science.

How does knowledge construction (i.e. learning) take place?

One of the key concerns from the start of the ACKiS programme was "the question of a model, or models of conceptual development" (Gilbert & Watts, 1983: 88). The RP was guided from the start by two metaphors – pupils as scientists, and learning as knowledge-construction.

Learners as scientists: do learners behave as intuitive scientists?

The metaphor of 'man[sic]-the scientist' (deriving from Kelly, 1963) or Pupil-as-scientist' (Driver, 1983, Driver & Erickson, 1983) is based around a recognition that human beings are predisposed to make sense of their environment, and construct mental models of the world that act as frameworks for making sense of future experience (e.g. Osborne and Wittrock, 1983: 492) to help them "predict and control" aspects of their worlds (Kelly, 1963: 5). These models are based on tentative hypotheses; tested against experience; and are modified when indicated (Pope and Gilbert, 1983, Gilbert & Swift, 1985).

When Gilbert and Swift provided their provisional Lakatosian analysis (1985), the idea of people developing unschooled notions through an application of hypothetico-deductive logic was central (providing the remaining 4 of the 6 suggested components of the their hard core):

3. Individuals use personally appealing explanatory hypotheses to cope with events in their environment
4. The individual tests these hypotheses through interaction with [experience] against personally appealing criteria

5. [Experience] provides guidance as to the adequacy of these hypotheses so tested
6. When hypotheses are judged inadequate by such testing, either the hypotheses or the test criteria by which they were judged are modified or replaced
(Gilbert & Swift, 1985: 689, with references to 'reality' substituted by 'experience'.)

The 'scientist' metaphor emphasises two points here that would receive widespread support within the ACKiS RP:

- learners actively develop ideas about aspects of the world (without needing to be 'taught' them)
- this can be seen as being (to some extent) a rational process.

The first point is basically a restatement of what I have labelled Tenet 1, and clearly derives from those Piagetian findings which had strongly influenced Driver's early work, and had become so familiar to those working in Science Education that they were probably taken-for-granted by most workers in the field (cf. Solomon, 1994). However, the second point goes beyond this and suggests that, as in science, there are rational reasons for selecting, changing or abandoning ways of looking at the world. There are of course *apriori* reasons for such an assumption: after all the evolution of a cognitive system which can form and rationally modify models based on experience is surely a more likely product of natural selection than a cognitive system which is completely random or irrational!

Gilbert and Swift (1985) only made two suggestions for the protective belt of the programme, one of these being Hewson's ideas on conceptual change. Hewson and colleagues were involved in considering a model of why people should change their minds, and their assumption was that this would be a rational process.

How rational are learners about changing their minds?

The notion that conceptual change should be rational may be seen as an early 'refutable variant' within the ACKiS RP and was explored by a number of authors (Posner, Strike, Hewson & Gertzog, 1982; Hewson & Hewson 1984; Strike & Posner 1985, 1992; Smith, diSessa & Roschelle, 1993). This leads to questions such as what it means to be rationale. Strike and Posner (1985) explored the conditions under which a person would be expected to change their mind and develop their ideas in response to criticisms (1992). This raised awareness of the importance of learners needing to have a good understanding of new ideas before they were likely to be taken seriously as alternatives to existing thinking (e.g., Nersessian 1992; Thagard 1992).

Solomon (1993a) has been critical of work using the notion of the pupil-as-scientist, suggesting that the way people think in everyday life is quite different from scientific thinking (a point taken up later in this paper). It was not however being suggested that learners necessarily have finely honed skills in forming, testing and developing 'hypotheses'. Driver's (1983) work clearly suggested they did not, and Kelly's man-the-scientist was certainly a very human scientist (Pope, 1982).

Solomon's perspective here is tied to her belief that formal science instruction relates to a particular domain of knowledge, with norms of knowledge-construction, that is alien to the 'life-world' domain relevant to learners' thinking about their knowledge - where social consensus takes precedence over the epistemological standards used in science. Solomon's notion of scientific and life-world knowledge occupying two distinct domains is considered in more detail below (Section 3, under discussion of Tenet 4). Solomon undoubtedly makes some important points, but perhaps over-emphasises differences in both the nature of knowledge, and the means of reaching consensus. Professional scientists are not always perfectly logical (Mahoney, 1976), and may be influenced by the desire for agreement (Ziman, 1991/1978), or disagree for personal and egotistical reasons as well as scientific ones (e.g. Park, 1988).

Meanwhile, as researchers collected examples of student talk in science classes (e.g. from the CLIS project, Brook and Driver, 1986; Johnston and Driver, 1991; Wightman, Green & Scott, 1986), plenty of classroom evidence accrued suggesting that school pupils do not always put the desire to seek social consensus before such considerations as intellectual coherence.

Significant features of the conceptual landscape

One useful metaphor that was adopted in this debate was that of a 'conceptual ecology' (Strike and Posner, 1985), an idea taken from Toulmin (Hewson, 1985). The notion of a conceptual ecology can be seen as having heuristic value, suggesting that there are many potentially relevant features of the 'internal' learning environment that influence the course of conceptual change. Driver & Erickson had suggested that one influence on learners' ideas would be "language and available metaphor" (1983: 42). Over time, learners' conceptual ecologies were 'populated' with anomalies, analogies and metaphors, exemplars and images, categories, explanatory ideals, metaphysical beliefs, motives and goals – as well as competing conceptions (Hewson & Hewson 1984; Strike & Posner

1985, 1992; Duschl & Hamilton 1992; Kitchener, 1992; Pintrich, Marx & Boyle 1993). The features of a conceptual ecology constrain and channel thinking, and so enable learning selectively (e.g. Tobin, 2000: 235).

Two types of conceptual change

Driver & Erickson reported how work they reviewed suggested it was useful to distinguish "between gradual, evolutionary changes and discontinuous, revolutionary changes in conceptual structure" (1983: 53). This distinction has commonly been taken up (e.g. Posner et al., 1982; Novak, 1985; Duschl, Hamilton & Grandy, 1992; Vosniadou 1992, 1994; Duit et al., 1998), sometimes being associated with the Piagetian processes of assimilation and accommodation (Posner, et al., 1982; Rowell & Dawson 1985; Dykstra, Boyle & Monarch, 1992; Pintrich et al., 1993), and possibly explained in terms of Chi's notion of ontological trees (discussed below under Tenet 4), where alternative conceptions are modelled in terms of the misclassification of concepts, and where reclassification is only possible within, but not between, the highest level of classification.

Construction of Knowledge

Locating the building site. The constructivist metaphor can be seen as quite powerful, with its notion of building up knowledge being like the construction of a building: firm 'foundations' are important, and 'scaffolding' (a Vygotskian notion, Daniels, 2001) may be needed until the construction is complete. The construction process takes place through a series of steps of limited size – the 'building blocks' of knowledge. Building needs a 'site', and much early work in the ACKiS RP has focussed on *the personal* construction of knowledge by individual learners – even when *social* factors were acknowledged (Phillips, 2000a). In part, this reflected the way that both Piaget and Kelly had developed their constructivist thinking in terms of individuals, and perhaps also reflects methodological considerations (as interviewing individuals is often more straightforward that collecting data from groups). Solomon, in particular, has been critical of research that ignored the way knowledge-construction is often (and in formal educational settings, usually) a socially mediated process, using language as a tool (1992, 1993a).

The social aspect of learning science was, at least, *acknowledged* from the beginning of the programme,

> What is often overlooked is the extent to which knowledge about the physical world consists of constructions about which there has to be social agreement. One function of instruction which cannot be achieved through simple interaction with the environment is to communicate the agreed conventions concerning useful ways of analyzing and interpreting events.
>
> (Driver and Easley, 1978: 76)

Driver and Easley (1978: 80) also referred to "exploratory work [that] suggests the important role that informal communication in small groups may play in this process" of conceptual change. Driver clearly wrote about the pupil-as-scientist working within a community of learners: "science as a cooperative exercise as opposed to an individual venture" (1983: 4). Gilbert and Watts suggested that in 1983 "it is not yet agreed whether the focus should be the individual as an isolate or the individual within a social group" (1983: 87). Despite this, there is no doubt that much, though not all (e.g., Gilbert & Pope, 1986), of the research published focussed on individual learners.

Solomon's own work (e.g., 1992) had a strong social focus, and some major studies concerning science learning have put an emphasis on the social context (Edwards and Mercer, 1987; Ogborn, Kress, Martins & McGillicuddy, 1996; Mortimer & Scott, 2003). These studies are often influenced by the work of Vygotsky (1978, 1986/1934) - and others working from socio-cultural and activity theory perspectives - subsequently developed by Bruner (e.g., 1986) and his colleagues (e.g., Wood, 1991), and championed in the field of Science Education by Solomon (1987, 1993a). From this perspective, there is a fundamental social aspect in learning, and understanding the construction of knowledge (in school as in science) means studying a socially mediated process (Scott, 1998). Such research sees the building site for science learning in terms of Vygostky's (1986) Zone of Proximal Development (ZPD).

It is not necessary to see 'personal' and 'social' construction of knowledge as opposing ideas (Gergen, 1999): clearly in a school or similar institutionalised setting there is a social context for learning, and researchers may choose to construe the social mediation as part of the input to an individual's mind, or as the focus for study. Indeed, as Solomon herself recognises, "if we consider the ambiance of any classroom, we can see that both social and personal forces are involved" (2000: 299). The debate over 'personal construction of knowledge vs. social construction of knowledge', informed by the positive heuristic of the RP (i.e., Question A in Table 1), has helped researchers think about whether to focus upon individuals or interactions within particular studies. For example, Duit, Roth, Komorek & Wilbers report their research in the following terms,

> …the present study evenly emphasizes individual and social construction of knowledge and acknowledges not only students' previous (pre-instructional) conceptions as co-producers of knowledge (as mainstream constructivist views do) but also the social and material setting of the learning environment.
>
> (Duit et al, 1998: 1059)

Learning Quanta – building bricks of knowledge construction

A feature of the 'construction' metaphor that offers considerable heuristic power in relation to cognitive processes is the notion of 'building blocks'. Construction implies a process of building up a structure, piece-meal, and this suggests that constructing any sophisticated structure will be a long process. Apart from the physical constraints of moving each building brick into place, careful builders have to leave time during the overall process for foundations to settle, for concrete to set, and for mortar to dry out. The metaphor may suggest parallels here with what we know about learning.

The limited capacity of working memory (Miller, 1968) is a major constraint on cognition that has been studied, but usually in problem-solving contexts (e.g., Tsaparlis, 1994), rather than in terms of conceptual learning. Research also shows that when new learning is not sufficiently reinforced and consolidated, it is often difficult to retrieve accurate memories, and this can lead to reconstructive recall (where what is 'remembered' is part recall, and partly the brain filling-in to give a plausible coherent account). Considering the significance of 'forgetting' as a phenomena in everyday life, it seems to have been largely ignored as a specific research focus in science education, despite the potentially very significant early findings of Gauld (1989) about how students may have false memories of classroom experiences. (For one study that reviews relevant memory research and presents a case study of student 'forgetting' see Taber, 2003b).

Research (such as that discussed in Taber, 2003b) suggests that the process of laying-down and consolidating new memories (i.e., integrating them with existing memory) takes place over timescales of weeks and months or longer. This might suggest that student learning may be changing from being 'fragile' to 'robust' over these timescales, something that could be significant for learning difficulties in science topics where new concepts accrue quickly (Taber, 2004). At the outset of the RP, when Gilbert, Osborne and Fensham (1982) discussed the types of outcomes possible in teaching situations (see Section 1), they suggested that sometimes there would be partial learning of ideas, as there was a limit to how much new material could be learnt at one time. Despite this 'heuristic signal' there seems to have been very limited attention within the RP given to memory as a specific focus in studies of learning science.

Cognitive constraints on learning

Since the ACKiS RP was initiated, there have been considerable developments in related areas of cognitive science, and ideas and metaphors from these related fields should offer some fertile directions to develop aspects of understanding about learning in science.

To some extent, ACKiS might be considered to be a RP considering science learning as concept learning in terms of *conceptual* development in science, that grew out of dissatisfaction with the *cognitive* approach of Piagetian research. However, it was recognised in Driver's early position papers (Driver and Easley, 1978, Driver & Erickson, 1983) that a better understanding of science learning had to take into account the cognitive processes by which learning occurred, and that information processing models could be useful here; and Wittrock's generative learning model (e.g. Osborne & Wittrock, 1983) was a constructivist information-processing model of learning in science. One of the challenges that Gilbert and Watts recognised was to find an overview that explained the apparently contrary findings from the two approaches, i.e.:

> the question of the relation between the outcomes of research conducted with the assumption of context-independent learning [where it is "possible to show an age-related graduation in the quality of understanding of a particular content"]… and that conducted with the assumption of context-dependent learning …[where] no evidence of age relatedness can be found
>
> (Gilbert and Watts, 1983: 87)

Johnstone (1989, 1991) has been critical of the vast amount of research into learners' ideas, suggesting that research based on information processing approaches would be more fruitful. In terms of the present analysis, it might be suggested that in terms of the heuristic of the RP, there has been disproportionate attention to some indicated avenues of research rather than others.

In recent years, there have been attempts to draw upon new ideas in the cognitive sciences to inform our understanding of science learning (Lawson, 2003, 2004). Roth (2000: 64) favours a 'neurocomputational' account of science learning, informed by artificial neural networks, suggesting that "based on recent research in various neuroscience domains, I argue for a change in the basic models science educators use for learning and development".

This discussion of Tenet 1 has considered some of the key literature looking at the nature of learning in science as a process of active construction of knowledge. Two important consequences of learning being an active process are that children will develop ideas about many scientific topics before formal instruction, and that each learner will have learning constrained and channelled by existing ideas in a unique way. These consequences will be explored in the discussion of Tenets 2 and 3 respectively.

Tenet 2. Learners come to science learning with existing ideas about many natural phenomena

Driver and Erickson's (1983) first empirical premise (reported above) was that students came to science classes having already 'constructed' frameworks that would be used to interpret the phenomena to be studied. This premise was based on an already existing body of research (some reviewed in Driver & Erickson, 1983 and Gilbert & Watts, 1983) exploring learners' ideas across a range of topics.

One obvious question raised is 'What ideas do learners bring to science classes…?', and undoubtedly much research within the ACKiS RP has explored that question. Indeed, as the papers cited by Driver and Erickson, and Gilbert and Watts, show, this avenue of work was already well underway. However, much of this work had previously been framed as exploring learners' *misconceptions* in science (cf. Smith et al., 1993), and a key feature of the new programme was based around the question 'what is the nature of these ideas?' There has been considerable debate within the programme on this point.

What ideas do learners' bring to science classes…?

Driver and Erickson's premise is now even more strongly clearly supported by the vast corpus of research into learners' ideas (e.g., Carmichael et al., 1990; Duit, 1991; Driver, Squires, Rushworth & Wood-Robinson, 1994; Gilbert, 1994), which includes many studies detailing pre-schooled thinking about aspects of the natural world.

At the establishment of the ACKiS RP, Gilbert and Watts made the point that "once basic research skills have been acquired…the opportunities for enquiry are immense" (1983: 82). Over the following years, large numbers of researchers took up this challenge, exploring the scientific ideas of learners of a wide range of ages (including university students and trainee teachers for example), in most areas of the science curriculum.

...and what is the nature of these ideas?

Driver and Easley's seminal (1978) paper began by asking whether students' references to 'heat molecules', etcetera indicate "misconceptions, errors, partial understandings or misunderstandings?" or - in Ausubelian terms - 'preconceptions' (pp.61-2). Driver and Easley suggested these terms were inappropriate as learners' own notions could have the status of models and theories (1978: 62), and in particular 'misconception' implied a misunderstanding of teaching rather than "the situation in which pupils have developed autonomous *frameworks* for conceptualising their experience of the physical world" (p.62). Suggesting that learners hold alternative conceptual frameworks provided a rationale for much of the research that has followed.

There has been considerable debate in the literature about the nature of learners' ideas. There is no significant doubt that even quite young children offer ideas about many aspects of the world, which are inconsistent with the curriculum models of school science. Piaget had found this, long before, but he had also pointed out that elicited ideas could sometimes be little more than romanced responses to the investigator's questions (1973/1929). An elicited idea could reflect deep-rooted well-considered and significant beliefs about the world, or just a 'throw-away' suggestion.

A difficulty for the ACKiS RP here is that researchers are largely interested in the relatively stable knowledge structures held by learners, but research techniques tend to trigger cognitive processes that provide evidence of thinking (cognition). Thinking clearly makes use of (and is constrained by) the learners' conceptual structures, but only gives indirect evidence of them (e.g. Hammer, 2004). Claxton points out that such utterances made in research interviews may be reflections of specific circumstances ("an unprecedented question … a unique nexus of opportunities, abilities, constraints and personal history") as much as underlying conceptual structure (1993: 45). In these circumstances, the researcher's finding of an 'alternative framework' may be no more than an "ephemeral reflection" (p.45) – a "transitory artefact" of the interview itself (Ault, Novak and Gowin, 1984: 447). This is one area of research where the data can significantly underdetermine the models researchers build. Awareness of this problem indicates the need to devise suitable methodology (Driver et al., 1985c: 196).

So there has been a good deal of discussion in the literature about the nature of those frameworks or conceptions proposed on the basis of research (and whether terms such as framework are even appropriate). In their 1983 paper, Driver & Erickson, reported that "the question of which types of frameworks are more … stable, and which are … fluid, is one which is currently being investigated empirically" (1983: 42). This debate has concerned the question of whether the features reported by researchers are, or are not, stable; are, or are not, coherent and consistent; have, or do not have, wide ranges of application, etc. Where Driver, and Gilbert and Watts, clearly felt that learners demonstrated 'alternative conceptions' or frameworks that are 'theory-like', others characterised learners' ideas as inconsistent and context-dependent (e.g., Solomon, 1992, 1994), as mini-theories: fragmentary, invented *ad hoc*, "whose limits of applicability … may be rather circumscribed" (Claxton, 1993: 46-47, see also Millar, 1989).

Different literature purports to discuss evidence offering very different interpretations of learners' ideas in science, even when similar techniques have been used to collect data. Despite the doubts of Millar, Solomon, Claxton and others, the literature also claims that

- "many notions children hold are used in a range of situations and have the characteristics of elementary models or theories" (Driver & Easley, 1978: 62);
- learners have "conceptual structures which provide a sensible and coherent understanding of the world from the child's point of view", and which could be held "very strongly" (Gilbert et al., 1982: 623, cf. Driver et al., 1985b), so that "the person resolutely holds on to the original model and rejects those of others" (Pope & Gilbert, 1983: 201).

This polarity of findings could suggest an impasse, but is perhaps better understood as indicating that *learners ideas vary along a range of dimensions* (stability, commitment, coherence, range of application etc., e.g., Taber & Watts, 2000), and (as Driver and Erickson indicated) this might indicate that the RP should be exploring the factors which are associated with these variations. For example, Driver and Erickson had conjectured that

> content which lacks some experiential foundations (either physical or linguistic) may well be more labile and more readily displaced by subsequent instruction than is content which is built upon a firm experiential foundation
>
> (Driver & Erickson, 1983: 49)

It is important to explore these dimensions of stability, coherence, etc., discretely, as, for example, "students' interpretations and conceptions are often contradictory, but none the less stable" (Driver et al, 1985b: 3-4). The heuristic of the RP would here guide researchers to study learners' ideas:

- to explore whether they are applied across a range of contexts (e.g. Clough and Driver, 1991/1986);
- or in relation to, for example, stability versus lability of conceptions (e.g., Taber, 1995).

Learning recapitulates history?

Another feature of learners' ideas which has been intermittently highlighted since Driver and Easley (1978) is how some common alternative conceptions seem to reflect historical, but now discredited, scientific models. This finding is not so surprising (as presumably early scientists would have acquired some similar naïve conceptions of the world on which to base their ideas as present-day learners). The extent to which this analogy may be more or less superficial, and whether historical sequences of models may have some value as either a heuristic guide to studying conceptual trajectories - or indeed as a pedagogical tool to design learning pathways - does not yet seem to have been explored in any depth. In any case, as in the biological notion of ontogeny recapitulating phylogeny, recapitulation is certainly not a general rule that applies to all alternative conceptions.

Tenet 3. Each individual has a unique set of ideas

Another important characteristic of the ACKiS RP is its focus on individual learners. Although the RP can be considered to have developed from the Piagetian RP (Driver & Easley, 1978), it contrasts with it in terms of its concern with the distinct knowing of individual learners. The research programme suggested by Driver and Easley would "sensitise educators to variety and to help them respond to it, as [much as] aid planning for conformity" (1978: 80).

Driver and Easley were aware that nomothetic and ideographic studies draw upon different traditions - used in different types of research looking to answer different kinds of questions - and that this implied a major methodological paradox for the RP (and one which in part contributes to the confusions over the philosophical underpinnings of the programme, see under Tenet 1).

The paradox was that informing teaching required developing theory - and so presenting generalisations that could guide science teachers - yet the phenomena to be studied (learners' ideas and how they develop) were complex, subtle, nuanced, and very much tied to the individuality of particular learners.

> "Though we may search for trends and patterns in development and indeed seek to make use of what is known about these in planning effective instruction it is important not to overlook the essential individuality of learning."
>
> (Driver and Easley, 1978: 80)

In principle, this could have been a terminal problem, requiring researchers to either trivialise their study of the phenomena in order to produce general findings, or to be true to the phenomena by abandoning a desire to produce results useful in teaching. However, Driver and Easley argued that it was possible to use "idiographic studies … [where] the focus is on an individual's personal experience" (1978: 68), without giving up of the search for general findings, as their review of ideographic studies indicated "common features in children's alternative frameworks" (1978: 79-80). By 1983, Driver and Erickson claimed that "the question of which types of frameworks are more universal … and which are idiosyncratic…is one which is currently being investigated empirically" (1983: 42).

How much commonality is there between learners' ideas in science?

This is one area where the ACKiS RP has produced a great deal of potentially useful material for informing science teaching. The literature, although based on a range of methodological approaches (some more likely to highlight individual differences, some more likely to over-estimate similarities), and reported in diverse terms (see the discussion under Tenet 5 in Section 3), provides evidence of both the idiosyncratic nature of individual knowledge structures, and common types of alternative conceptions.

One example of a very common alternative conceptual framework that is largely derived from intuitive interpretations of experience concerns the relationship between force and motion (e.g. Gilbert & Zylbersztajn, 1985). Whilst there are doubtless fine distinctions between the detailed thinking of different learners, it seems that most youngsters tend to think that a force is needed to maintain motion, rather than only to produce an acceleration (Watts and Zylbersztajn, 1981).

Similarly, research suggests that most 'high school' level students of chemistry are likely to develop a conceptual framework for understanding chemical processes based on a principle that chemical species interact to obtain full shells / octets of electrons (Taber, 1998). This research was based on in-depth studies of individual learners (supplemented by data collected from a wider range of informants). Strictly, each learner had a unique set of ideas (e.g., in the range of application of the central principle), but there was enough of a common core shared by learners to build a model of 'the octet framework' suitable for informing teaching. Although the original research was undertaken in one educational context (the UK), key findings have been found to be reflected in studies of students from other systems – e.g. in the U.S. (Nicoll, 2001), Australia and New Zealand (Coll & Taylor, 2002) and Hong Kong (Tan et al., 2003).

This particular study made an explicit attempt to respond to the challenge of bridging between sets of case studies and a general model. Many studies either report findings based on detailed work with small numbers of students, or the outcomes of survey approaches - that either present learners with choices between predetermined response categories, or categorise responses in necessarily reductionist ways. Much existing research therefore gives insight into ways of thinking that may not be common, or information on common response categories without providing any indication on how such a response fits into wider ways of thinking (e.g. range of application, consistency of use, etc.) Finding ways to combine the complementary strengths of these two approaches is an important methodological issue for the RP.

Section 3: Modelling learners' conceptual structures

In the previous section, the basic notion of active construction of knowledge was explored, as was the way children tend consequentially to develop a wide range of informal ideas about the natural world prior to formal teaching. In this section, the fourth and fifth Tenets of the RP will be considered in terms of how scientific knowledge may be 'stored' or represented in the learners' brain, and so how best to model learners' ideas.

Tenet 4. Knowledge is represented in the brain as a conceptual structure

It is generally accepted that in some way the brain of a learner is able to represent information in a relatively stable and non-random way,

> Concepts do not lie in the child's mind like peas in a bag, without any bonds between them. If that were the case, no intellectual operation requiring coordination of thoughts would be possible, nor would any general conception of the world. Not even separate concepts as such could exist; their very nature presupposes a system.
>
> (Vygotsky 1986/1934, p.197)

This seems to be a largely implicit assumption in much writing from within the RP, and may seem to be obvious. Yet, this assumption is clearly axiomatic in the programme, and the questions it raises (*how* is knowledge structured, *how* could we represent this?) are important features of the protective belt.

Vygotsky claimed that 'scientific' or 'academic' concepts (i.e. formally taught concepts, as opposed to tacit intuitive concepts) made up a system (1986/1934: 205). A term that is commonly used is 'cognitive structure' (e.g. White, 1985), although it could be argued that it is useful to keep the descriptor 'cognitive' as a referent for mental *processes*, and use 'conceptual' to refer to the ideas that are represented. As we saw in considering Tenet 2 in the previous section, it is not always clear the extent to which a learner's utterance reflects represented knowledge, rather than the creative act of constructing knowledge *in situ*. Structure, the substrate for cognition, is modified at the synaptic level by the very processing of its content. Although it is not possible for us to always distinguish absolutely between process and structure, a 'first-order' cognitive/conceptual distinction is here considered to be useful, i.e. to have heuristic value for the RP. We could define a learner's *conceptual* structure as *the knowledge, concepts, propositions, theories, and raw perceptual data that the learner has available at any point in time, and the manner in which it is arranged* (after Ausubel & Robinson, 1969, and White, 1985).

Despite advances in many areas of the cognitive sciences, we are still some way from being able to relate conceptual structure to the physiological structure of the brain: it is not possible to find correspondence between neural circuits and concepts, beliefs, etc. Indeed, it is not clear the extent to which this may be possible in principle. This need not be a problem for the ACKiS RP. There is a tradition within cognitive science that phenomena may be studied at different levels of analysis (Dawson, 1998) – so for example, information processing models of cognition posit structural features that are given ontological significance in research without needing to be mapped onto particular physiological structures. It is also believed that the brain retains considerable (though not unlimited) plasticity throughout life (Thomas, 2003) so that it is quite possible that structures at the level of, for example, 'stored concept' could remain intact without being tied to a constant physical location.

While analysis at the level of conceptual structure may continue independently, it can also be usefully informed by advances in neurology (for example Redish, 2003), in an analogous way to how chemists can use molecular level models to inform their understanding of the properties of substances at the molar scale (Taber 2000c).

How is knowledge organised in the brain?

Evidence that conceptual structure *is* organised can be obtained through research that uses word association type tasks (e.g., Bogner, 1998); and the ability of informants to draw concept maps (e.g. ,Wandersee, 1990), and answer sequences of interview questions (e.g., Bell, 1995) implies some level of structuring.

Domains

One of the outcomes of children's science interacting with formal instruction identified by Gilbert and co-workers, at the outset of the RP (see Section 1), was the 'two outcomes' perspective. Sometimes students learn presented theories and explanations, and can use them in class and in tests, but revert to their existing ideas in everyday conversation and problem-solving (Gilbert, Osborne & Fensham, 1982: 624, cf. Carraher et al., 1991 for a parallel from mathematics education). Solomon (1993a) has discussed this phenomenon in terms of the distinction between what might be considered two 'domains' of knowledge, the 'symbolic' and the 'life-world' (Driver and Erickson, 1983, p.37), which might be understood as two largely distinct, non-interacting 'regions' of conceptual structure. For Solomon, these domains would be more than just well-separated knowledge stores, but rather two different *systems of knowledge* (1994: 8), characterised by distinct modes of cognition. According to Solomon, school science concerns a 'symbolic universe of knowledge', kept "in a different compartment from that of the familiar life-world thought of daily discourse" (1993a: 96). In the life-world domain, cognition involves permeable categories, ready generalisation, and fragmented learning structures.

According to Solomon, the domains of life-world and symbolic knowledge are dissimilar in genesis (cf. Vygotsky, 1986/1934, see the discussion of Tenet 6 in Section 4) and mode of operation - and crossover involves discontinuity of thought (Solomon, 1994: 8). Solomon's notions, in part derived from research into learning about the abstract notion of energy, leads to testable conjectures:

- a lapse of time (between instruction and questioning) will select preferentially for the life-world structure of meaning if there is no further reinforcement of symbolic knowledge;
- successful crossing over and back from one domain to another will be more difficult than continuous operation in one domain, and is indicative of a deeper level of understanding (Solomon, 1992: 110).

There is a good deal of evidence to support the analysis Solomon produces, and it is widely accepted that people have different 'ways of seeing' that are appropriate in different contexts (Driver, 1989: 486). Work into 'everyday cognition' (Rogoff & Lave, 1984), 'situated learning' (Lave and Wenger, 1991) - and related notions of 'practical intelligence' (Sternberg et al., 2000) – suggest that

- formal scientific knowledge is not usually perceived as relevant to everyday life, and
- does not tend to be activated in the absence of the (perceived) appropriate context: and so
- would need to be "reconstructed" and re-contextualised before it could be used in everyday life situations (Hennessy, 1993: 26).

Aikenhead has talked of life-world knowledge and the world of school science as distinct sub-cultures, and has described the 'border crossing' involved in learning curriculum science when "students experience a change in culture when moving from their life-worlds into the world of school science" (2000: 24). This perspective derives to some extent from the particular "problems experienced by students who have an indigenous traditional background and who attempt to learn a subject matter grounded in western culture" (Fensham, 1999). Aikenhead, whilst pointing out that such border-crossings are 'smoother' for some students than others, suggests that for *all* students "learning becomes culture acquisition which requires students to cross cultural borders from their life-world subcultures (associated with, for example, family, peers, school, and media) to the subcultures of science and school science" (1996: 40).

The notion of 'domains' in cognitive structure potentially links to a major area of research informed by ideas about the evolution of brains in modern humans (Hirschfeld & Gelman, 1994), which suggests that cognitive 'modules' may well have evolved to deal with different key areas of experience such as social interactions, materials, and natural history (Mithen, 1998). It has been suggested that the modularisation is still present to some extent in our brain structures, leading to such domains as intuitive physics, folk knowledge of the living world, and folk psychology. It has even been suggested that the ability to re-represent ideas from one module to another is a central aspect of human cognition (Karmiloff-Smith, 1994). These ideas could provide useful impetus for the RP, 'refutable variants' for further study, as it is clear that learners do sometimes apply different conceptions depending upon the perceived context, and this may have important consequences both for context-based science courses, and attempts to set examinations 'in context' to make questions more accessible (Ahmed & Pollitt, 2001).

Fundamental levels of conceptual structure

A related area of work considers aspects of conceptual structure that may be considered to be operating at a quite fundamental, and often tacit level (Watts and Taber, 1996): "the unspoken assumptions or the unreflected aspects of thought which lead one to assert that something is obvious" (Désautels, 1998, p.128). Some of this work may not commonly be thought to be 'constructivist', but certainly fits within the ACKiS RP as set out here. Space only allows a brief reference to some of the more influential ideas.

The notion of Gestalt (Perls, Hefferline & Goodman, 1973/1951) describes how we often perceive patterns as coherent wholes rather than in terms of individual elements. Andersson (1986) suggested that many alternative conceptions in physics might result from perceiving a wide range of interactions as fitting a common pattern (of actor-agent-object) even when this is not the most appropriate way of conceptualising the interaction. This experiential gestalt of causation is an example of a p-prim, or phenomenological primitive, a way of interpreting perceptions considered to be applied early in the processing of perceptual data (diSessa, 1983; Hammer, 1996). If our brains develop to be 'hard-wired' to scan sense perceptions for certain likely patterns (such as actor-agent-object, or nearer-means-stronger), then such patterns may seem intuitively obvious when re-cognised.

Focus on this level of cognition, suggests interpreting learners' responses less in terms of fixed alternative conceptual frameworks, and more in terms of the repertoire of cognitive resources available to generate ideas (Hammer, 1996 cf. Claxton, 1993) – something that would seem to link to the conceptual ecology notion. This perspective provides a significant heuristic impetus to the ACKiS RP, as it sees alternative frameworks as the current combination of more elementary and stable aspects of cognition (Smith, et al, 1993). These fixed elements are not in themselves barriers to target knowledge, but are capable of being de-selected, and a new combination organised to provide conceptual change (just as a fixed lexicon of words can be used to form different sentences). However, the work of Stavy and Tirosh (2000) suggests that some of the 'intuitive rules' that learners apply in their understanding of scientific phenomena may be widely as well as readily applied, so that such 'de-selection' may depend upon substantive teacher input.

Chi has explored another fundamental aspect of conceptual structure that may be considered to be applied largely tacitly, and that may have considerable implications for learning science. Chi and her colleagues have discussed learners' ontologies of their worlds, which Chi models in terms of several major 'ontological trees' that branch to give conceptual categories representing the entities making up the individual's mental model of the world (Chi, 1992; Chi, Slotta & de Leeuw, 1994). Chi's ideas suggest that some types of desired conceptual change may be difficult to achieve, "… concepts whose true ontological status mismatches the student's naive conceptions will be referred to as incompatible concepts" (Chi et al., 1994: 34). In particular, Chi explains that the tendency for categorising phenomena that are understood in physics as processes (such as heat and light, force, etc.) as objects makes it difficult for learners to acquire the meaning intended in the curriculum.

Manifold conceptions and multiple frameworks

From the beginning of the ACKiS RP, it has been accepted that learners often seem to apply a number of alternative sets of ideas in the same topic,

> it is far from clear how representative of an individual's thinking a particular framework is. Indeed, given the manner in which such frameworks are obtained from interview (and other) data, it may well be that an individual's conceptions make use of several frameworks.
>
> (Gilbert and Watts, 1983: 86)

This does not only apply when an individual is asked about both 'scientific' and 'life-world' contexts, and this feature has been the focus of much discussion. To some, this finding leads to questions about the adequacy of the researchers' descriptions of students' conceptions (e.g., Kuiper, 1994); or suggests that school-age learners' ideas are not theory-like (e.g., Claxton, 1993). Both of these responses may sometimes be appropriate. However, even scientists do not hold unitary versions of scientific concepts (see the discussion of Tenet 5, below), and sometimes see alternative models as part of a conceptual toolkit from which to select. Reports of students using several alternative conceptual frameworks *could* therefore indicate an inadequacy in the research, *or* a genuine feature of learners' conceptual structures (Pope & Denicolo, 1996),

It was clear from the beginning of the RP that the need to distinguish these cases would inform appropriate methodology: "a careful interpretation of successive re-enquiries into the frameworks of a particular word used by an individual over an extended period of time, e.g. several years" (Gilbert and Watts, 1983: 87).

Few of the early studies into learners' ideas followed such an approach, however in recent years such studies have started to appear. So as examples, Petri and Niedderer (1998) discuss layers in conceptual structure, Harrison and Treagust (2000) talks about the variety of mental models applied by one learner, and Taber reports how one learner's use of manifold conceptions (2000b) 'shifted' in response to his evolving conceptual ecology (2001a).

Tenet 5. It is possible to model learners' conceptual structures

Driver and her co-workers discussed the nature of learners' ideas (they could be theory-like, coherent, consistently applied), and characterised them as alternative conceptual 'frameworks' (Driver & Easley, 1978, p.68), and this term became widely used (Solomon, 1994). Driver's comments in the early papers were largely referring to learners' ideas in abstract (rather than labelling particular examples), and did not consider in detail how research findings should be presented – although there was a clear assumption that it was possible to model learners' thinking. Gilbert and Watts (1983), however, did consider more explicitly how to represent the findings from research.

Unfortunately a lexicon that all researchers within the ACKiS RP might use was never established when the programme was first established. Consequently, terminology has been confused (Abimbola, 1988) so that different researchers sometimes use the same terms to label different entities, and use different terms when they may be referring to the same phenomena. With many potentially related terms in currency (misconceptions, alternative conceptions, alternative frameworks, preconceptions, intuitive physics, naive ideas, etc.), this has been a major obstacle to clear communication between researchers. As one example, Kuiper (1994) fails to 'replicate' Watts' alternative frameworks for force (1983), but has a different understanding of the term, and so uses methodology that is inappropriate to check Watts' findings (see Taber, 1998).

What are the most appropriate models and representations?

Phillips (1987) has, rightly, been very critical of writing which does not clearly distinguish between the structure of an academic discipline such as science, cognitive structures inferred in learners' minds, and researchers' representations of aspects of learners' cognitive structures. Unfortunately, at the same time that Driver and her colleagues was recommending one meaning for alternative framework, Gilbert and his colleagues were recommending a very different usage. So, an alternative framework could be either

- "the mental organisation imposed by an individual" (Driver and Erickson, 1983: 39) which was utilised "for conceptualising their experience of the physical world" (Driver and Easley, 1978: 62); or
- "a composite picture based upon ideas shared by a number of pupils" (Watts, Gilbert and Pope, 1982: 15), i.e., "generalised non-individual descriptions" and "thematic interpretations of data, stylised, mild caricatures of the responses made by students" (Gilbert and Watts, 1983: 69).

One contested construct is that of 'multiple frameworks' (see the discussion under Tenet 4 above). Pope and Denicolo argued that to 'disaggregate' a learner's statements into smaller parts (that could *independently* be fitted to the different mooted frameworks in the researcher's scheme) would not provide an authentic representation of utterances that *seemed* to genuinely encompass several categories (1986: 159). It could be argued that the notion of multiple frameworks is something of a 'catch-all' (i.e. an *ad-hoc* modification to the protective belt to 'save the phenomenon'): that any data that does not fit into a single framework could *post-hoc* be carved-up and classified according to as many frameworks as might seem necessary. This is a criticism that needs to be taken seriously, but bearing in mind that even professional scientists may operate with diffuse manifold conceptions of key scientific concepts (Bachelard, 1968/1940). Mortimer (1995) has suggested that conceptual change may sometimes be best modelled as a shift in a Bachelardian conceptual profile. Where research follows the thinking of individual students over extended periods of time, to explore the development of their ideas, there is certainly evidence that the individual learner may indeed hold several distinct and relatively stable conceptions for a concept area (Petri & Niedderer, 1998; Harrison & Treagust, 2000; Taber, 2000b). Then, conceptual change can be seen as a gradual shifting in the choice between the manifold conceptions (Taber, 2001a).

Section 4: Consequences for teaching

Many of the research foci considered in the previous two sections are undoubtedly of considerable interest as academic questions in their own right. However, any RP within education must be directed towards pedagogic concerns. Education is about facilitating learning, and so teaching is always a central concern (Pring, 2000). Some criticism of constructivist research in science education has been based around its apparent focus on learners' ideas themselves, rather than on how teachers should respond to them. In this Section the final two tenets of the RP will be considered, as it is here that the research findings deriving from the studies considered above can begin to be used to inform pedagogy.

Tenet 6. The learners' existing ideas have consequences for the learning of science

This statement provides the justification for investigating learners' ideas within the context of educational research. In particular, it draws on the ideas of Ausubel (e.g., 2000) and his notion of meaningful learning. The ACKiS RP grew out of perceptions that teaching the curriculum models of science was often ineffective (Driver & Erickson, 1983: 43), and of the role played by the ideas that learners brought to class (Driver and Easley, 1978).

Driver and Erickson's second empirical premise was that,

> these student frameworks [i.e. existing ideas] often result in conceptual confusion as they lead to different predictions and explanations from those frameworks sanctioned by school science
>
> (Driver & Erickson, 1983: 39)

In their early characterisation of the RP, Gilbert and Swift (1985) only felt confident in proposing two features of the protective belt of the programme: one of which was Gilbert, Osborne and Fensham's "taxonomy for alternative conceptions…based on the notions of 'children's science', 'teacher's science' and 'scientist's science'..." (Gilbert & Swift, 1985: 689). As reported in Section 1, Gilbert and his colleagues suggested that there were a range of outcomes when children's science 'met' teacher's science in science teaching – from teacher's science being adopted, to having no influence, but including various intermediate positions as "children's science and teachers' science can co-exist in varying proportions" (Gilbert, Osborne & Fensham, 1982: 624).

How do learners' ideas interact with teaching?

The basic assumption here, that science teaching interacts with existing knowledge, is not widely contested, and suggested a focus for research, i.e., "identifying and carefully analysing the nature of those possible interactions…" (Driver & Erickson, 1983: 49). Recognising "a danger in a proliferation of 'natural history' studies of student ideas…being documented in the absence of any systematic rationale", Driver and Erickson (1983: 55, cf. Watts, 1988; Black, 1989) identified three "issues that require further consideration if this field of inquiry is to lead to an improvement in students' classroom learning in science":

- developing techniques for assessing knowledge-in-action (cf. Gilbert & Watts, 1983: 83);
- longitudinal studies of students' scientific conceptualisations both during and after formal schooling [which] would make a useful contribution to our understanding of conceptual change;
- more classroom intervention studies… guided by perspectives on learning that take account of the learner's ideas while studying the effectiveness of various strategies aimed at promoting conceptual change (Driver & Erickson, 1983: 54).

So one key priority for research was to investigate intact classes,

> we feel that these types of naturalistic classroom studies are necessary and important in determining the nature of the interactions between student frameworks and various types of instructional practices and in identifying some of the constraints which must be considered in designing more formal instructional techniques and models
>
> (Driver & Erickson, 1983: 50)

Driver and Erickson's call for longitudinal studies was echoed by Gilbert and Watts' argument for "successive re-inquiries" into the frameworks used by individuals over several years (1983: 87, see under Tenet 4 in Section 3). This is one direction where the positive heuristic is leading to useful research. Many of the early studies took a 'snap-shot' approach of exploring learners' ideas at one moment in time. However, there have in more recent years been a number of studies which have explored *individual* learners' ideas over the course of a science topic (e.g., Scott, 1992), or even over a course of study (e.g., Taber, 1995; Harrison & Treagust, 2000), or even explored progression in learning at a *class* level (Johnson, 1998). These studies are starting to offer a deeper insight into the conceptual trajectories or learning pathways that students' thinking follows over time.

One useful perspective here, that does not yet seem to have been taken up as a research focus, is Vygotsky's notion of two classes of concepts. These are the spontaneous, those which "emerge from the child's own reflections on everyday experience", and those he labels scientific - or academic (Vygotsky, 1934) - and which the learner meets through formal instruction (Kozulin, 1985: xxxiii-xxxiv) and which are given verbal definitions and are taught explicitly, unlike spontaneous concepts (Newman and Holzman, 1993: 61). Although spontaneous concepts do not necessarily remain tacit, the distinction *in origin* was very significant for Vygotsky,

> The child becomes conscious of his spontaneous concepts relatively late; the ability to define them in words, to operate with them at will, appears long after he has acquired the concepts…The development of a scientific concept, on the other hand, usually begins with its verbal definition and its use in nonspontaneous operations - with working on the concept itself. It starts life in the child's mind at the level that his spontaneous concepts reach only later.
>
> (Vygotsky 1986/1934: 192)

Vygotsky believed that conceptual development involved a process of convergence as the concrete becomes abstracted, and the abstract is made concrete (1986/1934: 193). Over time, spontaneous concepts would acquire a formal structure and be open to conscious use, and formal scientific concepts would evolve connections with real experience (1986/1934: 194) - indeed scientific concepts provide the frameworks within which a learner could become aware of his tacit spontaneous concepts (Crain, 1992: 213). Research into the possible relevance and utility of Vygostky's model would seem to be indicated by the positive heuristic of the RP.

Tenet 7. It is possible to teach science more effectively, if account is taken of the learner's existing ideas

Tenet 7 may be considered as a logical consequence of Tenet 6, and, again, part of the justification for investigating learners' ideas within the context of educational research. From the beginning, Driver and Easley were concerned with encouraging a research programme that enabled "progress [to] be made in instructional terms" (1978: 68). The third of Driver and Erickson's empirical premises was that,

> Well–planned instruction employing teaching strategies which take account of student frameworks will result in the development of frameworks that conform more closely to school science
>
> (Driver & Erickson, 1983: 39)

The problem was restated more recently by Michael Matthews, who has been very critical of some interpretations of constructivist approaches,

> Many science educators are interested in finding out how, on constructivist principles, one teaches a body of scientific knowledge that is in large part abstract (depending on notions such as velocity, acceleration, force, gene), that is removed from experience (propositions about atomic structure, cellular processes, astronomic events), that has no connection with prior conceptions (ideas of viruses, antibodies, molten core, evolution, electromagnetic radiation), and that is alien to common sense and in conflict with everyday experience, expectations and concepts?
>
> (Matthews, 2000: 179)

Some might question the value of teaching any body of scientific knowledge that is in large part abstract, removed from experience, has no connection with prior conceptions, is alien to common sense and in conflict with everyday experience, expectations and concepts (cf. Millar & Osborne, 1998)! Matthews is one who would feel that any pedagogy based on expecting learners to re-discover the concepts of gene, virus, electromagnetic radiation etcetera, is misguided (Matthews, 1994a), but – as was pointed out above (see under Tenet 1) – a naive discovery approach was never indicated in the ACKiS RP.

There certainly are suggestions in the literature for how teachers might make practical use of research findings – for example by identifying 'learning demand' (Leach & Scott, 1995, 2002) or diagnosing system bugs due to 'learning impediments' (Taber, 2004). However, Millar (1989) has argued that the constructivist model of learning has been (inappropriately) associated with a particular model of instruction. Solomon suggested in 1994 that the 'jury' was still 'out' on the efficacy of the teaching approaches recommended by CLISP (see below), and claimed that "understanding the nature of 'constructivist teaching' is still difficult" (1994: 11, cf. Harlen, 1999). By 2000, Tobin, in reflecting on the constructivist programme, offers a rather circumspect view of what constructivist teaching might mean,

> From a constructivist perspective teachers should take account of what students know and what they can do, how students can negotiate meaning and build consensus by interacting with one another and with artefacts, and how students can put their knowledge to the test and receive feedback on its adequacy
>
> (Tobin, 2000: 233)

How should 'constructivist' teachers teach science?

According to Driver and Erickson "the predominant instructional question…is one of how to facilitate some sort of 'conceptual change' in the learner" (1983: 48). Again, the early position papers provided suggestions for how to proceed. One very significant consideration for conceptual learning in science, that has perhaps not been taken as seriously as it should (for example, certainly not by the curriculum authority in England), was made at the outset of the ACKiS RP. Driver (1983) discussed how alternative frameworks did not seem to be extinguished by teaching. She pointed out that where learners were presented with material at odds with their cognitive structures, then they had to both understand the new ideas, and to be prepared to move outside of their existing modes of thinking, in order "to make the intellectual leap of possibly abandoning an alternative framework which until that time had worked well for them" (1983: 9). It seemed clear that *the time-scale* over which substantial conceptual learning could be expected to occur would be long term: "if we are concerned to influence students' thinking in a substantial and permanent way during schooling then it is realistic to be planning learning programmes over months and years" (Driver and Erickson, 1983: 54). This has clear implications for 'constructivist' schemes of work and curricula. Of the directions Driver and Erickson proposed for research, they suggested that "the most useful information will be obtained from studies of instructional programmes which are undertaken from an explicit theoretical perspective" (1983: 55).

Gilbert and Watts reviewed models of conceptual change and suggested that teaching had to start from the learners' existing conceptual frameworks and "seek to educate by the expansion of applicability of those frameworks or seek to modify them towards the consensus view of formal science" (1983: 83). This approach clearly meant that one key stage in teaching involved making learners' existing frameworks explicit. This consideration led to researchers (see for example, Driver, 1989) positing new conceptual entities as potential objects of research: conceptual trajectories, and the intermediate conceptions that these trajectories may pass through as frameworks become modified.

The CLIS project moved beyond exploring learners' ideas in topics, to investigating teaching, and designing teaching approaches - a constructivist approach to curriculum development (Driver & Oldham, 1986). So, for example, in the topic area of particle theory, several phases of work may be identified. During the first phase, data that had been collected in schools, as part of a national survey, was analysed (Brook, Briggs & Driver, 1984). Subsequently the project explored cases of the existing teaching of the topic in case-study classrooms with teachers sympathetic to the research and keen to try out constructivist-inspired ideas (Wightman et al., 1986). The working group moved to a stage of writing, implementing and evaluating new curriculum materials based on a constructivist approach to the topic (Johnston & Driver, 1991).

The outcomes of the curriculum development seemed to represent the culmination of the work Driver had embarked on at Leeds. However, the degree to which the approaches developed are being applied successfully in English schools is unknown, and are almost certainly constrained by teachers' perceptions of curriculum constraints and the expectations of government inspectors (cf. the situation in New Zealand where curriculum policy is quite different, Bell, Jones & Car, 1995). Certainly, some critics are not yet convinced,

> One point of view, expressed by Rosalind Driver and Valerie Oldham, was that the impasse between the pupils' articulated ideas and the received scientific view could be evolved by getting students to observe and discuss some experiment or data designed to stimulate conceptual change in them. This turned out to be no easy process
>
> (Solomon, 2000: 285)

Despite this, key ideas from the ACKiS RP (e.g., the expectation that learners will have alternative conceptions that need to be addressed in teaching) have become commonplace, and are certainly now part of the orthodox curriculum guidance in science teaching in the UK (e.g., DfES, 2002).

Section 5: Discussion.

This paper has presented a thematic review of research into learning in science, from the perspective of a particular conceptualisation, that of considering a RP deriving from 'constructivist' notions of learning. This review shows that it is possible to identify both a common 'hard core' for the ACKiS RP and its positive heuristic, i.e., to suggest key research questions which directed research "right at the start" (Lakatos, 1970: 175). Different proposals for a hard core could be mooted, leading to an alternative demarcation and characterisation of the RP. However, the present analysis presents a model which is considered to be both inclusive (offering a set of tenets that seem consistent with a wide literature, including studies commonly seen as deriving from several traditions), and coherent enough to offer genuine heuristic guidance to those entering the field.

Despite being a substantial paper, this review is far from comprehensive – as the corpus of work that could potentially be considered part of this RP is immense. Thus the importance of attempting to organise the field from a perspective that might offer some form of synthesis, and in particular give guidance to researchers on fruitful directions for future enquiry.

There have been a range of criticisms of constructivism in science education, as might be expected for any well-established, influential 'movement', especially one which has been recognised as dominating a field. A particular conceptualisation provides a perspective or frame for considering these various criticisms. The frame of a Lakatosian RP allows criticisms to be seen in terms of the hard core and protective belt of the programme (see Taber, in press). Criticisms of the fundamental assumptions of the programme, of the hard core, are potentially (that is, if supportable) serious for the ACKiS RP. However, in the terms in which the hard core has been characterised here, there is little serious challenge in the literature. I would certainly suggest that there is virtually no serious argument in the field of Science Education about the substance (rather than the wording and consequences) of Tenets 2, 3, 4, 5 and 6. Even Tenet 7 is likely to receive very broad support: that is all science educators would surely concede that finding out about learners' ideas and the conditions under which they may change is in principle able to inform science teaching. Disagreements about how this general principle may lead to a notion of 'constructivist' science teaching may be important, but belong in the protective belt - they are proper subjects of debate in the ACKiS RP.

The strongest criticisms of constructivist studies have often come from those who object to the relativist epistemology that is considered to support some of the constructivist literature in science and mathematics education (see the comments under Tenet 1 in Section 2). It would be wrong to disregard issues of epistemology, which are clearly important in science; in the image of science that is reflected through the constructed entity of 'school (and college) science' (Kind & Taber, 2005); and which should guide educational researchers in framing their own research questions, and making methodological decisions about how to address them. Yet, in the model presented here, the hard core of the ACKiS RP posits an assumption about how learners come to ideas about the world, but does not imply assumptions about the nature of knowledge and reality.

Most of the criticism of constructivist research in science education, then, may be seen as arguments about aspects of the auxiliary theory that makes up the protective belt of the programme. From this perspective the critics are entering into valid debate about areas indicated by the positive heuristic of the programme: how learning occurs, what kind of advice the programme can offer to teachers, the nature and significance of learners' ideas. Some of the critics may be uneasy with the 'constructivist' label, or wish to qualify it, but would not seem to object to what I have identified as the hard core of the ACKiS RP.

Some general findings of this review are that:

- the field has been hampered by the lack of coherence in the theoretical constructs used by different researchers; but that
- considerable useful work has been undertaken in relation to some aspects of the ACKiS RP; whilst
- some research directions indicated by the heuristic of the programme have received much less attention (often for understandable reasons).

It is certainly true that progress on some of the research questions indicated by the positive heuristic has been limited, but that need not negate the value of the RP: as Lakatos recognised: "One must treat budding programmes leniently: programmes may take decades before they get off the ground and become empirically progressive" (1981/1974: 120).

It is clear that research has led to a range of useful constructs that can guide aspects of the RP – the 'refutable variants' that can be challenged through further research, "work within a single research programme involves the expansion and modification of its protective belt by the addition and articulation of various hypotheses" (Chalmers, 1982: 84).

Table 2 presents some examples of relevant theoretical notions conjectured in the research reviewed above. This selection is intended to be *purely illustrative*, to demonstrate how such 'refutable variants' allow more specific and detailed research questions to be posed (i.e., Table 2 cf. Table 1) and so develop the positive heuristic of the RP.

In the Lakatosian model, a RP remains progressive by changing, with new refutable variants developed through the research indicated by the positive heuristic. I would suggest that this review indicates that whilst some of the initial research questions remain largely unanswered, the research that has been undertaken has moved the positive heuristic forward: we now have more nuanced and better conceptualised research questions about science learning than could have be proposed by Gilbert and Swift when they characterised the RP in 1985.Beyond constructivism?

The tag of 'constructivism' originally attached to much of the research in this RP has acted as a catchy descriptor, but is perhaps now something of a burden when

- the term is also being used as way of describing a particular approach to social research (which would not encompass all the research within the ACKiS RP), and
- constructivism has become strongly identified in some quarters with brands of relativism that would be supported by few in science education.

examples of refutable variants	heuristic guidance offered: some questions suggested
conceptual ecology	• what type of entities populate the ecology? • how and when are different entities significant for further learning?
convergence of spontaneous and scientific concepts	• to what extent can experiential and formal conceptual learning be organised to be mutually reinforcing?
domains	• to what extent is school science learning compartmentalised by learners, and are there significant individual differences in this? • to what extent is such compartmentalisation due to genetically endowed brain structure rather than learning context (e.g. presenting material under designated curriculum subject and 'topic' headings)?
explanatory coherence	• how coherent are learners' ideas? • to what extent do learners share scientists' epistemological commitments to coherence, consistency etc.
intermediate conceptions	• what are the factors that characterise an intermediate conception which facilitates progression towards target knowledge? • can teachers design effective instruction around intermediate conceptions?
learning demand	• can teachers effectively use diagnostic assessment to identify the learning demand when planning science topics? • what features of the learning demand suggest progression may be more difficult?
learning impediments	• which categories should be included in a typology of learning impediments useful to teachers? • to what extent can a research-informed typology of learning impediments help teachers diagnose failures-to-learn?
learning quanta	• to what extent does working memory restrict the rate at which new science material can be effectively processed? • how can teachers identify a suitable learning quantum? • can teachers help learners 'chunk' material to allow larger learning quanta?
p-prims	• to what extent/when does research elicit stable frameworks rather than provoke the construction of explanations based on more fine-grained conceptual resources? • how fixed are the fundamental units available for cognition? • do all humans share the same p-prims? • what is/are the set(s) of p-prims available to learners?
time for consolidating learning – fragile and robust learning	• does the consolidation period vary significantly, and - if so - which factors does it depend upon? • can reinforcement significantly accelerate the consolidation process? • does learning always have to be 'robust' before it can act as suitable foundations for further learning? (and if not, what are the conditions that determine this?)
two types of conceptual change	• to what extent is this a dichotomy rather than a continuum? • to what extent are different instructional strategies indicated to bring about the two type of change? • how can teachers know which type of change is indicated in particular cases? • how useful is the notion of an ontological tree as a model of conceptual structure?

Table 2: Some examples of 'refutable variants' (theoretical constructs and conjectures making up the protective belt of the ACKiS RP) and questions raised

The active role of the learner *is* still a cornerstone of research, but 'construction' is perhaps just one useful descriptor: learning is also *contingent* (upon the cognitive resources available, on the teaching provided, on the ideas triggered through student dialogue), and so the new *connections* made are *constrained* and *channelled*. Understanding *learning in science* requires research into the contingencies that constrain and channel the connections made during the construction process.

Perhaps Solomon (1994) was premature in suggesting the fall of constructivism, as old RP (at least when progressive) undergo metamorphosis rather than fade away, "I had not reflected then that when an educational perspective is no longer new it is far more susceptible to change than to extinction" (Solomon, 2000: 285)

Rather than suggest that constructivist research is a spent force, this Lakatosian analysis suggests that this body of work can be understood as an important, if flawed and uneven, part of an ongoing progressive research programme into learning in science. Perhaps the 'constructivist' label is now passé or disreputable in some quarters, but the hard core of the constructivist programme identified here seems sound. Perhaps being "commonplace and unremarkable…and…too well known to be thought worthy of comment" (Solomon, 1994: 6) is exactly how we *should* expect the hard core to appear to those working in a RP.

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