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Constructivism in Education: Interpretations and Criticisms from Science Education

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Abstract

Constructivism has been widely adopted as a referent for research, curriculum development and recommended pedagogy in education. This chapter considers key issues relating to the adoption of constructivist thinking in education which have arisen within the field of science education. Constructivism has been mooted as a dominant paradigm in science education, where it has informed a major research programme over some decades. However, the application of constructivist ideas in science education has also been subject to a range of critiques. This chapter gives an outline of the developing influence of constructivism in science education, and the common understandings of the term in relation to science teaching and learning; it reports on the main areas where the influence of constructivist thinking has been heavily criticised, and discusses how these criticisms are countered within the research programme; it considers some major directions for research within the research programme; and it evaluates the level of influence of constructivism in contemporary science education practice.

Keywords:

Alternative Conceptions, Alternative Frameworks, Constructive Alternativism, Contingency in Science Learning, George Kelly, Genetic Epistemology, Imre Lakatos, Jean Piaget, Pedagogic Constructivism, Personal Constructivism, Psychological Constructivism, Radical Constructivism, Scientific Research Programmes, Science Pedagogy

Introduction

Constructivism is a term that is commonly met in educational and wider social science discourse, although it is used with a range of different meanings and associations relating variously to educational philosophy, research epistemology, cognitive development, learning theory, and approaches to pedagogy (see Figure 1). Constructivism has - or, perhaps more accurately, 'constructivisms' have - been especially influential in science and mathematics education, although the mantra 'we are all constructivists now' (Wheeler, 1987, p. 57) has been propagated (Brubaker, 2009; Donmoyer, 2012) - and challenged (Bader, 2001; Lesh & Sriraman, 2010) - much more widely. Constructivism is sometimes associated with philosophical and sociological stances that have questioned traditional views of the nature of public knowledge and its 'production'. So a naive notion of the nature and production of scientific knowledge has not only been challenged through scholarship in the philosophy of science (e.g., see Taber, 2009a), but through the increasing importance of the sociology of knowledge with its focus on the social construction of (what is taken in particular cultural contexts as) reality (Berger & Luckmann, 1991), and which has drawn attention to the social and institutional aspects of knowledge production (G. N. Gilbert & Mulkay, 1984; Latour & Woolgar, 1986).

Whilst these debates about the nature of canonical knowledge and how it is acquired are potentially important for fundamental educational questions relating to the purposes of schooling and the structuring and selection of curriculum, the form of constructivism which has arguably had the most impact on classrooms around the world is constructivism as *a perspective on learning that has consequences for how to teach canonical knowledge*. Constructivist learning theory is certainly not divorced from wider epistemological considerations, but can inform teaching practice without requiring commitment to the more contentious forms of constructivism. This chapter will argue that this is already a common situation in science classes around the world where constructivist thinking on pedagogy has been widely influential. Although the chapter draws upon the specifics of science education - where constructivist influence has been both widespread and often vigorously debated - the 'hard core' premises of the constructivist research programme in science education (as detailed below) would seem to be equally applicable to any area of the curriculum that is concerned with teaching a body of canonical public knowledge (Sjøberg, 2010).

The chapter discusses then how constructivism has been understood and adopted as a referent in science education. Constructivism has been a key idea underpinning much research, curriculum innovation, and teacher development in science education since the 1970s. However, constructivism has been understood in different ways, and the 'flavour' of constructivism widely adopted within science education has been of a kind sometimes called pedagogic constructivism or psychological constructivism (see Figure 1), which is not completely aligned with some forms of constructivism that have been influential in other areas of scholarship (for example the use of the term constructivism as a label associated with a particular epistemological stance adopted in some educational research and evaluation). This is discussed further later in this chapter.

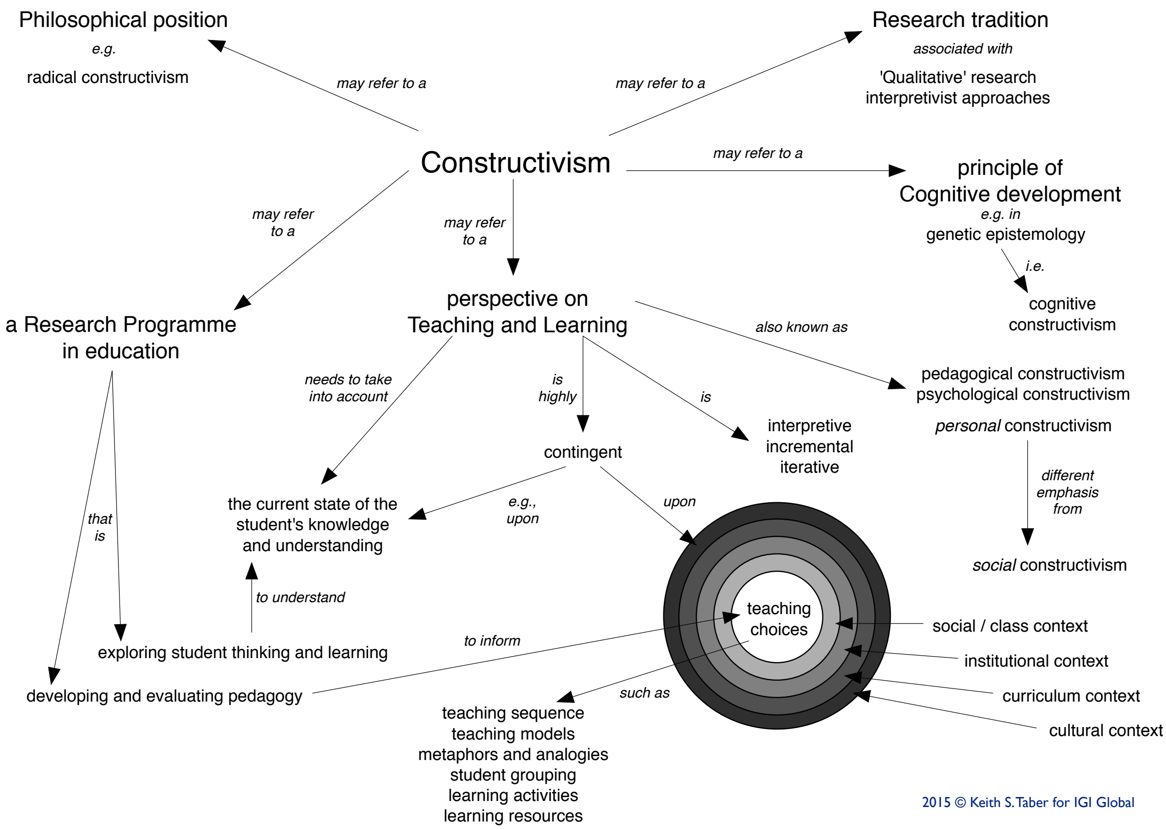

Figure 1: Constructivism in Education

Perhaps due at least in part to a lack of a consensual understanding around what being a 'constructivist' in science education entails, the constructivist movement in science education has been subjected to a range of critiques from both within and beyond the field. These critiques have concerned the underpinning commitments of constructivism, and the desirability of its perceived aims, as well as its value in informing effective science teaching. Despite the diversity of presentations of constructivism in the science education literature, and - in particular - the lack of consistency in nomenclature in the field, it is possible to identify a canon of seminal literature which offers a basically consistent representation of what can be considered the 'hard core' of a constructivist research programme - in the sense that the philosopher of science Imre Lakatos (1970) described scientific or 'progressive' research programmes. Consequently, an analysis of constructivism in science education as a Lakatosian research programme can provide a basis for exploring the relative merits and limitations of the common critiques of constructivism in science education (Taber, 2006b) as well as offering guidance on productive directions for further work in this area (Taber, 2009a).

This chapter will:

- offer an account of the nature and influence of constructivist ideas in science education;
- summarise how this area of work can be understood as a scientific research programme;
- describe the nature of the main critiques that constructivism in science education has faced, and offer an analysis of the these critiques;
- provide an overview of the current status of constructivist thinking in science education and main directions for continuing research.

Background

Constructivism became highly influential in science education as a result of a shift in research focus that took place in the late 1970s and early 1980s away from the domain-general approach to exploring cognition in science learning that drew in particular upon Piaget's (1929/1973, 1959/2002, 1970/1972) work towards a concern with how learners understood different concept areas in the sciences (Driver & Easley, 1978; Driver & Erickson, 1983; J. K. Gilbert, Osborne, & Fensham, 1982; J. K. Gilbert & Watts, 1983; Osborne & Wittrock, 1985). This shift led to a wide interest in exploring student thinking (prior to, but also after, instruction) in a wide range of science topics.

Piaget (1970/1972) had over many years developed a theory labelled genetic epistemology that described cognitive development in terms of a series of invariant stages through which all learners would pass. The types of mental operations available to a child were considered to be determined (and so constrained) by the stage of cognitive development reached. Of particular relevance to science education, Piaget's work suggested that the kind of theoretical thinking characteristic of science - where abstract concepts are themselves made the subject of mental operations, formal operational thinking - was only developed by most learners during adolescence. This implied that many school age children, even in the secondary grades, were not equipped to master many of the abstract scientific ideas that are commonly specified in school science curricula (Shayer & Adey, 1981).

Piaget's ideas had been, and to a lesser extent continue to be, very influential in science education (Adey, 1999; Bliss, 1993), but their implications came to be seen to be largely in terms of setting out *limitations* on student thinking and learning. Although one reading of Piaget's model of cognitive development is that it sets out the new forms of thinking that become available to the developing mind at each stage, this entails the corollary that other more advanced forms of thinking are not yet available to the developing person at this stage. This perspective was being challenged by the more optimistic message deriving from educational thinkers such as Bruner (1960) who suggested that teachers could find ways to teach appropriate simplifications of complex and abstract material to even quite young children.

Another feature of Piaget's work which has attracted criticism was his identification of the stage of formal operations as the end-point of human cognitive development. It was suggested that this was too strongly tied to the kind of logical thinking associated with activities like mathematical deduction and scientific hypothesis-testing that in an ideal form concerned closed systems of logic - where problems had an unambiguous solution based on sufficient and clear evidence. It was argued that real world problem-solving was seldom as tidy as this ideal and commonly involved seeking the best available of several suboptimal solutions given incomplete, potentially unreliable, and often somewhat contradictory information (Arlin, 1975; Kramer, 1983). Some thinkers pointed to the notion of wisdom as reflecting higher cognitive abilities beyond formal operations, and explored ideas about the development of wisdom over the human lifespan (Sternberg, 2009). Theorists who examined development beyond logical thinking to encompass moral and ethical reasoning highlighted the continuing development of cognitive abilities well into adulthood (Kohlberg & Hersh, 1977; Maslow, 1970; Perry, 1970). Such more mature modes of thinking become especially important when students are learning about socioscientific issues (Sadler & Zeidler, 2009) where scientific understanding informs value-based thinking about economic, environmental, medical and other complex contexts.

Whilst Piaget's stage theory remained influential it became used less as a key referent for work in science education. Some other aspects of Piaget's work continued to be seen as widely valuable. One such feature was how Piaget's theory posited an iterative aspect to development: with the attainment of each stage providing the basis for subsequent development. Whilst work within the constructivist programme in science education was not generally tied to the Piagetian stages, the notion that conceptual learning was iterative - so that current conceptual understanding acts as a basis for interpreting new learning - became widely accepted. Moreover, Piagetian terms such as accommodation and assimilation were widely adopted within the constructivist literature for discussing conceptual change (J. K. Gilbert & Watts, 1983) - that is, in considering how a person changes their conceptual understanding of some scientific topic.

In Piaget's model, the 'assimilation' of new experience may lead to a 'disequilibrium' - but Piaget considered that evolution had equipped human cognition with the ability to respond to this by producing an 'accommodation' that returned the system to 'equilibrium'. Within later constructivist work the terms 'assimilation' and 'accommodation' were sometimes recruited (and in the process distorted) to refer to two different kinds of conceptual learning (Posner, Strike, Hewson, & Gertzog, 1982), where Piaget had considered assimilation and accommodation as two steps in a single overall process of change. Assimilation was commonly used as a label for learning new ideas that could be unproblematically adopted within existing ways of thinking, whilst accommodation was used to describe the learning of new ideas that required a shift in previous thinking - a restructuring of existing conceptual structures. Consider for example a student who knew about a number of common metals (perhaps iron, copper, aluminium) and believed that all metals are magnetic. From a scientific perspective only a few metals are magnetic (that is, ferrormagnetic). This student could assimilate learning that cobalt is a metal, and is magnetic, with the existing idea that metals are magnetic. However, learning that tungsten is a metal which is *not* magnetic would need to be accommodated by modifying the existing belief that all metals are magnetic.

Piaget's methodology - the clinical interview - was also widely adopted among constructivist researchers as a means to explore the details of student thinking about a topic. Piaget had adopted this approach after recognising the methodological challenges of using naturalistic observation of youngsters' spontaneous talk to identify the patterns in their thinking (Piaget, 1959/2002). Most importantly, the constructivist ethos of Piaget's work was influential - the idea that the individual is constructing an internal representation of the outside world as the basis for making sense of, and planning action in, that world. This was a strong theme, for example, in the work of Ernst von Glasersfeld (1989) who became highly influential in both mathematics education and science education. Glasersfeld, who referred to his stance as radical constructivism (discussed further below) also cited the Neapolitan philosopher Giambattista Vico who had written about constructivist epistemology at the start of the eighteenth century as a major influence (Glasersfeld, 1990).

The term constructivism drew upon the adoption of a notion of coming to knowledge as a process of *constructing* internal mental representations of the world. Viewed from this perspective, learning is a process of knowledge construction, that depends upon both the 'tools' (such as available cognitive operations) and 'materials' (aspects of existing thinking that can provide the basis for making sense of new information) that the learner can access. It should be noted that the meaning of the term knowledge when referring to knowledge construction is somewhat different to traditional philosophical notions of knowledge as justified true belief (Bhaskar, 1981): constructivist researchers are interested in the mental constructions that comprise what people "believe to be the case or simply consider as a viable possibility" (Taber, 2013c, p. 179). The Piagetian model suggested that the general cognitive operations (i.e., the 'tools') available to a learner at a particular stage of cognitive development were limited - although one Piaget-inspired research programme (Adey, 1999) investigated how to 'accelerate' progress through the stages - and many researchers in science education thought that a more productive focus for research was to investigate the resources learners had available for science learning in terms of their existing ideas (i.e., the 'materials') prior to teaching.

Where Piaget had interviewed children in detail with a view to identifying underlying structures supporting their thinking across domains, science education researchers adopted interviews to explore the ways students thought about different specific science topics, and in particular sought to identify common 'alternative conceptions' or 'alternative frameworks' that students adopted, but which were inconsistent with canonical scientific theories and concepts. Researchers found children's and students' (and, when tested, adults' - often including science graduates' and teachers') ways of making sense of scientific topics were often non-canonical and unexpected, and some researchers found learners' alternative ideas completely fascinating. The sense that some research was exploring students' ideas as a phenomena of interest in its own right, regardless of the practical value of knowing about them to inform teaching, become the basis of one criticism that was sometimes directed at this area of research (an issue considered below).

A major research tradition developed based upon exploring learners' intuitive ideas and 'alternative conceptions' before, during, and after instruction (Duit, 2009) and this has continued, albeit with somewhat reduced intensity, to the present day. The research programme (Taber, 2006a, 2009a) was intended to inform curriculum development and pedagogy by providing a better understanding of the nature and origins of students' ideas and how these influenced the way learners understood teaching (Driver & Oldham, 1986). This programme was sometimes labelled as the 'alternative conceptions movement' (J. K. Gilbert & Swift, 1985), and became referred to as 'misconceptions research' as one main outcome was a developing literature base cataloging the great many ways learners could misunderstand the concepts presented in science teaching. The research programme was certainly extensive (Duit, 2009), and did find examples of alternative conceptions presented by learners at all stages of education in all areas of science investigated - whether questioned before of after being taught topics.

One of the most significant claims made was that learners' alternative conceptions could be very tenacious, being resistant to change such that simply presenting the canonical science was unlikely in itself to lead to learners abandoning their existing ways of thinking to adopt scientifically sound understanding. Students' ideas were worth studying because they had consequences for teaching and learning in science classes (Driver & Easley, 1978; Driver & Erickson, 1983; J. K. Gilbert et al., 1982; J. K. Gilbert & Watts, 1983; Osborne & Wittrock, 1983). This claim was both widely made, and sometimes challenged (as discussed below) but became part of the orthodoxy within the constructivist programme.

This led to a major focus on the nature of conceptual change and the development of conceptual change pedagogy (Duit & Treagust, 2012; Vosniadou, 2008) - finding ways to teach which could bring about significant and permanent changes in student thinking about scientific concept areas. A key recommendation from much of this work was that teaching should often begin with an exploration of students' current thinking (Driver & Oldham, 1986; Russell & Osborne, 1993). The constructivist notion of learning implied teaching should be informed by knowledge of students' current state of knowledge and understanding, but recommendations for constructivist pedagogy went beyond this to suggest that learners *themselves* had to make explicit their existing understanding as a prelude to engaging in learning activities that could support the restructuring of their thinking.

By the last decade of the twentieth century a number of commentators observed that constructivism had come to dominate thinking in science education, such that it became the theoretical perspective underpinning a good deal of the research, teacher development and curriculum development activity in science education (Fensham, 2004; J. K. Gilbert, 1995; Solomon, 1994). Indeed constructivism was said to be the dominant paradigm in the sense that Kuhn (1996) referred to paradigms of 'normal science' being established in a field of research. This extended beyond the research community to influence governments' educational policies (Bell, Jones, & Car, 1995; Taber, 2010).

The constructivist research programme in science education

The flavour(s) of constructivism informing science education

The term 'constructivism' has been used inconsistently in the wider literature, which leads to the term having different entailments in different contexts (Bickhard, 1998; Bodner, Klobuchar, & Geelan, 2001; Phillips, 1995) as suggested by Figure 1. Constructivism is sometimes linked to general epistemological commitments or to approaches to research. So constructivism may be associated with a broad epistemological stance at odds with traditional positivist scientific assumptions about the possibility of developing objective knowledge of an external world that exists independently of human minds (Glasersfeld, 1989). This may sometimes also be associated with idealist notions that reality itself is constructed by the human mind, although it has also been argued that there is a sense in which constructivist ideas transcend (or at least make less relevant) the traditional philosophical opposition of realism (that there is an external world open to objective investigation) and idealism (that reality is the construction of human minds) (Chiari & Nuzzo, 1996).

The label 'constructivist' is also sometimes associated with a paradigm, or research tradition, within social research that collects and analyses qualitative data to explore peoples' perceptions and experiences. Guba and Lincoln (2005) consider that constructivism as a research paradigm has a relativist ontology and a transactional or subjectivist epistemology. They suggest the appropriate methodologies to apply in constructivist research are hermeneutical or dialectical. Whilst such descriptors might certainly be applied to *some* constructivist research in science education, other studies have proceeded with a positivistic stance towards what is being researched and attempted to apply nomothetic methodology (Taber, 2014a).

This lack of clear agreement over the ontology of what is being studied, and the appropriate epistemological commitments to adopt, can be seen as one of the reasons why researchers have sometimes failed to agree on the conclusions to be drawn from research (Taber, 2013c). An example of this would be Kuiper's (1994) failure to 'replicate' the findings of Watts (1983) when exploring students' conceptions of the force concept. Although both authors referred to the possibility of students holding 'alternative frameworks' for the force concept, they presented inconsistent notions of this construct and Juiper employed a positivistic approach to identifying students' conceptual frameworks inconsistent with the more hermeneutical interpretivist methods used by Watts. This example, which has been analysed in more detail elsewhere (Taber, 2013a, pp. 61-66), reflects a wider tendency for researchers in this field to either define research constructs loosely or to fail to adopt a common terminology for the foci of research (Abimbola, 1988; Taber, 2013c).

The forms of constructivism that became popularly espoused in science education were usually personal and psychological, and sometimes explicitly cognitivist (in the sense developed later in this section). They commonly drew upon the personal constructivist aspects of Piaget's (1929/1973) work with its focus on the individual epistemic subject building knowledge structures for interpreting the world, and were also widely influenced by the personal construct theory of Kelly (1963) which suggests that an individual develops a unique system of 'personal constructs' that are (often implicitly) applied in making discriminations - i.e. in making sense of perceptual data. Kelly referred to his perspective as 'constructive alternativism', a term which reflects both how each individual constructs their own unique system for construing experience, and also how the individual can come to shift their construct system to construe their experiences differently (something especially relevant to Kelly's clinical practice as a therapist).

A leading activist for Piaget-influenced constructivism who had a considerable impact on science (and mathematics) education at this time was von Glasersfeld (1989) through his 'radical' constructivism (Glasersfeld, 1990). This form of constructivism was *psychological*, in the sense that it was concerned with mental phenomena - how the mind constructs understanding of the external world - rather than arguing that reality itself was actually constructed. Other strong influences were Ausubel (1968) who had written about the conditions for meaningful learning in terms of a learner being able to relate teaching to material already available in his or her existing cognitive structure (work that can be considered to complement Gagné's (1970) ideas about the conditions needed for learning to occur), and Vygotsky (1934/1986, 1978) who had long before written about, *inter alia*, the role of language as a tool for thinking and the way taught concepts - that is 'scientific' or 'academic' concepts (Vygotsky, 1934/1994) - were understood by a learner in relation to his or her spontaneously developed concepts.

This form of constructivism was also *personal*, in the sense that the focus was on how the individual came to construct their personal knowledge, a standpoint that had been adopted in the Piagetian programme. However, the perspective was also personal in a sense in which Piaget's work was not: as whereas Piaget was concerned with an epistemic subject who could represent any human with 'normal' cognitive development (a nomothetic perspective), the constructivist programme in science education also expressed a concern with individual differences. The role of social interactions in learning was certainly acknowledged in the developing research programme - something emphasised in the writings of Vygotsky and his champion Bruner (1986) - but the focus was on how social activity structured the processes by which the minds of individual learners came to acquire aspects of human culture (such as the theories and models of canonical scientific thought).

In some topics researchers found very common alternative conceptions or alternative frameworks, and some work considered useful to teachers concentrated on identifying the common alternative ideas likely to be found among students in most classes. Perhaps the archetypical example comes from the topic of force and motion where studies suggest the vast majority of people come to adopt fundamentally the same 'alternative framework' for making sense of how forces influence the motion of objects (J. K. Gilbert & Zylbersztajn, 1985; McCloskey, 1983; Watts & Zylbersztajn, 1981) - a framework where force changes the speed (not acceleration) of an object and where (counter to Newtonian physics) an object moving (even if with constant velocity) is considered to necessarily be subject to a force. This is sometimes denoted F-v thinking (Viennot, 1985) because force is considered to be associated with velocity rather than acceleration (canonical F-a thinking). This way of thinking does seem to be very common across many different sampled populations, suggesting there is something common to most people that leads to them being likely to think in this way. Indeed, given everyday experience of objects in the world, the common alternative framework can be understood as a fairly reasonable abstraction of a great deal of experience: where school physics models object movement in terms of ideal situations such as frictionless systems, actual objects we move around in everyday life are subject to resistive forces that soon bring them to a stop when we do not continue to apply a force to move them.

Force and motion is not the only topic where learners have been found to present with common alternative conceptions and frameworks. An example that is not so easy to explain in terms of everyday life experience is a very common alternative framework (the 'octet' framework) found among chemistry learners who think about key theoretical topics such as chemical stability, chemical reactions and chemical bonding in terms of a need for atoms to acquire particular electronic configurations (Taber, 1998, 2013b). Common alternative conceptions are also found in many other scientific topics, although in most cases they do not reach the dominance of F-v thinking in mechanics or the octet framework in chemistry. It should also be noted that although research suggests that most learners adopt these ideas when studying these topics, they do not use them exclusively. Studies suggest that learners commonly switch between different conceptions depending upon contextual factors (Mestre, Thaden-koch, Dufresne, & Gerace, 2004). So, for example, although most students of school age investigated have been found to commonly use a form of F-v thinking in at least some contexts, it is also found that varying contextual details of a question that would be considered irrelevant from a physical perspective can lead to respondents switching between different conceptions of force and motion (Palmer, 1997). The philosopher (and former school science teacher) Gaston Bachelard (1940/1968) had argued that scientists' concepts tend to be multilevelled as they reflect the impressions of the different phases of the development of scientific ideas. In the case of the 'octet' conceptual framework in chemistry, it has been found that progression in learning (conceptual change) can be observed to be a gradual shift away from the tendency to reason within this framework towards a greater adoption of other more physical principles based on interactions between charges rather than the desires of atoms (Taber, 2001). It has been suggested that conceptual change in science learning may be more widely understood as a shift in the profile of use of aspects of manifold concepts (Mortimer, 1995).

Moreover, even in a topic such as force and motion where research suggests widespread adoption of the 'same' non-canonical reasoning pattern across diverse populations of students, there is a sense in which it is inappropriate to refer to different learners adopting the 'same' alternative conceptions. In-depth studies of individuals suggest that each learner develops their own unique (and sometimes idiosyncratic) associations - and so therefore responses to particular contextual cues - that make each person's conceptions personal in the sense of being unique to that individual. So when studies explore the ideas of small numbers of individuals in detail, they reveal a range of ways of making sense of a scientific topic area such as force and motion (Watts, 1983). There is then within the constructivist programme in science education work that tends to focus on the commonalities found among different learners in terms of alternative ways of understanding science topics that appear in high frequency when populations are surveyed; but also work which explores the thinking of individuals in great detail, seeking to characterise particular, and potentially unique, conceptualisations of those individuals. This can be seen to give rise to a tension between a more nomothetic and a more idiographic commitment within the research programme, although these different stances may better be seen as complementary (Taber, 2009a).

The form of constructivism adopted in science education could also be considered *cognitivist* in the sense that the learner's coming to make sense of the world was often conceptualised as the outcome of processing information in the learner's cognitive system (Taber, 2013c) Some early champions of constructivism in science education emphasised the information processing aspects of cognition which underpinned knowledge construction. This was particularly so in the work of Osborne and Wittrock (1983, 1985) who developed what they called a 'generative' learning model.

Key commitments of the constructivist research programme in science education

According to Lakatos (1970), a scientific research programme has a hard core of assumptions that are established as its inception. The hard core is the set of ideas that are taken as starting points for a programme and are inherent within it (such that abandonment of those commitments is in effect abandonment of the research programme). It has been argued that if key literature dating from the late 1970s and early 1980s (e.g., Driver & Easley, 1978; Driver & Erickson, 1983; J. K. Gilbert et al., 1982; J. K. Gilbert & Watts, 1983; Osborne & Wittrock, 1985) is examined, it is possible to identify just such a hard core. This hard core has been represented (Taber, 2006a, 2009a) as a series of fundamental tenets adopted in the programme. Although the first four tenets make explicit reference to science learning and teaching they could easily be reformulated to reflect other subject areas, or academic learning in general:

- Learning science is an active process of constructing personal knowledge;
- Learners come to science learning with existing ideas about many natural phenomena;
- The learner's existing ideas have consequences for the learning of science;
- It is possible to teach science more effectively if account is taken of the learner's existing ideas;
- Knowledge is represented in the brain as a conceptual structure;
- Learners' conceptual structures exhibit both commonalities and idiosyncratic features;
- It is possible to meaningfully model learners' conceptual structures.

The nature of scholarly work in education (or indeed many other fields) is such that although research reports are generally expected to begin by contextualising a study within the existing literature, authors do not necessarily offer a strong association of their work to an explicit research programme. Indeed although some attempts had been made to offer a programmatic perspective on constructivism in science education much earlier (most notably J. K. Gilbert & Swift, 1985), the formal detailed analysis of the programme drawn upon here was only made after work had been continuing for several decades. Consequently, whether a particular study should be considered as falling within the constructivist research programme in science education is a matter for interpretation. However, it is clear that there is a vast literature in science education which is based upon the premises above (or the subset of them relevant to the particular study). Sometimes these points are explicitly made by authors in setting out the conceptual framework for their research, although there also many studies where such commitments are not stated, but seem to be implicit given the nature of the research undertaken (Taber, 2013c).

Critiques of constructivism in science education

The constructivist tradition in science education began to to be widely criticised along several lines in the 1990s. The key criticisms were (Taber, 2006b, 2009a) that

(a) the approach unduly dominated the field, but had not produced the promised advances in effective pedagogy (Solomon, 1994);

(b) constructivism was an inherently relativist perspective that was incompatible with the nature of science itself (Cromer, 1997; Matthews, 1994a; Scerri, 2003);

(c) constructivist pedagogy has been shown to be inferior to 'direct instruction' (Kirschner, Sweller, & Clark, 2006);

(d) constructivism was being applied as an imperialist tool to undermine indigenous cultures through imported approaches to education in developing countries (Bowers, 2007);

(e) personal constructivism was inconsistent with developments in sociocultural and cultural-historical theory within the field (Smardon, 2009);

(f) student conceptions did not amount to the impediments to learning claimed by some researchers (Claxton, 1993; Solomon, 1994).

Each of these challenges to the influence of constructivism has met robust responses (Taber, 2006b, 2009a). Some of the criticisms certainly have some merit, but can be understood to highlight aspects of the programme that need further development and to suggest directions for further work, rather than implying that the programme is fundamentally flawed. The following sections are structured in relation to these areas of key criticism.

The constructivist programme has provided a valuable knowledge base that informs good practice

Whether the dominant influence of constructivist thinking on research undertaken in science education (in the 1980-1990s for example) distorted the field is a moot point, but there was certainly a great deal of research activity within this programme, some of which can be considered to be akin to a natural history approach (focusing on identifying and characterising alternative conceptions in different areas of science) and which therefore made limited contribution to theoretical development of the field. That is, much research was premised on the generally accepted principle that teaching should be informed by a knowledge of the ideas students are likely to bring to class, and therefore it would be useful to survey different student populations to identify particular conceptions and report how frequently students within samples presented with those conceptions. Such research contributed to the 'breadth' of work in the field, and could indeed be drawn upon in reviews to inform teachers (e.g., Driver, Squires, Rushworth, & Wood-Robinson, 1994), but did not lead to a 'deeper' understanding of student conceptualisations and how they developed.

Yet not all work was of this kind, and advances were made in appreciating the dimensions along which student conceptions varied and how this linked to how tenacious they might be and therefore the kinds of teaching strategies that could be expected to bring about conceptual change. Particular issues here were (i) the extent to which learners' ideas could be understood as relatively isolated notions (Claxton, 1993) or well integrated into extensive conceptual systems (Taber, 1998); (ii) the significance of the manifold (multiple) nature of students' conceptualisations of scientific concepts for the processes of learning (Petri & Niedderer, 1998; Taber, 2000); and (iii) the extent to which the ideas learners presented within research derived from explicit knowledge structures that are available to conscious reflection rather than largely implicit knowledge structures that insidiously inform conscious thought (diSessa, 1993).

Research suggests that student conceptualisation varies across such dimensions so that it is not possible to consider all kinds of conceptions to have the same nature and status within an individual's cognitive structure: some ideas are isolated, and readily abandoned; some are well established as part of highly integrated ways of thinking and not easily challenged by the teacher's authority or the presentation of apparently disconfirming evidence. Some ideas learners present with are informed by explicit, verbalisable/visualisable representations that are available to conscious examination and reflection - but others are based on tacit knowledge that is not open to direct introspection and leads to what is just taken for granted as the natural way of things (Schutz & Luckmann, 1973) and so not questioned (Karmiloff-Smith, 1996). Sometimes learners only bring one way to think about a topic to class: but sometimes their ideas are manifold - perhaps leading to cuing of particular ways of thinking according to context - giving the possibility of teaching being able to encourage shifts towards the (scientifically) most productive available way of thinking about a topic (Hammer, 2004; Taber, 2001). The research has shown that constructivist pedagogy needs to be sensitive to this variability, and to how different students in a class may not only present with different conceptions about a concept area, but may appear to have the 'same' alternative conception without it having the same status in their thinking.

Pedagogic constructivism is consistent with scientific realism

Criticisms about constructivism in terms of its philosophical leanings (Cromer, 1997; Matthews, 1994a; Scerri, 2003) have sometimes reflected a lack of clarity about such matters in the reports of researchers (Taber, 2013c). This has allowed criticisms that science educators adopting constructivism are espousing ontological or epistemological positions inconsistent with the science they claim to be seeking to teach. In practice, most 'constructivist' science educators accept the existence of an external reality (beyond the mind) and so the possibility in principle of seeking objective knowledge about the world. However, constructivist theorists may argue (i.e. so called radical constructivism) that all the individual can *directly* know is the model of external reality they are able to construct through their interpretations of sensory data (including the representations of the ideas of others through speech, writing etc) and so *certain* knowledge of the nature of the external reality is not possible (Glasersfeld, 1989, 1997). When presented in these terms, the constructivist position does not seem greatly at odds with post-positivist accounts of the nature of science (Taber, 2009a).

Earlier in this chapter it was noted that the constructivist notion of learning as knowledge construction uses the term knowledge in a somewhat different way to the traditional philosophical definition of knowledge. Knowledge was at one time widely understood in philosophy to refer to true, justified belief. That is, for something that someone believes to be considered knowledge then what they believe must be objectively correct, and they must have valid grounds for that belief. This is a definition therefore which relies upon an notion of there being absolute standards for judging what is the case, assuming an objectively knowable world. Before someone can be said to have knowledge (in these terms) that water is a compound with the formula H_2O, we must be able to say with certainty that water is a compound with the formula H_2O. For most sensible purposes scientists and science educators would consider a statement such as 'water is a compound with the formula H_2O' to be an objective fact - something that is known for sure about the world in which we live (that is, a reality beyond our individual minds which is objectively shared by us all).

However, the requirement that knowledge must be justified true belief, rather than simply a true belief, adds a complication. We might ask what kind and level of justification is sufficient before we consider a student to be considered to hold knowledge that 'water is a compound with the formula H_2O'. We might ask if it is enough that the student has acquired this information by reading a recommended textbook or listening to her teacher, or whether justification has to involve a full understanding of the scientific evidence and arguments which led to the statement that 'water is a compound with the formula H_2O' becoming considered canonical knowledge in science. Even if we did not feel that was necessary, we might ask whether the student can be considered to have knowledge that 'water is a compound with the formula H_2O' if - for example - their personal conception of the concept of a chemical compound is known to be seriously flawed.

Moreover, if we consider other examples we find further difficulties with the traditional notion of knowledge. We might wonder whether Lamarck had 'knowledge' of evolution given that his model of evolution was later discredited. We might ask (for example) whether a student could have 'knowledge' that 'the molecular orbitals in the compound methane derive from overlap of sp^3 hybridised atomic orbitals on the carbon atom' if they considered this to be a definitive description of objective reality rather than a theoretical statement reflecting a scientific model. Given such complications, constructivist researchers have explored student 'knowledge' in broad terms to include beliefs and other notions being given serous consideration as viable accounts of aspects of the world (Taber, 2013c).

Constructivist teaching is optimally guided instruction

The claim that constructivist teaching is actually inferior to what is referred to as direct instruction has been a key feature of a major debate (especially in the United States) about effective pedagogy (Tobias & Duffy, 2009). This claim appears contrary to a great many research reports in the science education literature that have claimed constructivist approaches were superior to 'traditional' teaching methods when tested in a wide range of contexts. In part the contention here reflects the difficulty in setting up fair tests in educational research given such complications as novelty effects, expectancy effects, teacher effects, and the time needed for teachers to adopt a new mindset and develop expertise when asked to teach in an unfamiliar way. In part the debate links to questions about which educational objectives are being used to judge teaching effectiveness: to some extent there is a 'horses for courses' factor, in that different teaching approaches may (for example) differentially support the learning of canonical knowledge, rather than developing transferrable enquiry skills. However, a major problem with the work of the critics of constructivist approaches (Kirschner et al., 2006) is how they characterise constructivist pedagogy as involving minimal guidance, that is as learners proceeding with limited input from the teacher. This is certainly not how constructivist teaching is understood in science education (Driver, 1983; Driver & Oldham, 1986).

One critic goes as far as asking why constructivists think learners should "construct for themselves" such scientific concepts as potential energy and valency (Matthews, 2002, p. 130). Yet one of the initiators of the constructivist programme in science education had made it very clear that students were very unlikely to re-invent scientific concepts for themselves without strong guidance from teachers (Driver, 1983).

Constructivist teaching assumes that learning is a process of personal knowledge construction that necessarily occurs within the minds (and so brains) of individual learners and which is contingent upon the resources the learner has available to interpret teaching. Therefore teaching involves activities to identify and activate relevant prior knowledge (including drawing upon students' own interests and experiences), and includes 'active' learning that encourage students to reflect on their thinking and ongoing learning - often mediated through discussion work (Devetak & Glažar, 2014). This does not however equate to a low level of teacher guidance. Although the constructivist teacher intersperses periods of 'telling' the class the accepted science narrative with periods when students are exploring, testing and developing their own ideas (Mortimer & Scott, 2003; Scott, 1998), the lesson activities are structured and coordinated by the teacher, who aims to provide the optimal level of guidance to encourage learning (Taber, 2011).

Some critics of the constructivist approach (Cromer, 1997; Matthews, 2002) have taken description as prescription. The key constructivist thinkers in science education were not arguing that students *should* construct their own knowledge (and so they should be allowed by teachers to get on with it), but rather that it is the nature of human cognition that learners *will* need to construct their own knowledge. Therefore teaching has to take that into account and so be designed to guide knowledge construction rather than attempt to transfer knowledge wholesale into student minds: something that any science teacher knows tends to have limited success as an instructional strategy.

Constructivist education supports cultural transmission of 'public knowledge'

The criticism of constructivism as a form of pedagogic imperialism being exported from Western countries and undermining indigenous cultures is similarly based on a misunderstanding of constructivist teaching (at least as understood in science education). A key feature of the argument made by Bowers (2007) hinges on the claim that knowledge cannot be transferred - a claim that Bowers describes as mistaken and absurd - and the implication that cultural transmission should therefore not be possible, but rather each student must reinvent culture anew. Constructivist theory does indeed suggest that knowledge cannot be simply transferred from one mind to another: rather one individual (such as a teacher) has to represent their ideas in a form (e.g. speech) that allows others to *interpret* and *make sense of* those representations, and so construct their own knowledge (Taber, 2013c). There seems no question - from the vast amount of research into learning in science - that this is indeed the case, else students would unproblematically be acquiring canonical knowledge of natural selection, thermodynamics, a.c. circuit theory, and so forth whenever knowledgable teachers offer clear expositions of their topic. Research, and indeed everyday teaching experience, makes it clear that there are very often failures to learn what has been clearly taught, with students either not making sense of, or misconstruing, teaching, This is the problem the constructivist research programme in science education seeks to address. Science education *is* inherently concerned with cultural transmission - albeit in the limited area of scientific knowledge and thinking. Constructivists do not consider that learning of accepted knowledge is impossible: simply that it is not straightforward (as each learner has to make their own sense of teaching, based on the resources they already have to interpret it), and so requires careful pedagogy.

Arguably this area of contention is in part at least based upon an unproblematic acceptance of the notion of 'public knowledge' (the analysis offered in the next few papragraphs is developed in more detail in Taber, 2013c) of the kind science is said to produce (Ziman, 1968). It is commonly said that for a scientific achievement to 'count' it must be reported in a formal way that allows the possibility of replication. It is also commonly considered that science comprises of a race to be the first to publish a particular result or idea - something that in part at least reflects the mentality of some practising scientists (Watson, 1968/1980). Science is a community activity, where the evaluation of scientific work is a communal judgement. Scientific knowledge is considered public knowledge both in the sense of knowledge that has been published, and in the sense of knowledge that has reached consensual status through a public process of critique and evaluation.

This is fine as far as it goes - as a principled notion. However, in practice, science is an on-going process, where all scientific results and conclusions are open to re-inspection and re-evaluation at any time in the light of new evidence or perspectives (Losee, 1993). So no scientific ideas, even those widely seen as canonical, are considered as a 'final word'. This is commonly illustrated with examples such as Newton's mechanics which was seen as definitive for centuries before Einstein's work demonstrated that Newton's conceptualisation had to be considered imprecise or incomplete. So scientific knowledge may be public knowledge, but must considered to always be at least potentially in flux.

From a (personal) constructivist perspective, however, there is another serious limitation of the notion of science as public knowledge, which relates to the ontological status of knowledge. Knowledge, from the constructivist perspective, requires a knower. That is, knowledge is ontologically 'of' the mental world, and only exists in minds. Scientific knowledge, then, can be understood to refer to the most appropriate accounts of the natural world developed in the minds of scientists. Yet the scientific community cannot be considered to be of one mind. For one thing, most scientists are only experts in a limited area. For another, each scientist would (according to personal constructivist thinking) have developed their own unique conceptualisations. Within a research community, key conceptualisations will generally be similar enough across scientists to allow them to make progress in the communal work. Outside that research community it is likely that conceptualisation of that specialist area will be more diffuse, less detailed, more diverse, and more likely to include what the 'experts' might consider alternative conceptions.

The student of science at university level may well be taught by some recognised top experts in some of their courses. However, it is likely that they will be taught many topics by those who are not, and perhaps never were, actively involved in the research community of that specialism, and so are not engaged at the 'cutting edge' of current thinking. Below university level this will nearly always be the case. Therefore students, and their teachers, tend to rely upon indirect sources: perhaps the research literature; text books; internet sources; documentaries and so forth. Yet such sources are not minds, and so cannot be considered to somehow 'contain' knowledge. Rather, from a constructivist perspective, texts and other sources are the (necessarily imperfect) representations of their author's thinking, and need to be interpreted by the reader in constructing their own knowledge. Even when speaking to an expert, the student only hears a representation (in speech) of their thinking and so of their knowledge - although as Bruner (1987) has pointed out engaging in direct conversation can allow us to iteratively move towards an understanding of the other's ideas through the interactive nature of conversation (Kvale, 1996).

Reading scientific literature is problematic for learners both because it is pitched at the expert colleagues already familiar with the current state of the field, and because each study is part of an extended discourse gradually setting out the (constantly shifting) state of knowledge in the field. Secondary sources, such as textbooks, are the representations of re-interpreters of the scientific literature who have had to interpret the primary sources through their own existing resources (their own conceptual frameworks and conceptions) and who then attempt to represent these ideas in text in a form suitable for the academic level of particular learners. The student (or teacher) then has to interpret the representations of the textbook author's understandings though their own personal interpretation apparatus - their own existing set of conceptual frameworks, conceptualisations, meanings for words and so forth.

The constructivist research programme in science education is indeed then premised on the notion that knowledge cannot be transferred from one mind to another - from teachers to students, or from elders to the young of the community. However, this is not a judgement on *the merits* of knowledge transfer or cultural transmission - but an observation on the mechanism. Science educators adopting a personal constructivist stance are arguing that high fidelity 'transmission' of knowledge cannot happen because of technical constraints in human cognition and communication, but are certainly not suggesting there is nothing worth communicating.

Transferring knowledge between minds is not strictly possible even when it would be very convenient. Having the learner construct knowledge anew is the only way for them to come to knowledge, so the issue then becomes how best to guide that knowledge construction process to help learners acquire knowledge that is sufficiently canonical for them to be considered to be knowledgable in their societies. This leads to the focus in the constructivist programme on instruction that is optimally guided (as considered above).

Personal constructivism can complement social constructivist perspectives

One area of criticism of the constructivist research programme in science education has concerned the focus on the individual learner (Coll & Taylor, 2001; Solomon, 1987). In part this can be seen to be a continuation of the Piagetian tradition where Piaget - coming from a natural science perspective - focused on the individual subject as an organism that interacted with its environment. The person senses, acts on, and constructs internal models of the external world. A strong focus on the individual was also found in Kelly's (1963) 'constructive alternativism' with its focus on how each person develops their own unique system of personal constructs for construing the world.

Kelly certainly did not ignore the importance of social interaction in learning: indeed, in his role as a counsellor Kelly worked with clients to help them explore how they might construe their lives differently. Kelly saw the clinical psychologist's work with a client as a kind of joint research project where the therapist invited the 'patient' to be a partner in the research enterprise (Kelly, 1958/1969). For that matter, Piaget (1950/2001) actually considered social interactions an important part of the individual's interaction with his or her surroundings and so a major influence for modifying patterns of thought, but he framed most of his work as though the individual epistemic subject was the system of interest - and other people were therefore treated as though components of the environment. This is largely a matter of presentation, as references to sensory input from the environment can refer to the new born child exploring what happens when she pushes, sucks, clasps, etc, objects in her environment, but can just as much refer to listening to talk, reading text, observing a demonstration and so forth. A similar stance can be found in much constructivist writing, where it is not always made explicit that the learner should not be thought of as a lone individual interacting with the material world and constructing his or her own models of that world uninfluenced by the conceptions of others. Personal constructivism with its cognitivist or psychological flavour tends to treat the brain or mind of the individual as the primary focus for considering learning and cognition, and as a corollary treats others people as more peripheral features.

Somewhat in contrast to these types of personal constructivist accounts are constructivist accounts of teaching and learning which have a strong focus on how what is to be learnt is often a cultural product (e.g. a scientific theory) and how teaching is often essential to support that learning. No school age learner is likely to develop a scientifically acceptable model of plant nutrition, atomic structure, or stellar life cycles (or any of hundreds of other taught concepts) *ab initio* through interaction with the natural world, without mediation from someone who has already learnt about such ideas (whether such mediation is direct as when working with a teacher or more advanced student, or indirectly through reading a book or watching a documentary etc.) Vygotsky (1934/1986, 1978) recognised that learning such 'scientific' or 'academic' concepts required mediation through social interaction with the support of cultural tools such as language. However, Vygotsky (1967) thought that learners were only able to make sense of such mediated concepts by interpreting them in terms of their own intuitive concepts that did derive from abstracting direct experience of the physical world (cf. Lakoff & Johnson, 1980). In effect then, Vygotsky's thinking suggests that the concept that a learner makes their own is not strictly the academic concept that is taught but rather what might be called a melded concept (Taber, 2013c), which is the outcome of a mental process where intuitive concepts help interpret taught concepts (and vice versa).

Vygotsky's ideas have been highly influential in education. This is particularly true of his notion of a zone of proximal (or next) development which suggests that teaching should focus on what the student cannot yet achieve unaided, but could achieve if supported by someone with greater expertise (such as a teacher or more advanced peer). This led to the concept of 'scaffolding' learning (Wood, 1988) where the learner gets vicarious support whilst not yet able to complete a task alone, but which is then faded as greater competence is achieved. A great deal of teaching can be seen to take this form - teachers offering a structure that the learner can use as a scaffold - whilst the learner comes to internalise the material sufficiently to be successful without the scaffold. Indeed one principle proposed by Vygotsky (1934/1986) was that cultural development occurred sequentially in two planes - first on the social plane, and then on the psychological plane. Whilst such ideas are not part of the hard core of the constructivist programme set out above, they can certainly be seen as consistent. Vygotsky's ideas about the expert teacher modelling and structuring tasks for the novice learner would seem to resonate with the constructivist programme in science education's premise (see above) about the need for a teacher to take into account the student's current knowledge (Scott, 1998).

Vygotsky's thinking was developed by others into forms of cultural-historical activity theory (Smardon, 2009) where the focus is on learning as mediation through various cultural tools, and his ideas influenced notions of learning as induction into communities of practice (Hennessy, 1993; Lave & Wenger, 1991). Whilst the foci and terminology of these approaches are quite distinct from a personal constructivist position, they are generally open to synthesis with personal constructivist premises and so can be seen as complementary.

Somewhat more difficult to fit with a personal constructivist perspective are some constructionist stances which view knowledge as distributed across social connected networks of people (Kafai, 2006). For example, Collins (2010) argues that knowledge should not be seen as located in the individual mind, but rather that the individual should be considered as a parasite on communal knowledge that is distributed across a community. Such a claim raises interesting issues about the relationship of individual and community and about the nature of knowledge (Taber, 2013d), but is difficult to fit in any coherent way with the personal constructivist perspective of the research programme in science education.

The Learner's Alternative Conceptions can be (but are not always) Serious Impediments to Progression in Learning

One early criticism of the constructivist research programme in science education was that the claims made about the consequences of students' alternative ideas for learning science were simply not justified (Claxton, 1993; Solomon, 1994). Claxton (1993) argued that learners' ideas were generally local, transient, and labile. Solomon (1987, 1992) discussed how students could often completely shift their way of talking about a topic when they moved between formal instructional and informal social contexts. So not only did learners' ways of thinking about a topic depend upon perceived salience according to contextual cues in a science question, but they could also depend upon where they were asked the question and by whom. This suggested that claims that students held deeply embedded alternative conceptions which remained tenacious in the face of instruction was unfounded.

With the benefit of hindsight provided by extensive research over some decades, it seems clear that it is much too simplistic to characterise learners' alternative conceptions (collectively) as either tenacious or transient. When an individual learner's thinking about a science topic is investigated over extended periods of time it is found that some features of their thinking are indeed labile and readily shift - whilst other features are stable and not significantly impacted upon by instruction (Taber, 1995). This is one rationale for research which focuses on the thinking of individuals in depth, and over time periods of weeks, months or years. Although each individual case is unique and so reports of the developing thinking of a particular student cannot directly inform teachers, such detailed case studies are needed to better understand the factors which make particular types of ideas especially tenacious, and to explore the ways in which student thinking can be shifted over time. No doubt some researchers did find exploring students' idiosyncratic knowledge structures fascinating in their own right, but this work was also well motivated by the 'positive heuristic' (Lakatos, 1970) - the research agenda - of the programme (Taber, 2009a).

Solutions and recommendations

Constructivist ideas have been highly influential in science curriculum development in many parts of the world - although implementation has often been sub-optimal and curricular changes have often been subject to ideological criticism (Bell et al., 1995; Taber, 2010). The research programme has demonstrated that influences on learning science are sometimes subtle and often complex and so often there are no simple fixes (Taber, 2014c), and that constructivist teaching cannot be simply characterised (Taber, 2011). Despite this, there is much evidence that the constructivist perspective is fundamentally sound as a basis for understanding learning in science and for planning science curriculum and teaching - even if developing effective constructivist pedagogy has sometimes proved to be far from straightforward (Pritchard & Woollard, 2010; Sjøberg, 2010).

Personal constructivism remains both a key referent for science education pedagogy and a major driver for research, but it no longer dominates research activity in the field to the extent it once did. For one thing there has been a shift towards focusing more on the social and cultural aspects of teaching and learning through perspectives such as cultural historical activity theory (Smardon, 2009), and a shift in research attention from psychological aspects of learning to sociologically driven concerns with issues of inclusion and social equity in science classrooms (Fraser, Tobin, & MacRobbie, 2012; Mansour & Wegerif, 2013).

In part the declining dominance of constructivism as a research programme can be understood as a sense of the programme offering diminishing returns. The 'natural history' approach of collecting data about the thinking of groups of learners in different science topics is no longer considered cutting-edge research, and studies that explore the nature of student thinking and learning in depth, or attempt to develop and evaluate pedagogic strategies, have proved to be demanding and to seldom offer immediate and simple results. However, this research programme is directly linked to the key foci of teaching and learning in science education, and so remains of great importance.

The first phase of constructivist research in science education produced a great deal of data to inform science teaching and offered simple generally-applicable ideas about the learning of science that have been widely adopted into what is seen as 'good science teaching'. Continuing research in this programme is exploring the more nuanced and complex aspects of the contingent nature of science learning and how this interacts with teaching - with a view to offering more sophisticated and specific guidance to science teachers on how to best teach particular science content to different groups of learners.

Future research directions

It is only possible here to offer a sketch of some of the promising directions in the research programme into the contingent nature of learning in science (i.e. the constructivist programme). In Lakatos' (1970) model of scientific research programmes he described how a developing programme builds up a 'protective belt' of auxiliary theory consistent with the hard core but itself open to refutation within the programme (whereas refuting the premises of the hard core amounted to abandoning the programme). He referred to these auxiliary ideas as offering 'refutable variants' of the programme. Since the initial establishment of the constructivist research programme there has been a great deal of work undertaken which has led to a great many exemplifications of the original principles (in terms of student learning at various ages, in various contexts, of various science topics), and there have also been a range of theoretical proposals to develop the programme (Taber, 2009a), and space here only allows brief discussion of three of the most promising directions for research.

The constructivist programme is basically a research enterprise exploring the contingent nature of student learning. A major area of contingency is the learner's internal 'conceptual ecology' (diSessa, 2002) - the mental 'space' containing beliefs, ideas, predispositions etc in which concepts are developed. One key development has been in relation to understanding the nature of learners' cognitive resources for learning. In particular the notion that knowledge elements that are preconscious (and non-verbal) may be highly influential in thinking though acting tacitly (diSessa, 1993; Smith, diSessa, & Roschelle, 1993) has been increasingly influential (Taber, 2014b) and challenged the notion that the ideas students represent in their writing and speech (for example in research contexts) necessarily reflect existing conscious accessible and stable conceptions. Student utterances and inscriptions may reflect explicit conceptions of that kind, but are often rather the outcome of the *in situ* construction of responses drawing upon tacit knowledge elements. The importance of tacit knowledge to the practice of science was highlighted by the chemist-philosopher Michael Polanyi (1962, 1962/1969) who argued that scientists depend upon implicit knowledge they develop through practice, and which complements their consciously accessible knowledge. Indeed it has been suggested that accounts of new scientific techniques in the research literature are often insufficient for transferring methods between laboratories (Collins, 2010) as they necessarily omit details of technique that the scientists themselves are not consciously aware of. This idea has been developed more generally in the notion that human cognition is based upon the parallel use of two distinct 'systems' which have distinct characteristics - one system more suitable for reflective decision making - the other more intuitive approach supporting quick decision-making (Evans, 2008). This leads to the questions of (a) how to distinguish between these two forms of knowledge (Hammer, 1996), and (b) when teachers should focus on challenging well-established formal conceptions (Driver & Oldham, 1986; Heddy & Sinatra, 2013), and when they should seek to channel student thinking to draw upon the most productive implicit knowledge elements in relation to particular canonical concepts (Hammer, 2000, 2004).

Another issue that is relatively under-explored in research to date, despite being potentially very important, is the influence of cultural influences on how students construct their understanding of scientific concepts. Just as the learner's internal conceptual ecology will channel their response to teaching, so the cultural environment (such as peculiarities of the language of instruction; the specific choices informing curriculum-making; the use of locally salient metaphors and similes) will shape how scientific concepts will be represented in instruction (see Figure 1). Research suggests that there are many commonalities between the ways students in different national instructional contexts develop alternative conceptions (Liu & Tang, 2004; Tan et al., 2008). However there also seem to be differences that may link to the specifics of the cultural contexts of learning. Investigating these differences not only has practical value in informing teachers working in particular contexts, but may also be revealing in helping researchers tease out which tendencies in student thinking are largely contingent on the shared apparatus of human cognition, and which may be influenced more readily by modifications in the way ideas are presented in teaching (Taber, 2012). This direction for research also has much potential to inform a synthesis between personal and social constructivist perspectives on the contingent nature of human learning.

As reported above, the genesis of the constructivist programme in science education linked to a shift in focus from generic thinking skills to understanding student thinking in specific concepts areas such as forces, energy, plant nutrition or chemical bonding. Since the advent of the programme there has been much discussion about the nature of the science curriculum, and in particular of the relative importance of teaching about specific science topics compared with teaching young people about the nature of science itself (Clough & Olson, 2008; Holbrook & Rannikmae, 2007; McComas, 1998; Millar & Osborne, 1998). Advocates for giving more emphasis to teaching that includes the history and philosophy of science (Abd-El-Khalick & Lederman, 2000; Allchin, 2013; Hodson, 2009; Matthews, 1994b) have been vocal in the field. The need for learners to think about science in relation to key social issues has reinforced the notion that science education has to take students beyond formal operational thinking (Sadler, 2011; Sadler & Zeidler, 2009). It has also been suggested that such 'post-formal' modes of thinking are important for learners to fully understand the provisional nature of scientific knowledge and the ontological status of scientific theories and models (Taber, 2015). This opens up a major strand for the constructivist programme into the contingent nature of science learning in investigating the nature of students' developing thinking about nature of science (Taber, 2009b).

At the opening of this Chapter it was suggested that the major premises of the constructivist research programme in science education were likely to be generally applicable across the curriculum - and certainly some of the findings of research looking at the general nature of conceptual change are likely to be widely applicable. However each academic discipline has its own conceptual structure, epistemological commitments, and forms of practice. The extent to which the constructivist programme in science education could, or should, be replicated in other curriculum areas (where the implications of constructivist thinking for classroom teaching have not yet been explored in such detail) is a question for scholars in those fields to consider. Clearly, however, there are potentially important avenues for research relating to a variety of curriculum subjects.

Conclusion

The constructivist research programme in science education has produced a great deal of research evidence relating to students' thinking and learning in science subjects. The premises that learners come to science learning with existing ideas about many natural phenomena and that these existing ideas have consequences for the learning of science are so well supported by the evidence base that these notions are now generally accepted within the teaching community and not seen as problematic. That it is possible to teach science more effectively if account is taken of the learner's existing ideas has been widely demonstrated, although this has not led to the development of a simple and widely applicable pedagogy that can be offered to teachers to apply algorithmically - and this no longer seems a realistic aspiration. Some work offers teaching approaches or resources to support learning of particular topics at particular educational levels, but one outcome of the research programme is a recognition that the interaction between an individual learner (with a unique set of resources for interpreting teaching, and personal motivations, interests and dispositions) and a particular instructional approach in a particular social context (with learning mediated by interactions with teacher and peers, and various cultural tools that can be accessed in that learning context) is highly complex.

The research programme has offered general principles that are applicable in the classroom, but given the continent nature of student learning, these principles need to be applied on a case-by-case basis. This reinforces the highly skilled nature of successful science (or indeed any academic) teaching. Successful teaching will likely always rely on teachers who are well prepared, and able to be flexible and responsive in classrooms - adopting a forensic approach to diagnosing their students' current states of knowledge and understanding, and teaching accordingly (Taber, 2014c). In this perspective, science teaching is a kind of clinical practice, where general principles and past cases are drawn upon to inform teaching of each unique class and learner.

It is unrealistic to expect that the science education research community can ever offer direct research-informed specific pedagogy to cover all curriculum topics, educational levels, and cultural contexts where science teachers will be attempting to guide learners from their disparate, and sometimes entrenched, starting points towards canonical curriculum representations of science topics. However, there remains considerable scope for the research programme to make further progress in understanding how to effectively teach science in the light of various contingencies, and so to offer models of instruction to fit different types of science teaching context that can inform classroom practitioners in their own professional case-by-case enquiry into how to best teach science to their particular classes.

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Key terms and definitions

Alternative conceptions: Conceptions formed by learners which are judged to be inconsistent with the canonical concepts presented in science curriculum

Constructivism: A blanket term used to describe a set of diverse ideas related to how people come to knowledge.

Constructivism in Science Education: The adoption of constructivist ideas about how people learn to inform research, curriculum development and pedagogy in the teaching and learning of science.

Contingency in learning: The idea, inherent in personal constructivism, that what a person learns in a particular situation will be highly contingent (in particular upon their existing knowledge and understanding, but also upon the learning context).

Learning: Learning is taken as a change in the potential for behaviour, such as a change in the potential to verbally respond to a teacher's question.

Personal Constructivism: A perspective that considers each individual actively constructs their own ways of understanding the world and so identifies the locus of knowledge as the individual mind.

Radical Constructivism: A epistemological stance that accepts the ontological reality of the external world but considers that all a person ever directly knows is their own internally constructed mental representation of that external world.

Scientific Research Programme: An ongoing programme of enquiries undertaken by a community of researchers adopting a common set of 'hard core' assumptions and guided by common heuristics.

Teaching: Teaching is considered as deliberate actions undertaken with the intention of facilitating learning.