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Conceptual change theory: A recapitulation or resolution of the learning paradox?

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Several recent reviews have documented the large amount of research in science education on students' concepts of natural phenomena (e.g., Confrey, 1990; Hashweh, 1988; Hills, 1989). The major findings of this research are that prior to institutionalised instruction, students hold systems of concepts or beliefs which are very different from accepted scientific theories, and that despite instruction, many students do not acquire scientific concepts and continue to hold their own belief systems.

Generally, researchers have claimed that students' conceptual systems are resistant to change through 'traditional' methods of instruction, and some investigators have advocated the use of certain alternative teaching methods, presumably according to their theories of how changes occur in students' conceptual systems (Hasweh, 1988). Most of these researchers "do not carefully describe and defend" (p. 122) their theories, and thereby fail to provide a coherent rationale for "why a certain intervention should induce change" (p. 122). Exceptions to this lack of theoretical rigour are two relatively more explicit 'models' of how change occurs, known as conceptual change theory (e.g., Gunstone, Gray & Searle, 1992; Posner, Strike, Hewson & Gertzog, 1982; Hewson & Hewson, 1984; Roth, 1990) and the

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generative model of learning (e.g., Osborne & Wittrock, 1983, 1985).

The first section of this paper comprises brief analyses of conceptual change theory, as originally formulated by Posner, et al., and the generative model of learning. Both models fail to explain exactly how students' acquire new concepts; in particular, in the former model, the process of learning appears simply to be taken for granted. These models recapitulate the learning paradox (Bereiter, 1985), which arises when claims are made about novel thought despite the lack of an 'intrinsic generative mechanism' that makes this thought possible (Juckes, 1991).

The second section reviews Stenhouse's (1986) suggestion for a solution to the problem of how conceptual change takes place.

Stenhouse adopts Wittgenstein's (1963) concept of the 'language game' and recommends that science teachers use children's 'own language games' to facilitate change.

The main purpose of the third section is to promote a neuroscientific theoretical basis for a resolution of the learning paradox, and, in particular, to show how this 'non-psychological' theory predicts the successful use of analogies in promoting conceptual change (e.g., Brown, 1992; Duit, 1991). While aspects of Stenhouse's framework are problematic, several parallels between the latter and the former theory are briefly examined.

1. Problems in current theory

Conceptual change theory

Conceptual change theory stems from a seminal paper by Posner, et al. (1982) in which the authors elaborate a model of learning or change in students' thinking based on the works of Kuhn and Lakatos in the history and philosophy of science. Learning is first characterised as "the result of the interaction between what ... student(s) (are) taught and (their) current ideas or concepts" (p. 211). The authors claim that this view can be traced to the theories of Ausubel and the Gestalt psychologists. While the latter assertion is questionable, more problematic is the claim that learning is the result of an interaction; it is as if Posner, et al. use the term 'learning' to mean newly acquired knowledge, whereas the nature of the interaction, or presumably the learning process itself, remains undefined and tacit.

However, Posner, et al. also claim that learning is "the process by which peoples' central, organising concepts change from one set of concepts to another, incompatible with the first" (p.

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211), and that a central problem is how students' concepts change "under the impact of new ideas and new evidence" (p. 212). Thus these authors use the word 'learning' to mean both the result of an interaction and the interaction itself, or a process of change.

The process of change is partly accounted for by the impact of new ideas, but what is meant by 'impact' is never made clear. This is despite the fact that the 'model' which the authors propose is intended to account for how change occurs (identified as a central problem), or is meant to "illuminate learning" (p. 211-212). The process of change or accommodation is specifically defined as a replacement or reorganisation of concepts; accommodation is most likely to occur when students become dissatisfied with their existing beliefs, and consider new concepts to be intelligible, plausible and fruitful (Confrey, 1990; Posner, et al. 1982). In particular, accommodation occurs when "dissatisfaction with (an) existing (concept) ... is followed by (the) learning of an ... alternative" (Posner, et al. 1982, p. 221). But this statement clearly begs the question, in that, the very process which is to be accounted for (learning or conceptual change) is used to explain itself.

The generative model of learning

Wittrock and associates propose that conceptual change or learning occurs when students construct or generate links between incoming information and 'stored' information (e.g., Osborne & Wittrock, 1983, 1985). The generation of a link occurs via the operation of students' 'information-processing strategies' (Osborne & Wittrock, 1983). Osborne and Wittrock (1985) qualify the theory slightly when they state that generated links and 'sensory input' are used to construct new meaning; thus, learning consists of both a process of generation of links and a process of construction. But the question of precisely how the process of construction occurs is never addressed (Hendry, 1992; Hendry & King, man. sub. for pub.).

Despite an emphasis on students' prior knowledge in conceptual change theory and the generative model of learning, both models appear to reflect the transmission view of learning. In this view, concepts exist 'out there' (Parker, 1992) in the world of books and science curricula; they exist independently of scientists', curriculum authors' and teachers' minds, and the minds of students. Learning occurs when these external concepts are transmitted to students chiefly via the means of language - concepts can be carried in words into students' minds - and somehow interact with or 'impact' upon (Posner, et al. 1982), or are retained and linked with, student's existing knowledge (e.g.,

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Osborne & Wittrock, 1983, 1985).

This problematic view perhaps underlies Posner, et al.'s suggestion that conceptual change is promoted when new concepts are considered to be intelligible, plausible and fruitful by students (Confrey, 1990). These 'important conditions' "must be fulfilled before ... accommodation is likely to occur" (Posner, et al. 1982, p. 214) (emphasis added). Students must somehow know new concepts 'out there' and make judgements about the latter, before they change their conceptual systems. Roth (1990) also argues that for conceptual change to occur, "a student must know what the new idea means ... and be able to construct a representation of it" (p. 159). It is as if the 'new idea' exists independently of knowing minds, and can be transmitted by a teacher to students, who then make or 'construct', by some process, a representation.

A simple thought experiment reveals the inadequacy of the transmission view. Imagine a person speaking and another listening; the speaker, by certain processes, generates concepts, and bodily movements which vibrate the surrounding air. Upon reaching the listener's inner ear, vibrations of the atmosphere generate in the listener, by certain processes, a meaning of what was said. Ipso facto it cannot be said that the speakers' concepts crossed over in the atmosphere, nor can it be said that the meaning generated in the listener was the only one possible.

Thus communication is the relative evocation, rather than the transmission, of meaning (Wheatley, 1991). The concepts evoked in others might be the same as or different from a speaker's or writer's, and in communication, it can be said only that the same meaning is evoked in others when they use contexts or wordings which do not result in the generation of concepts different from those we intended. It follows that we cannot ascertain whether meaning evoked in others is either the same as or different from our own without, minimally, discussion or 'extended production of various contexts' (Hendry, 1992; Hendry & King, man. sub. for pub.).

Summarising, the models reviewed above do not constitute explanations of how conceptual change occurs, or how students' generate novel concepts from prior thought. But in falling short of their objectives, the authors of these models highlight the current problematic status in education of the relationship between learning, knowing, concepts, meaning and language. In particular, what do we mean by the word 'concept'? What is a concept?

2. Language games

Stenhouse, writing in 1986, claimed then that an unresolved

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problem in science education was "the question of how conceptual changes actually take place in individual students" (p. 413).

The latter author suggested that in order to explain how concepts change, we must first address the non-trivial question of what a concept or conceptual knowledge actually is. The former author rejects the assumption that concepts are images or 'mental pictures' (although is it not made clear why), and recommends that we adopt the 'solution' proposed by Wittgenstein (1963).

According to Stenhouse, Wittgenstein's solution is that having a concept or knowing the meaning of a word is "knowing the rules for the use of a word (or the symbol of a concept) ... in (a) language game" (Stenhouse, 1986, p. 416) (emphasis added). The term 'language game' refers to a set of socially accepted expressions (Bartley, 1974) or a language-using activity (Grayling, 1988); words may be shared across different language games, thus 'game' denotes the optional nature of word use. In this context, Wittgenstein's view is not a solution to the problem of what a concept is; rather, Stenhouse's interpretation simply restates the problem in terms of 'knowledge of rules of use'.

Regardless, Wittgenstein's view reinforces the argument above that in speaking and writing it can only be said that we know others have the same concepts as us when they use contexts which do not result in the evocation of concepts different from our own, that is, when they use the same 'language game'. Stenhouse claims it is this principle which as educators we intuitively apply in the assessment of students' learning: "we judge whether or not a student (has acquired) a concept by whether or not he or she can correctly use the words (or symbols) relating to that concept" (p. 417).

However, while students who have acquired intended concepts will necessarily also be proficient at playing the appropriate language game - given that to have a concept is to know how its word-symbol is used in a game (Stenhouse, 1986) - importantly, the reverse need not apply. That is, we can memorise or learn by rote certain contexts or wordings which can give the impression to others that we have acquired the corresponding concepts. Parker (1992) reviews recent research in which it was found that students tended to "regurgitate their teachers' formal science vocabulary in a relatively meaningless way. Indeed they were so adept at this that it actually acted as a disguise for their lack of understanding of the concepts involved. They had, in other words, learned science vocabulary well enough to feign an understanding of scientific principles" (p. 30). This finding not only renders questionable the way in which science is

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traditionally taught, but also the way in which the quality of students' learning is typically assessed in science education.

Stenhouse claims that language games can 'freely' relate to each other; "one language game (can inter-grade) with another, and that one with yet (another), and so on indefinitely" (p. 417). The latter author's main point is that in the same way that the language games of "ordinary life" were used "in the setting up" (p. 417) of the language games of science by the theorists who created them, teachers must somehow use the former games to help students acquire the latter (and de novo the correlated concepts). Science teachers must change their views of students' language games; teachers must see that word usage which is different from their own is not wrong, but is just different (Stenhouse, 1986).

On this point, it is important to note that in a recent review, Hills (1989) has argued that the original perspective of students' concepts taken by many researchers was that compared to accepted science concepts, the former were "in error, false, incorrect, mistaken, wrong, or in some other respect, defective" (p. 161). Thus relative to concepts in science, students' concepts were labelled 'misconceptions' or 'misunderstandings'. More recently, this 'traditional misconceptions perspective' (Hills, 1989) has been rejected in favour of the view that students' concepts form part of a total system of beliefs about the topic in question. However, these systems of belief are still compared to theories in science and are seen as "being in some sense prior, either developmentally or historically (when compared with similar views in the past, e.g., Aristotelian physics), to the latter" (p. 164).

An alternative position is that students' systems of beliefs simply constitute the commonsense or everyday theories of natural phenomena which we all share (Dawson, 1992; Hills, 1989), and "which are similar in important respects to full-blooded, mature theories in science" (Hills, 1989, p. 172). For example, in our everyday conversations we tend to think of animals as fairly large and furry, four-legged, terrestrial creatures (e.g., Bell, 1981; Osborne, Bell & Gilbert, 1983); people are not animals in the language of the staffroom, but they are in the language of the science classroom (cf. Hills, 1989).

Thus while Stenhouse's framework has much to recommend it, in particular, the idea that teachers must use children's language to teach science concepts, we are still faced with the following central problems: 'how does conceptual change take place?' and, more importantly, 'what is a concept?'.

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3. Concepts as patterns of nerve impulses

To answer the second question, I suggest that rather than looking to philosophy, or psychology, for a definition of a concept, it may be more useful to define what we call concepts, ideas or knowledge in neuroscientific terms. This is not to argue for the reification of concepts, nor is such an approach 'reductionistic'; rather, it is simply to claim that it may be more fruitful to draw on neuroscientific theory, or a different theoretical domain, for a definition of a concept and thereby the basis of an explanation of how conceptual change occurs.

In fact, several recent authors have forcefully argued for closer ties between neuroscientific theory and education (Berninger & Abbott, 1992; Wittrock, 1991). In particular, Berninger and Abbott contend that "educational psychology should not only follow the lead of cognitive psychology in adopting a neuropsychological perspective but should also take a leadership role in developing a cognitive neuroscience that is educationally relevant" (p. 223).

Beginning with Thomas Young's early nineteenth century theory of colour vision, neuroscientific theory has developed along two distinct but complementary lines of thought concerning nervous tissue and the electrical activity it generates. On the one hand, a great deal of research has focused on the structure of the single nerve cell or neuron, and on the nature of activity it generates over very short periods. On the other, research has focused on the nature of combined activity generated over longer periods in whole, three-dimensional groups or populations of neurons (e.g., Erickson, 1984; Hoyenga & Hoyenga, 1988). The first research tradition has yielded principles of synaptic functioning, or how 'weak' activity or synaptic potentials are produced and combine or sum in neurons to form 'strong' activity or impulses, which, in turn, influence 'weak' activity in other cells across synapses. The second research tradition is gaining increasing momentum but has yet to yield principles of the same degree of wide applicability, although a recent study employing

real-time, video-rate imaging of voltage-sensitive dyes in vivo has clearly demonstrated the stimulus-relatedness and stability of patterns of impulses in visual cortex (Blasdel & Salama, 1986).

However, given the principles of synaptic functioning yielded by the first research tradition, it follows that the spatial distribution or patterning of impulses in a group of neurons of fixed synaptic arrangement fundamentally depends on the timing of impulses. This means that as the timing of impulses varies,

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different patterns of impulses may grow and contract in the same area of cortex, or may grow into and contract in other areas. The principles referred to above also suggest that patterns combine and may integrate, forming larger patterns, or may disintegrate, reducing each other, depending on the timing of impulses. For clarity, this process of reciprocal disintegration is called reduction; it plays a crucial role in the explanation of how conceptual change occurs outlined below.

To summarise, healthy, awake people interacting with their surroundings are imagined, in a very general way, to be generating integrative/disintegrative, transient patterns of concentrated activity in certain cortical areas over very long periods.

It may therefore be useful to proceed as if some of these patterns of concentrated activity are concepts, just as we have proceeded in the past as if nodes in a network were concepts. But unlike nodes and links in a network, patterns do not continue to exist inside a person's head, rather, they are transient concentrations of activity (cf. Iran-Nejad & Ortony, 1984). And whereas the relations between nodes are fixed, one-to-one links, the relations between patterns of concentrated activity are transient and can be one-to-many (cf. Sadoski, Paivio & Goetz, 1991); given the principles of synaptic functioning mentioned above, the same pattern can combine with different patterns, or vice versa.

Thus the pattern theory of concepts, like Paivio's dual coding theory of cognition, can account for "the great flexibility noted in human cognition" (Sadoski, et al. 1991, p. 473). Of course, the number of possible relations between patterns is not infinite, but is constrained by existing cortical synaptic arrangements. Recent anatomical research (e.g., Marin-Padilla, 1990) and longtitudinal EEG studies (Hudspeth & Pribram, 1990) show that synaptic arrangements change drastically during development. As Piaget originally suggested, the growth of neuronal processes and new synapses during development 'opens up' possibilities for what he called the construction of new logico-mathematical structures (e.g., Piaget, 1970).

Herein lies a solution to the learning paradox, or how new concepts can be created from within out of prior concepts; it may be that when patterns which can be generated given existing synaptic arrangements in a specific cortical area 'interfere' with each other, the functioning of existing synapses is altered and/or new synapses are formed. The subsequent timing and thereby the spatial distribution, or patterning, of impulses qua concept generated in this cortical area will be changed.

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However, in order to put this very general hypothesis to use in explaining how conceptual change occurs in classrooms, several more assumptions must be made. The first of these assumptions concerns the evocation, as opposed to the transmission, of meaning.

Like dual coding theory, pattern theory specifies that patterns generated in different areas of the cortex, or various 'modalities', correlate with different types of 'mental representations' (Sadoski, et al. 1991) or kinds of knowledge (Hendry, 1992; Hendry & King, man. sub. for pub.). For example, patterns generated according to the same principles of synaptic functioning in different areas of the cortex may correlate with morphemes, graphemes or images, schemes for motor activity, logico-mathematical knowledge (e.g., Piaget, 1970) or what Wittgenstein has called imageless thought (Bartley, 1974). Damasio (1990) reviews research which shows that patients with damage to specific areas of the cortex experience recognition deficits with respect to certain conceptual categories. For example, some patients are able to recognise and name examples of a manufactured tool (e.g., hammer, screwdriver), but are unable to recognise examples of clothing, an animal or food, while others "who fail many living and animate categories may do superbly with some particular natural exemplars" (p. 97). These findings are consistent with the view that conceptual knowledge correlates with concentrated patterns of cortical activity; the generation of patterns is severely disrupted when widespread damage occurs to synaptic arrangements in specific areas of the cortex.

The first additional assumption referred to above is that patterns generated in certain areas of the cortex are relatively more generative of other patterns; in particular, patterns which correlate with words systematically generate patterns which correlate with concepts, and vice versa. As Sadoski, et al. (1991) assume, "language can evoke imagery, and imagery can evoke language" (p. 473).

The second and third major assumptions are that reciprocal disintegration or reduction results in an alteration of synaptic functioning in an area of the cortex, and that the stability of altered synaptic functioning depends on the range of reduction. Small and large ranges of reduction result in a minimum number of alterations in synaptic functioning which are relatively unstable and support the generation of new patterns for only a short time, while medium ranges result in more alterations which are more stable and ultimately result in synaptogenesis.

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Thus if students hold systems of concepts which systematically generate language; that is, if students generate patterns of concentrated activity which uniformly generate, given existing synaptic arrangements, other patterns of activity correlated to words, then in order for children to form completely new patterns of activity coordinated to words, their patterns correlated to concepts must somehow be brought into disintegrative combinations which result in medium ranges of reduction and stable alterations in synaptic functioning. In this way, students will undergo conceptual change, although note that the new patterns qua concepts that students construct may not be those intended. As a result, students will begin to use their language in a slightly different way; borrowing Wittgenstein's terminology, they may begin to play the language game of science.

It is following this initial constructive phase that students can reason about any shortcomings in their former ways of thinking. Once having created a new intended concept, they will necessarily think it to be 'intelligible' (Posner, et al. 1982). As students combine their newly formed pattern with other patterns in a variety of situations or apply their new idea to a variety of perceived phenomena (the timely provision of which can be made by science teachers), they may also begin to think of their new concept as being 'plausible' and 'fruitful' (Posner, et. 1982).

In this context, Posner, et al.'s 'conditions' for accommodation are reinterpreted as being 'conditions' for the consolidation and extension of initial change.

Of course, the crucial question is how can students bring, or be helped to bring, their existing integrative patterns into disintegrative combinations which will result in the construction of an intended concept?

Consistent with Stenhouse's suggestion above that teachers use the language games of 'ordinary life' to promote conceptual change, to increase the likelihood that intended concepts will be constructed, teachers must use those parts of students' language which generate for teachers concepts which are most similar to science concepts; that is, teachers must use those parts of the language of students which generate patterns that are maximally similar in their patterning to other patterns corresponding to science concepts. By definition, this means using students' language in ways which are not normally used by students themselves. Thus these unusual ways of use will generate unusual combinations of concepts qua patterns in students, or systems of altered timing of activity, resulting in medium ranges of reduction and stable alteration of existing synaptic arrangements in a specific cortical area.

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Some of the best teachers already do this through the use of analogies (Robert Young, personal communication). They say that a system of concepts in science is like another system of concepts, which is communicated using students' language. Thus for teachers an analogy consists of a 'structural identity' that exists between two systems of their 'representations' (Duit, 1991) (systems of concentrated patterns of activity). By definition, the analogy itself cannot be evoked in students, since they have not yet acquired the intended science concepts; rather, students' constructions of the latter begin when the teacher, using students' language in ways not normally used by students themselves, compares, by definition, a unusually related series of their concepts with those to-be-acquired. The best teachers seem to know intuitively just what to say, and in what order, to promote learning; they use 'powerful' analogies.

In a recent study, Brown (1992) used a series of multiple analogies or a bridging explanation, which consisted of several short paragraphs in everyday language about a series of unusual situations, to explain Newton's third law to fourteen secondary students. These situations included a hand pushing down on a spring (and the spring 'pushing' back on the hand), a book compressing a spring, a book resting on a plank laid across two trestles, a book resting on a block of stiff foam rubber and finally a book resting on a table which is composed of tiny molecules which are connected to each other by bonds that are 'springy'. All fourteen students "initially maintained that a table does not exert an upward force on a book resting on it" (p. 22) and answered a problem about this situation incorrectly. Of these fourteen students, seven read the bridging explanation and seven read an excerpt from a popular secondary physics textbook. Results were that all students who read the bridging explanation "answered the post-question about the book on the table correctly and with high confidence (the average confidence score was 2.79 out of 3). They also indicated that this answer made a great deal of sense to them (the average sense rating was 4.64 out of 5)" (p. 22). As well, six of these seven students correctly answered a difficult transfer problem about a 200 kilo steel block (A) resting on a 40 kilo steel block (B). Brown points out that many students, even after a full year of physics instruction, answer the latter problem incorrectly, typically saying that "block A ... exerts the larger force since it is heavier" (p. 23). Of the seven students who read the excerpt from the textbook, only two correctly answered the table problem, and none successfully completed the steel blocks problem.

Other researchers have used experientially based analogies to promote conceptual change. Studies have shown that the meaning most children have for 'speed' is that it is the movement of whole objects; all parts of a moving object move together and therefore all parts move at the same speed (Levin, et al. 1990). However, "in scientific contexts ... speed refers to the movement of a point" (p. 270), and in rotational motion points move at different speeds (Levin, et al. 1990). The latter authors report a study in which the different speeds of parts of a rotating object were compared with the kinaesthetic perceptions of walking in a circle holding a rod which pivoted at one end. Specifically, "the child and the experimenter walked together four times around a circle while holding a two metre long rod, attached at one of its ends to a fixed axis of rotation. First, the experimenter held the rod near the pivot, and the child held it near the outer edge. Next, they reversed their positions. After this, they moved closer together, holding the rod near its middle. Finally, they exchanged places again. Children were asked after each trial to compare their speed with that of the experimenter and to explain the judgement" (p. 274-275). Results were that 50 per cent of the children who participated in this 'kinaesthetic training' condition acquired the idea that parts of rotating objects move at different speeds.

When these children were asked to explain their judgements about the differences in their rates of walking, medium ranges of reduction occurred as their patterns qua concepts of speed were coordinated, through a process of immediate recall, to patterns generated in a sensory modality. Perhaps if a language-based analogy had also been used, more children would have experienced conceptual change. For example, after reflection, one child spontaneously generated the following analog: "see, if you were sitting on a carousel just like this one, and you were at the end, you would be circling at an extreme speed and you would be more frightened ... you would be feeling that you are circling faster than the one who is closer to the centre" (p. 277).

The important role that analogy plays in thinking is reinforced by the finding that experts, and students themselves, use analogies during problem-solving (Confrey, 1990; Duit, 1991), while Nersessian (1989) emphasises the role that analogy, and limiting case analysis, thought experiment and imagery, has played in concept formation throughout the history of science; "scientific representations ... are made, not stumbled upon or found" (p. 178). (Of course, concept formation in science invokes the learning paradox at another level; a solution to this problem, viz. an explanation of scientific creativity, is clearly beyond the scope of the present paper.)

All of this is not to say that using analogies is the only way to teach science. Any situation in which children's language and/or

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familiar, everyday objects are used (either in drawings or demonstrations) in ways slightly different from those with which students are familiar may result in medium ranges of reduction and conceptual change. This may also occur during discussion between students themselves or during students' interaction with computer simulations. It is also not to deny that a teacher who predominantly uses science language may occasionally facilitate medium ranges of reduction, but to do this often and for all students and to promote the construction of intended concepts, as Stenhouse suggested, teachers must consistently make use of

children's language.

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