Learning in Schools: A Modelling Approach

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This article claims that constructivism is both incomplete and inadequate for the effective learning and teaching of mathematics and science at the upper secondary school level. The article briefly reviews the reforms that have occurred over the past 50 years on mathematics and science education from the perspectives provided by advances in knowledge on the physical and biological sciences, in developmental and cognitive psychology, in educational research and in the emerging field of neuroscience. It is argued that the finding from these many different fields of research must be brought together to advance learning through a modelling approach which requires that both individual and corporate knowledge must be tested not only for coherence, but also for adequacy against evidence obtained from the real world in which human beings are living and undertaking their inquiries.

Constructivism, social constructivism, cognitive development, hypothetico-deductive thinking, Piagetian theory, hypotheses testing, modelling, neuroscience, formal operational thinking, upper secondary schooling, learning in schools

INTRODUCTION

In the present-day world of schools, universities and lifelong learning institutions, the ideas of 'constructivism' pervade discussions on curriculum development, the learning experiences provided, and the procedures used for assessment of student achievement. If constructivist theories of knowing were limited to the simple principle that existing knowledge is used in the processes of building new knowledge not only by individuals but also by social groups and communities of scholars, there would be little cause for concern. However, Phillips (2000) has shown that constructivism in education extends well beyond this simple principle to take a wide variety of forms that confound those concerned with educational issues and that have serious implications for how learning occurs in schools and universities. Constructivist approaches also often distort what is acceptable as knowledge in a world where what is accepted as knowledge is growing at an extremely rapid pace. Furthermore, the constructivist approach is accepted by many as the only approach to learning at all levels and stages of learning in schools and universities as well as in everyday life. In addition, constructivism has tended to dominate teaching at levels of education where other approaches may be necessary or desirable.

It is the purpose of this article to examine the issues associated with the rise of constructivism and to argue that, at least in the fields of mathematics and science, the basic principles of constructivism are incomplete and inadequate for both learning and teaching in these fields. Moreover, the very many extensions of constructivism that have been advanced have a limited place in education in learning mathematics and science as well as in the establishment of the bodies of knowledge that are endorsed by scholars. A modelling approach both to learning and to the accumulation of knowledge is argued to be necessary, in so far as any models that are constructed must be tested for their coherence and adequacy, with recognition that certainty and the so-called 'truth' of knowledge can never be fully established.
In this article, the reforms that have occurred over the past 50 years and are currently occurring in science and mathematics education are briefly reviewed and set in the perspectives generated by advances in knowledge in the physical and biological sciences, in developmental and cognitive psychology, in education and in the emerging field of neuroscience. It is argued that the findings from these many different fields of research must be brought together to advance learning through a so-called ‘modelling approach’. This approach requires that both individual and corporate knowledge must be tested not only for coherence, but also against evidence obtained from the real world in which human beings are living and undertaking their inquiries.

A CONCERN FOR PROCESS IN EDUCATION

The first half of the twentieth century was the scene for the establishment of research activities in psychology and education, the emergence of the disciplines of sociology and statistics, and remarkable growth of knowledge in the fields of the sciences, mathematics and technology. These developments were accompanied by a rapid expansion of secondary education in the countries of the developed world, together with the growth of universities and institutes of technology, as well as the establishment of highly specialised research institutes. By the mid-1950s, it came to be recognised that the curriculum of schools and universities had changed little over the preceding decades and reform was urgently needed to take into account the growth in knowledge that had occurred.

Projects were established during the 1950s in the United States and the United Kingdom to reform the teaching of mathematics and the sciences in order to incorporate the new knowledge that had emerged during the previous half-century. By 1959, major programs had been launched by leading mathematicians, biologists, chemists and physicists into curriculum development for schools and universities. Concurrently, educators and psychologists were examining anew, the approaches to teaching and the structure of the curriculum in the light of the knowledge gained from their research. It was clear that an overall reappraisal of the teaching and learning of mathematics and science was urgently needed. As a consequence, a conference was held in September 1959 at Woods Hole on Cape Cod in the United States that was attended by leading scholars who were already engaged in major curriculum reform projects, as well as psychologists and teachers from some of the leading schools in the country. The discussions at the conference were summarised by Bruner (1960) in the volume *The Process of Education* that had very wide circulation throughout the Western world. Key ideas that were discussed involved the importance of structure in the curriculum, readiness for learning, intuitive and analytic thinking, and motivation and active learning. Consideration was given to the ideas of Piaget on children's thinking and the three stages of intellectual development of the child. As one conclusion, the proposition was advanced:

that any subject can be taught to any child in some honest form - then it should follow that a curriculum ought to be built around the great issues, principles, and values that a society deems worthy. (Bruner, 1960, p.52)

For probably the first time, educators and psychologists had the confidence, derived from research, to assert that there were principles on which the curriculum of schools and universities could be based. Whitehead, an Anglo-American philosopher, had argued several decades earlier for three stages of mental growth; he also argued against an educational process of “uniform steady advance undifferentiated by change of type or alteration of pace” (Whitehead, 1949, p. 27). He called these stages “the stage of romance, the stage of precision, and the stage of generalisation” (ibid, p. 28).

Shortly after the Woods Hole Conference, two books were published that drew widespread attention in North America and the English-speaking world to the work of Piaget in Switzerland,
and that challenged the current ideas of “fixed intelligence” and “predetermined development”. Hunt (1961) wrote on *Intelligence and Experience*, elaborating on Piaget's research from the perspective of information processing and summarising the emerging evidence from brain research and neuro-psychology. In addition, Flavell (1963) wrote on *The Developmental Psychology of Jean Piaget*, providing greater detail on Piaget's research, together with an excellent evaluation of the theories that Piaget had advanced. Flavell summarised some of Piaget's ideas in the following terms:

> the subject cognises only what is immediately apparent and obvious in things, i.e. just a few surface characteristics (phenomenism); on the other hand, he is unable to assess the contributions of his own perspective to the way things appear; he cannot turn his intellectual instruments back upon himself so as to make his own cognitions an object of critical inspection (egocentrism). It is the work of development to correct this initial egocentrism-phenomenism in two ways. Phenomenism gives way to a progressive *construction* [Flavell’s emphasis]: the subject penetrates more deeply and more extensively into the object of his cognition. And egocentrism is replaced by *reflection* [Flavell’s emphasis]; the subject rethinks and restructures aspects of an object of thought "constructed" earlier, critically reanalyses his initial assumptions about these aspects, and in general, submits his earlier cognitions to a searching *prise de conscience*. (Flavell 1963, p. 256)

The use of these processes of construction and reflection in learning and teaching is referred to as 'constructivism'; and it is the operations of both construction and reflection that are central to constructivism. Piaget extends these operations that recur in the minds of individuals, to apply to the evolutionary processes at work throughout the history of mathematics and physics. It is these ideas that have been extended and reformulated not only to give rise to psychological constructivism but also to other forms of constructivism (see Phillips, 2000).

It should be noted that the work of development in the key processes of construction and reflection corrects the initial egocentrism-phenomenism, and would appear to involve only the transition from the first to the second stages of cognitive development advanced by Piaget, namely the pre-operational stage to the concrete operational stage. However, Piaget's research shows that cognitive development undergoes a further transition during adolescence from the concrete operational stage to the formal operational stage, which involves the use of hypothetico-deductive thought processes. It is this further stage of development which goes beyond the two operations of construction and reflection that renders constructivism to be both incomplete and inadequate. Criticism of constructivism has also come from the field of neuropsychology. Before turning to consider findings from the area of neuropsychology, it is necessary to discuss another approach to constructivism that is referred to as 'social constructivism'.

**SOCIAL MEDIATION AND COGNITIVE GROWTH**

Vygotsky (1981), a psychologist who lived and worked in Russia, and who died in 1934 at the age of 38 years, argued that the social context in which learning took place had a marked effect on learning outcomes. Initially, his evidence of the effects of social mediation on learning was observed in testing programs in which students, assessed under formal objective testing conditions, performed very differently from assessment in an interview situation where the psychologist or test administrator interacted with the student through discussion or with apparatus. The mediating influence of a sympathetic adult assisted the student to succeed on conventional test items that the student was otherwise unable to do. Vygotsky extended these
ideas to learning situations where the student's learning was facilitated by social interaction with adults or peers:

Any function in the child's cultural development appears twice, or on two planes. First it appears on the social plane, and then on the psychological plane. First, it appears between people as an interpersonal category, and then with the child as an intra-psychological category. This is equally true with regard to voluntary attention, logical memory, the formation of concepts, and the development of volition. (Vygotsky, 1981, p. 163)

Vygotsky contended that instruction would only be effective if the instruction proceeded ahead of the associated cognitive development, was in a zone of proximal development (ZPD), and was close to and below the level of the learning required. Vygotsky's ideas have given rise to ideas variously referred to as 'social constructivism' and 'social constructionism'. Other forms of social constructivism have developed from Berger and Luckman's (1969) ideas on the social construction of reality.

**BRAIN RESEARCH**

Hunt (1961) recognised that an understanding of the processes of cognition and learning must be consistent with evidence drawn from neuro-psychology. During the 1950s and early 1960s, brain research was an emerging field of inquiry where significant advances were being made. Bransford, Brown and Cocking (1999) in *How People Learn* have recently reviewed the field of brain research from an educational perspective. It is evident that neural activity in the brain is central to the processes of learning. However, they argue that only a limited number of research findings are ready for implementation in educational practice. The connections set up in the brain and their functional organisation benefit significantly from experience. Cognitive development is not merely an unfolding process that is biologically driven, but is an active process that derives from experience. It is a function of education to advance this process by providing appropriate experiences.

Sweller (1999) has recently presented more detail on the cognitive architecture of working memory, long-term memory, schemas, automation and cognitive load theory, and the effects of split attention and redundancy of information. He questions strongly the efficacy of so-called 'constructivist based' learning procedures and argues that evidence for the effectiveness of these learning procedures is almost totally missing with a lack of systematic and controlled experimentation.

Recent studies in the field of connectionism that involve neural network accounts of brain functioning provide the best currently available theories of how the brain works. A recently published volume on *Issues in Educational Research* (Keeves and Lakomski, (1999) examines these ideas and relates them to the processes involved in learning and teaching from a coherentist perspective.

**SITUATED ACTION AND SOCIAL COGNITION**

Lakomski (1999) has examined the approaches to cognition of situated action and symbol processing and finds them both to provide an inadequate framework for the explanation of human action and thought in education and everyday life. Lakomski (1999) has discussed the idea of 'situated action' drawing on the writings of Lave (see Rogoff and Lave, 1984). The four key principles of situated action accepted by Lakomski are:

a) action is embedded in the concrete setting in which it takes place;
b) an individual does not automatically transfer knowledge from one context to a different context;

c) training through abstraction is rarely successful without extensive practice; and

d) instruction is affected by the complex social environment in which it occurs, but skills can be taught independently of the social context. (Lakomski, 1999, pp. 287-289)

Situated action is based on the idea of an interactive system that includes people, other materials and other systems. Learning occurs through individuals interacting in a concrete way with material and with other people within a contained system. However, in order to understand the way in which cognitive processing takes place, it is necessary to take into consideration the functioning of the brain. It would seem profitable to reject the historical dualism of brain and mind, and to consider the brain and the mind as a duality or even as one, since the strength of an information processing approach resides in directing attention to the individual and how the individual acquires knowledge.

In its simplest form, the symbol processing hypothesis advanced by Newell and Simon (1972), holds that rational thought and the knowledge generated involve the manipulation of linguistic and quasi-linguistic symbols in the head or the brain-mind duality. Thus, the emphasis in this approach is on the processing of cognitive structures and their symbolic representations by the brain. Simon's (1990) ideas have been derived from studies of eye movements, reaction times, and thinking aloud protocols as well as probes in the brain. Simon states:

   a system will be capable of intelligent behavior if and only if it is a physical symbol system .... [it] is a system capable of inputting, outputting, storing, and modifying symbol structures and of carrying out some of these actions in response to the symbols themselves. "Symbols" are any kinds of patterns on which these operations can be performed, where some of the patterns denote actions (that is, serve as commands or instructions). ... Information processing psychology claims that intelligence is achievable by physical symbol systems and only such systems. From that claim follow two empirically testable hypotheses:

1  that computers can be programmed to think; and

2  that the human brain is (at least) a physical symbol system.


It is important to recognise that symbols are not simply words or arithmetic and algebraic symbols, but may be diagrams, icons, mental pictures, and patterns formed by the senses of sight, sound, touch, smell and taste. Simon (1990) contends that the physical symbol system hypothesis has been examined extensively during recent decades, and while there are many unresolved issues, it must be considered to be well established.

The weakness of assuming a physical symbol system and symbol processing as the key process of human thought, is that the system is considered programmable and can be formulated in terms of rules. However, there would seem to be many cognitive phenomena that cannot be adequately explained by this approach, since these phenomena do not appear to involve chains of reasoning or the crunching of symbols, as is carried out in a computer. The ability to formulate rules for the operation of a system cannot be taken to imply that the system actually operates according to such prescribed rules.
It is evident that the situated action approach and social cognition that relate to aspects of constructivism do not provide a complete view of how learning takes place. Likewise, the symbol processing hypothesis fails to take into consideration many cognitive phenomena. Under these circumstances it would seem necessary to seek a new approach that takes into account all stages of Piagetian development, relating them to changes in brain structure and suggesting how the brain might operate under this new approach.

**TOWARDS A NEW APPROACH**

The first task involved in the development of a new approach is to reconsider the stages of cognitive development advanced by Piaget.

The research conducted by Piaget, and reviewed by Hunt (1961) and Flavell (1963), has been examined, explored and extended in a large body of educational and psychological research, but would appear to continue to be challenged and rejected by some research workers in North America on a wide variety of grounds. Nevertheless, to those who have taught mathematics and science in schools across the years of secondary schooling, Piaget's stages of development would appear to be highly consistent with their experience. Furthermore, for research workers who have employed scales to measure Piagetian levels of reasoning, and the corresponding levels of cognitive complexity such as the Solo Taxonomy (Biggs and Collis, 1982) and the *Arlin Test of Formal Reasoning* (Arlin, 1984) (for example, Alagumalai, 1999; Scholten et al. 2002), the use of these scales provides very rewarding explanatory evidence for such phenomena as problem solving and higher order thinking. Resnick (1987) has listed the characteristics of higher order thinking after consultation with educators, psychologists, philosophers and computer scientists, but appears to reject that they are consistent with and can be accounted for by Piaget's ideas of formal operational thinking.

Shayer and Adey (1981) have examined the evidence available from Piagetian research in the early 1980s and argued strongly for the use of Piagetian ideas of cognitive development in curriculum planning and construction. More recently, Adey and Shayer (1994) have again reviewed the evidence and argued for cognitive intervention programs, particularly in the teaching of science and mathematics in ways that are consistent with Piagetian theory and stages of development. It could well be that the poor results consistently reported from cross national achievement testing programs in the United States at the middle and upper secondary school levels conducted by the International Association for the Evaluation of Educational Achievement (IEA) (see for example, Keeves, 1995) and the Programme for International Student Assessment (PISA) (Lokan et al. 2001), can be attributed to the ways in which the science and mathematics curricula are organised and taught in the schools of the United States. Not only do the science and mathematics curricula continue to reject Bruner's (1960) advocacy for a "spiral curriculum" with a coherent structure, but they would also seem to reject the emphasis Bruner placed on cognitive stages of development that recognised the pre-operational, concrete operational and formal operational stages proposed by Piaget. It is the formal operational stage that is of particular relevance in this article, because it is during the years of secondary schooling that both science and mathematics are introduced into the school curriculum in a formal way.

Flavell (1963, pp.204-206) has stated:

> The most important general property of formal-operational thought, the one from which Piaget derives all others ... concerns the **real** versus the **possible**.... Several other characteristics of formal thought are implied by this new orientation.
1) A cognitive strategy which tries to determine reality within the context of possibility is fundamentally hypothetical-deductive in character.

2) Formal thought is above all propositional thinking …[Flavell's emphases]

3) This property of formal operational thought is closely affiliated with the newly developed orientation towards the possible and hypothetical.

Neither the ideas of 'propositional thinking' and 'hypothetico-deductive thinking' nor the ideas associated with 'symbol processing' simply do not receive consideration in discussions of constructivism. As indicated above constructivism is concerned with situated action and concrete operational thinking and does not relate to the formal operational thinking that occurs in the learning of science and mathematics at the middle and upper secondary school and university levels. As a consequence, the experiences that are necessary preparation for formal operational thinking do not appear to be considered in a school curriculum that is grounded in constructivism.

The ideas advanced by Flavell that have led to 'constructivism' and by Vygotski (1981) that have spawned 'social constructivism', as well as by Lakomski (1999) concerning 'situated action' are not necessarily erroneous, but are incomplete and inadequate when referred to the stage of formal operational thinking, and the type of thinking that is needed not only in learning science and mathematics, but also some of the social sciences at the upper secondary and university levels.

COGNITIVE DEVELOPMENT AND BRAIN GROWTH

If all stages of cognitive development are to be taken into consideration in the development of curricula, it is necessary that the nature and the phasing of the stages are consistent with current knowledge about the development of the human brain.

Shayer and Adey (1981, p.135) have reviewed the research of Epstein (1974, 1977), a brain physiologist, and other investigations that show that in both mammals and humans, there are, in general, critical periods of brain growth. In humans, spurts in brain growth occur around 11 and 15 years of age, with a quiescent stage occurring around 13 years of age. Shayer and Adey (1981, p.135) state:

In girls the earlier spurt is more marked, in boys the later. These two brain growth phases correspond to the periods of maximum rate of development of concrete and formal operational thinking … it was found that no evidence of formal thinking capacity could be found in children under the age of 10, no matter how clever they were.

Since the new brain growth that occurs is mainly the production of dendrite structures at the ends of nerve cells, without being assigned to any specific functions, it is only through experience and instruction that the reasoning transformations advanced by Piaget are produced; their development having been limited prior to the changes in brain growth (Epstein, 2001). Adey and Shayer (1994, pp.140-143) present further evidence to support Epstein's (1986) claims and call for intervention in schools to facilitate cognitive growth prior to and during these stages of brain development. However, it is important to recognise that these changes do not necessarily occur at highly specific ages and substantial variations are likely to be observed in practice, partly as a consequence of advanced or delayed development, and partly as a result of the learning experiences provided. Consequently, schools clearly need to take these developments into consideration in the planning of curricula by allowing in appropriate ways for individual differences between students.
TOWARDS A MODELLING APPROACH

The key characteristic of cognitive functioning at the stage of formal operational thinking involves propositional thought that is hypothetical in nature. Operational thinking involves the formulation of a proposition and the testing of that proposition in ways that provide support for the adequacy of the proposition or its rejection. Rarely are the situations under consideration so simple that a single hypothesis is involved. In general, situations are sufficiently complex for alternative propositions and hypotheses or multiple hypotheses that are interrelated, to be required. The interrelationships between hypotheses require some structuring of the hypotheses and in this way a so-called 'model' is formulated for testing.

Kaplan (1997, p. 117) has argued that the term 'model' is useful:

only when the symbolic system it refers to is significant as a structure - a system that allows for exact deductions and explicit correspondences. The value of the model lies in part in its abstractness, so that it can be given many interpretations, which thereby reveal unexpected similarities. The value lies also in the deductive fertility of the model, so that unexpected consequences can be predicted and then tested by observation and experiment.

Keeves (1997, pp. 386-7) argues that a model should satisfy several requirements:

a) a model should lead to a prediction of consequences that can be verified by observation;

b) a model should not only contain associative relationships, but also structural relationships that have a causal direction;

c) a model should reveal something of a causal mechanism, leading to explanation, as well as in some cases to prediction; and

d) in so far as a model contributes to explanation, it should give rise to new concepts and new relationships and thus to further inquiry.

Keeves (1997, pp. 388-390) has identified several different types of models: (a) analogue models, (b) semantic models, (c) schematic models, (d) mathematical models, and (e) causal models. However, some models may suffer from oversimplification and inappropriate signification in which significance is attached to inappropriate aspects of a model rather than reveal the structural aspect of importance.

In the framing of hypotheses, Quine and Ullian's five virtues would seem to apply:

a) conservatism - the hypothesis conflicts with as few previous beliefs as possible;

b) modesty - the events assumed are of the more usual and familiar kind;

c) simplicity - the simplest hypothesis is the most likely;

d) generality - the wider the range of applications of the hypothesis the better; and

e) refutability - the hypothesis can be refuted by the occurrence of unexpected events.

(Quine and Ullian, 1978, pp. 68-79)

The model or hypothesis serves to explain the past and predict the future. The testing of models should be carried out using the procedures of formal, mathematical, or symbolic logic. In addition, the testing of models must be done by controlled observation, experimentation, or the systematic collecting of evidence from the real world. In many situations statistical procedures for model testing are required with data expressed in a quantitative form. These procedures for a modelling approach were first advanced by Sir Ronald Fisher, but have recently been reformulated by
Lindsey (1995) to overcome the shortcomings and limitations of other statistical approaches, to be used with maximum likelihood procedures for the testing of models and the estimation of their parameters.

The advantages of working with the mathematical formulation of a model lie in the ease with which data can be employed to test the model, and the facility with which mathematical logic and mathematical algorithms can transform data and organise data for testing in appropriate ways. The maximum likelihood approach is now the basis of modern statistics, and is used for testing the adequacy of a model. Under this approach, the research worker develops a model, collects data with an assumed underlying generating distribution in order to test the model, and makes a decision to reject the model, or to accept that the model provides an adequate representation of the data collected from the real world. Choices can also be made between two or more models, but a model can never be verified, merely being accepted as an adequate representation of the observed phenomenon or situation in the real world.

In their simpler forms, these modelling processes might well be described as involving the processes of construction, and the term 'constructionism' employed. Nevertheless, the term 'constructionism' has already been used in association with social constructivism and in this context it has a very different meaning (see Nightingale and Cromby, 1999). Since commonly a simple construction with the characteristics of a model is not being built through social constructionism, the term 'constructionism' is best avoided and an alternative word sought. Consequently, the term 'modelling' has been adopted.

**TOWARDS A NEW APPROACH TO COGNITIVE PROCESSING IN SCHOOLS**

In this article the origins of the term 'constructivism' are discussed. In its simple form the term refers to cognitive processes that are involved in the incorporation of new knowledge in the brains and minds of individuals. In general, the sources of the knowledge are concrete experiences, as would be appropriate at the stage of concrete operational thinking. Furthermore, the social contexts in which the learning experiences occur are likely to have effects on the learning outcomes. As a consequence, some of the ideas associated with constructivism and social constructivism would appear to provide a meaningful account of the cognitive processes involved.

At around the age of 15 years, under circumstances where an individual student has had appropriate experiences in working with symbols of particular types, the student is prepared for thinking with formal operational processes that involve hypothetico-deductive operations. This is also the stage in learning when logical proof of relationships is meaningful and when formal problem solving tasks can be provided for solution.

During the stage of concrete operational thinking, learning through situated action would appear to be involved. Both the use of concrete operational thinking and learning through situated action continue in particular situations at times throughout life. However, added to these processes during the stage of formal operational thinking are both the capacity to engage in formal operational thought and to use symbol processing procedures in which the individual has been trained. Nevertheless, it is evident from university teaching that some students have not reached the stage of formal operational thinking even though they have sometimes attained the age of 20 years or more, and may never be capable of formal thought. Moreover, many people frequently revert to the use of concrete operational thought under particular circumstances, even though they are well capable of formal thinking.

Thus, the choice is not between a symbol processing approach or a situated action approach to learning, but rather the search for a further approach that encompasses both of these approaches,
each to be used in appropriate situations. To base learning experiences on one approach to the exclusion of the other during the years of schooling is to deny students the capacity to use one type of procedure in situations that demand its use. The development of a curriculum solely with the principles of constructivism in mind, or to base a curriculum only on the principles of social constructivism is to deny students the capacity to advance to formal operational thought. Likewise, to develop a curriculum based solely on formal operational thinking with a concentration on symbol processing procedures for students who have not been adequately prepared is to provide very frustrating learning experiences for those students who cannot cope with formal operational tasks.

These issues do not appear to be adequately acknowledged in educational circles in many Western countries, including Australia and the United States. Shayer and Adey (1981) in Britain would appear to be aware of the issues and have argued for 20 years and more for the development of appropriate curricula. A recent article by Penner (2001), titled 'Cognition, Computers, and Synthetic Science: Building Knowledge and Meaning through Modeling', laid excellent foundations for a shift towards what he recognises to be a modelling approach. This modelling approach is probably not new. However, Penner fails to recognise that a model must be tested for adequacy, not only in the accumulation of knowledge by scientists, but also by individual students in their learning of science and mathematics in schools and universities. The emphasis on practical work in English and American schools from the beginnings of the twentieth century, under Armstrong’s (1903) advocacy, has ensured that the testing of models in the learning of science has not been ignored during the past century. However, it is unfortunate that while Penner considers practical work in the traditional teaching of science, he does not see clearly the role of testing of models in a modelling approach.

Science education needs to move beyond the demonstrations and so-called experiments that are characteristic of school science. This requires that researchers and educators consider ways of engaging students that involve them in seeking to understand and explain natural phenomena. (Penner, 2001, p. 1)

Clearly, there is need to develop the modelling approach that Penner strongly endorses and to consider where it fits in the debate on the nature of the cognitive processing involved in the testing of ideas. Nevertheless, Penner rightly recognises the power of computers and synthetic science in the teaching of both science and mathematics. It is exciting to learn of the development of a computer based mathematics course that has adopted a modelling approach and is designed for use at the upper secondary school level in Australia. This work that is being carried out at the I. N. Baker Mathematics Centre in Adelaide has the potential to transform the teaching of mathematics in secondary schools through the adoption of a modelling approach.

**TOWARDS A NEW APPROACH TO COGNITIVE SCIENCE**

The partial rejection of both the situated action approach and the physical symbol processing hypothesis approach considered above demands a new theoretical approach to cognitive science. A connectionist theory and recent work on artificial neural networks (ANNs) has been presented by Evers (2000) with a taxonomy of the main models being employed together with a fairly detailed account of the workings of one particular type of model in an educational situation (Yuen, 2000). It is of interest that a first account of this work seen by this author in an educational setting should come from the University of Hong Kong in the Asia-Pacific Region. Are the new frontiers of educational research being established in the Asia-Pacific Region?
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