What are Cognitive Tools?

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1 Tools

Tools are extensions of human beings that partially differentiate humans from lower order species of animals. Other species of animals have discovered tools, but have been unable to conceive needs to construct tools or incorporate tools into their cultures. Throughout history, humans have developed mechanical tools to facilitate physical work. The wheel and lever provided humans with an enormous mechanical advantage. The industrial revolution added arilcial sources of power to extend that advantage. The electronic or information revolution has further extended that advantage by extending the functionality and speed of tools. Computers now perform tasks at speeds which are orders of magnitude greater than humans with or without more primitive tools were capable of.

Tools have been created for many purposes. They have typically evolved from functional needs � hunting, fanning, constructing, transporting, calculating, transmitting and so on. Mechanical tools were developed to facilitate physical needs. The bow and spear were developed as tools for hunting, the plough for tilling the soil, the wrench and bolt for fastening things together. Steam driven machinery was developed in the last century to support the manufacture and transport of products. The computer was developed in this century for calculating, storing and communicating information. Each technological revolution has generated increasingly more sophisticated tools with greater functionality. Often, as tools become more powerful in solving mechanical problems, their functionality narrows (can you think of any other applieation of a cotton gin than its intended one?). Electronic technologies, including the computer, have provided multiple information processing functions. Many of the software tools developed for the computer also have extensibility, that is, they can change forms and assume additional functionality. This book is about developing and adapting computer�based tools to extend cognitive functioning during learning.

The irony of education is that few tools have ever been designed or executed to facilitate learning. The chalk board is one of the few notable exceptions, particularly in light of its popularity and longevity. Other tools, such as pencils, paper, calculators, have become important to f duration. Many tools and media such as projectors, transmitters, and computers have been retroactively adapted to educational purposes, however few have been developed with learning as a goal.

This book is about learning tools�computer�based tools that have been adapted and/or developed to support learning. These tools are different from normal, task�specific tools. These are generalisable tools that can facilitate cognitive processing�hence cognitive tools. Just as a convection oven supports the cooking process, cognitive tools support the learning process. Derry (1990) defines cognitive tools as both mental and computational devices that support, guide, and extend the thinking processes of their users. Many cognitive tools, such as cognitive and metacognitive learning strategies (Tessmer & Jonassen, 1988), are internal to the learner. However, the tools described in this book are external, computer�based devices and environments that extend the thinking processes of learners. These are tools that are used to engage learners in meaningful cognitive processing of information. They are knowledge construction and facilitation tools that can be applied to a variety of subject matter domains. These cognitive tools include specially de,signed knowledge construction tools, such as semantic networking tools and micro worlds for mediating learning. Much of the book focuses on the use of application tools, such as expert systems and hypertext, for engaging cognitive processing and mediating teaming. In order to explain conceptually how cognitive tools work, we next consider the mediation of learning.

2 The Mediation of Learning

Technologies do not directly mediate learning. That is, people do not learn from computers, books, videos, or the other devices that were developed to transmit information. Rather, learning is mediated by thinking (mental processes). Thinking is activated by learning activities, and learning activities are mediated by instructional interventions, including technologies. Learning requires thinking by the learner. In order to more directly affect the learning process, therefore, we should concern ourselves less with the design of technologies of transmission and more with how learners are required to think in completing different tasks. Rather than developing ever more powerful teaching hardware, we should be teaching learners how to think more effectively. We should focus less on developing sophisticated multi�media delivery technologies and more on thinking technologies, those that engage thinking processes in the mind. The role of delivery technologies should be to display thinking tools, tools that facilitate thinking processes.

Cognitive tools, if properly conceived and executed, should activate cognitive and metacognitive learning strategies. They are computationally based tools that complement and extend the mind. They engage generative processing of information. Generative processing occurs when learners assign meaning to new information by relating it to prior knowledge (Wittrock, 1974). Deeper information processing results from activating appropriate schemata, using them to interpret new information, assimilating new information back into the schemata, reorganising them in light of the newly interpreted information, and then using those newly aggrandised schemata to explain, interpret, or infer new knowledge (Norman et al, 1978). Knowledge acquisition, according to these definitions, is a constructive process. Cognitive tools facilitate the processes of constructing knowledge by learners. They are knowledge construction tools� tools that extend the mind.

This workshop was about cognitive tools�computer�based tools that facilitate generative processing of information by learners. Cognitive tools represent learning with information processing technologies as opposed to learning of them (Salomon, Perkins & Globerson, in press). Leaming with technologies amplifies the learner's cognitive processes while using those technologies. Computer�based cognitive tools are in effect cognitive amplification tools that are part of the environment. Environments that employ cognitive tools distribute cognition to the person (Perkins, 1990). Cognitive tools are intelligent resources with which the learner cognitively collaborates in constructing knowledge.

3 Epistemological Basis for Cognitive Tools

The paradigm shift in learning psychology from behaviourism to cognitivism is well documented and seldom disputed as a step forward in learning theory. Generative learning assumes that the mind is necessary for learning and is responsible for knowledge acquisition through the engagement of cognitive processing by the learner. In this conception, knowledge is distinguished from infornnation. Information is the stimuli that are perceived and recorded by the mind. Cognitive learning theory assumes that learners interact with that information, interpret it, and build personal knowledge representations after relating that information to their prior knowledge. The information with which learners construct their reality represents the external reality. However, this information itself does not represent knowledge.

Traditional, materialistic conceptions of mind (objectivism) view thinking and learning quite differently. Objectivism treats knowledge as externally mediated information which is generated by a teacher and transmitted to leamers. The purpose of education is for the learner to acquire the knowledge of the teacher�to assimilate the knowledge of the teacher or expert. Objectivism equates information and knowledge as far as the learner is concerned. Knowledge, according to an objectivist epistemology, is determined by the teacher and not the leamer. There is an external reality that each individual can come to know in the same way. Knowledge is externally referenced rather than internally generated

Cognitive tools are are based upon a constructivist epistemology. The goals and design of constructivistic technologies differ from previous technological innovations (Figure 1). Traditional technologies such as programmed instruction and techniques such as instructional design are

objectivistic. That is, their intention is to transmit objective knowledge. Programmed instruction was both objectivistic and behavioristic. External reality was mapped onto learners by manipulating their behavioural patterns. Although instructional design is in transition from behavioristic to cognitivistic assumptions and techniques, it too remains objectivistic. Even the most advanced, computer�based learning technologies, such as intelligent tutoring, are largely objectivistic. Although intelligent tutors make cognitive assumptions about the learning process, they still assume that the expert's knowledge structure is mapped onto the students Tools that amplify thinking and facilitate knowledge construction can be thought of as constructivistic tools.

	Contructivism		
Behaviorism	Motor Skills	Cognitive tools	Cognitivism
	Programmed instruction	Intelligent Tutoring systems	
	Objectivism		

Figure 1. The goals and design of constructivic technologies

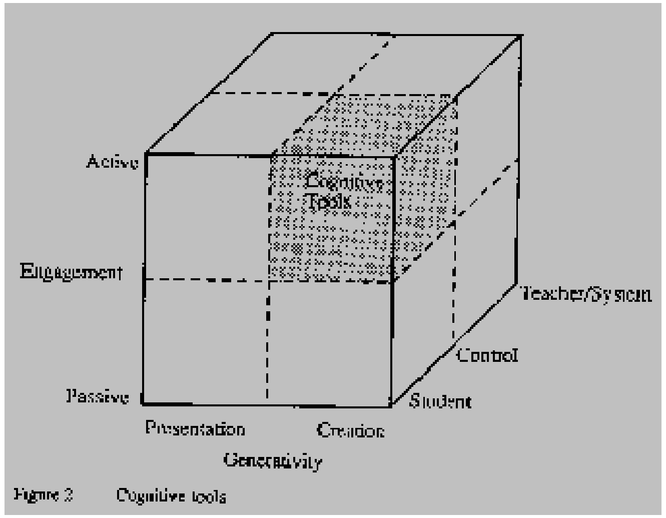

Figure 2. Cognitive tools

Cognitive tools are constructivistic because (as shown in Figure 2) they actively engage learners in creation of knowledge that reflects their comprehension and conception of the information rather than focusing on the presentation of objective knowledge.

Cognitive tools are learner controlled, not teacher or technology�driven. Cognitive tools are not designed to reduce information processing, that is, make a task necessarily easier, as has been the goal of instructional design and most instructional technologies. Nor are they "fingertip" tools (Perkins, 1990) that learners use naturally, effortlessly, and effectively. Rather cognitive tools provide an environment and vehicle that often requires learners to think harder about the subject matter domain being studied while generating thoughts that would be difficult without the tool. They are cognitive reflection and amplification tools that help learners to construct their own realities using the constructs and processes in the environment on a new content domain.

4 Cognitivism or Objectivism is not the Question

We have argued that cognitive tools are constructivistic, that they are designed to assist learners in acquiring, restructuring and tuning knowledge. But when and where are cognitive tools useful? Should they be used to facilitate all types of leaming? Should all learning be personally constructed, or should some remain externally referenced?

It is not reasonable to assume that all knowledge should be personally constructed. Socially constructed reality will always maintain an important role in society. It is the conceptual glue that holds societies together. If learners construct knowledge based upon faulty models, then the educational system has done them a disservice. Also, much knowledge is and should remain negotiated or socially constructed. Much of our collective knowledge is extrinsic, shared knowledge. Despite individual construction of knowledge, most of us develop the same or similar schemas for much of our knowledge. We all share a general conception of "chair" because our constructions of a "hair are common enough. If we didn't share these schema, that is, we did not share similar conceptions for many or most objects, then communication would be impossible. Completely idiosyncratic knowledge constructions would result in intellectual chaos. The societal good is also served by common, extrinsically driven schema construction. For instance, pilots and air traffic controllers should not be allowed to construct their own conceptions of flying in crowded air space. Knowledge should, to some degree, be personally constructed, but it also must be societally shared. To the degree that we can safely and successfully allow learners to construct their own knowledge, cognitive tools should be used to assist them in this endeavour.

5 Summary

Learning systems in the past two decades have become increasingly cognitively oriented, investing more intellectual responsibility and intentionality in Seamers. Designers of learning environments and instructional systems are engaging learners in more meaningful mental processing. The next logical step in this revolution is to invest additional responsibility in the learner for personally constructing knowledge where appropriate. If we do, learners should become more self�reliant thinkers better able to relate new information to existing knowledge arid better able to apply that new knowledge in novel situations. Effective cognitive tools are those that support cognitive processes, those that enable learners to engage in higher order thinking, that help learners engage in cognitive processes that would normally be impossible, or that allow learners to generate and test hypotheses in meaningful problem�solving situations (Lajoie, 1990). Learning systems and environments that employ cognitive tools that perform in these ways represent a further step in the constructivistic direction of learner empowerment

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Cognitive Tools: A Suitable Case for Learning

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Abstract

This paper discusses the idea of cognitive tools for learning. These are essentially comprehension tasks which require a learner to analyse material at a deeper conceptual level than would normally follow from a simple instruction "to learn". Deep learning results as a kind of byproduct of using a cognitive tools task, as indeed it does from any such analytical search for meaning. An empirical and theoretical underpinning for this approach is provided in the cognitive psychology literature by the levels of processing approach and by the enactment effect. An attempt is also made to position cognitive tools in the context of instructional theory, and an example is given of a cognitive tools approach to learning from hypermedia.

"Subjects remember not what was 'our there', but what they did during encoding"

Craik and Tulving, 1975

Keywords: Instructional techniques / comprehension / cognitive psychology / intentional learning / incidental learning / levels of processing / competence / metacognition / mental models

1 Introduction

The concept of a cognitive tool, as used in the workshop that has produced the current volume, is easy to describe. It is simply a device, or technique, for focusing the learner's analytical processes. A cognitive tool can be regarded as an instructional technique in so far as it involves a task, the explicit purpose of which is to lead to active and durable learning of the information manipulated or organised in some way by the task. The primary task is not learning per se. To instruct someone 'to learn' is in effect to say, 'perform some activity which results in understanding of, and durable memory for, this material'. Our idea of a cognitive tool is of one that gives the learner just such a ready�made task

The cognitive tool concept also carries the implication, as with any tool, that the user will become rnore skillful with practice, and the tool will therefore be more effective in the hands of an experienced user. This definition is broad enough to encompass a wide range of activities as cognitive tools, ranging from verbal debate to the playing of computer games. The idea is predicated on the assumption that learning is not a particular, discrete activity that can be turned on and off. Rather, learning is an inescapable by�product of comprehension. Nevertheless, we have to acquire techniques for comprehending. Many aspects of human cognitive development can be regarded as the acquisition of such techniques.

It is helpful to consider this at two levels. First, there is the development of skills for making sense of the world. These are metalearning processes. Then there is the business of actually employing these in the acquisition of knowledge. The idea underlying this workshop was that computers can offer interactive tasks which are effective at both these levels. The result is assumed to be a deeper level of comprehension of the currently analysed material, and as a consequence of this, deeper learning and thus more durable memory for that material. There is also the benefit of an improved capacity for such thinking in the future.

2 The Cognitive Psychology of Cognitive Tools

"...it is legitimate to say that all the cognitive processes that have been considered, from perceiving to thinking, are wa,,ys in which some fundamental 'effort after meaning' seeks expression."

F C Bartlett, 1932

Anderson (1990) describes a personal experience which illustrates the essential nature of learning very well. In a verbal learning experiment in which his sophomore class was required to learn paired�associates such as DAX�GIB, Anderson, determined to outperform the rest of his class, tried to burn the information into his memory by an intense process of repeating the paired associates over and over to himself as quickly and loudly as possible. By this method he achieved the worst performance in the group. His method neglected to make the pairs meaningful in any way. In fact, countless experiments have now demonstrated that meaningful information is better remembered than meaningless information. Only a very small amount of information can be retained by rote, and only for as long as it can be maintained in working memory by conscious attention. As soon as attention is diverted it is lost. It is almost impossible to recall anything if it has no meaningful structure to guide retrieval. By the same token, it is hardly possible not to learn something which has provided meaning. In fact, it does not seem to matter much whether there is an actual intention to learn or not. There is a long history of experimental findings on learning that demonstrate this.

It is evident that we learn all the time without making any special effort. Ask football devotees to tell the results of last Saturday's matches and not only will they do so, usually in great detail, but they would be astonished to be regarded as having had to make any kind of effort to learn that information. Once a sufficiently rich framework of understanding is in place, the pickup of information is indeed effortless. In fact, the whole concept of "processing" information has rather too deliberate and intentional a connotation. As we build a framework, or schema, for comprehension, we build a mechanism for automatic learning. New information is simply an elaboration, or a filling in of the slots, of what is already understood. No 'effort' is involved, beyond attending to the information in question. It is not so surprising, then, to find that learning done with the intention to remember is hardly any more effective than that done without such intention. Research on this question compares intentional learning with incidental learning.

A well�known experiment that illustrates the role of intention was performed by Hyde and Jenkins (1969). In this, the subjects were read a 24�word list and were subsequently asked to free recall as many of the words as they could. There were seven different groups of subjects, each receiving different instructions before hearing the list. One group was given intentional learning instructions. They knew that they were to be asked to recall the words subsequently. Three of the groups were not told that they would be asked to recall the words. They were given 'orienting tasks' which ensured that they would pay attention to the words as they were presented. One group rated each word, as it was presented, on a 'pleasantness�unpleasantness' dimension. The second group had simply to decide whether each word contained a letter "E". The third group estimated the number of letters in each word. Three remaining groups were given mixed intentional and incidental instructions. They were required to perform one of the three orienting tasks, but in addition were told that they would have to recall the words. From the results it was clear that learning was as effective when words were rated for pleasantness as when subjects were told to learn the words. The other two orienting tasks�detecting E's and estimating the number of letters�produced poor learning. Also, when combined with the intentional learning instructions, the inefficient orienting tasks interfered with learning. The intention to leam, per se, seemed not important. Much more important was attending to the material in a particular way. A pleasantness�unpleasantness judgment requires thinking about the meaning of each word. The other tasks merely require thinking about surface or structural features. These apparently interfere with the processing of meaning that is necessary for learning.

Other studies of incidental learning have shown that people often remember rather little about familiar objects. For instance, the study by Nickerson and Adams (1979) demonstrated the remarkably poor visual memory most subjects have for the detailed features on the face of a familiar coin. Of course, such detailed features are quite incidental to the functionality of a coin, receive only shallow processing and are therefore poorly remembered. This argument suggests that although it may contradict our model of our own minds that we seem to notice so little about the environment we "know", it is functional not to process the meaning of everything that impinges on us. An HCI example of this was provided by Mayes et al (1988b) who tested what users remember of the detailed content of the MacWrite interface. They found that even experienced users can recall little of the menu contents, even though during use those menus are the instruments of their successful performance. It seems that the necessary information is picked up, used, and discarded; it is not learned in the sense that commands are learned. More exactly, users retain only enough information for recognition, not the much greater amount required for recall. This study differs from previous studies because the learning which the subjects seemingly failed to do was not incidental but apparently central to their purposeful and skilful behaviour. Thus, it seems that users do not learn even things which are vital to their performance if they reliably find them in the environment when needed. Much of the "knowledge" that underwrites their performance seems to be left in the world, which is therefore used as a kind of extended memory. There is no point in 'comprehending' the visual detail on the face of a coin in order to use the coin. Similarly there is no need to comprehend the detailed features of a computer application, unless those features are crucial at the functional level of the user's task.

We learn as a by�product of understanding. Yet we can normally get by with 'understanding' less than we may like to think. Much successful performance can be based on an interaction with information in the environment. Only by requiring a learner to perform explicit comprehension tasks, where deep processing is necessary to complete the task, can we be sure that the learner is not constrained by the context of the particular learning experience.

The basic point here, as with much else in psychology, was succinctly made by William James (1890) who wrote: "...the one who thinks over his experiences most, and weaves them into systematic relations with each other will be the one with the best memory..". In its modem form in memory theory, the notion is one of levels of processing.

2.1 The Levels of Processing Approach

Craik and Lockhart (1972) argued for the understanding of human memory as a by�product of perceptual analysis and that the durability of memory would be a positive function of the depth to which the stimulus has been analysed. Thus, "..deeper levels of analysis are associated with more elaborate, longer lasting and stronger (memory) traces...". Normally only the results of the deeper analyses can be regarded as learning, the by�products of preliminary or 'surface' analysis are discarded. What is needed later is meaning, and the extraction of meaning involves the deeper levels of processing. Craik and Lockhart viewed processing levels as a continuum of analysis. At one extreme, sensory analysis in the visual or auditory analysis systems will give rise to memory traces that are transient and easily disrupted. At the other end of the continuum, the process of semantic analysis will lead to more or less permanent memory.

The levels approach assumes that information that seems immediately meaningful, perhaps because it is highly familiar, is easily remembered because it is compatible with previously existing cognitive structures. Such material will be easier to process to deep levels, and faster, although speed of analysis is not itself a very good predictor of subsequent retention. Depth of processing will be affected by several things: the amount of attention given, the relation to existing cognitive structures, and the amount of time available for perceptual analysis and processing.

Craik and Tulving (1975) undertook a long series of experiments in order to gain empirical evidence and to refine the levels of processing approach into a full�scale theory. The usual procedure followed in their experiments was to present words to subjects and to ask a variety of questions designed to influence depth of processing. Shallow levels of processing were achieved by asking about the nature of the typescript, (is the word in capital letters?); intermediate levels by asking for a judgment about phonemic similarity (does the word rhyme with...?); deep encodings were encouraged by asking whether the word would fit into a certain sentence frame or semantic category (is the word a member of the following set..?). For both recall and recognition tests, the deepest level of encoding took the longest time and produced the highest subsequent retention. Actually, time to encode was shown not to be the critical factor. A complex but shallow task will take longer to perform but will still yield lower memory scores than an easy but deeper processing task.

Craik and Tulving carried out one experiment where their subjects were asked to judge the apropriateness of the target word to fit sentences of varying complexity. For example, does the

word "pen" fit the sentence "she dropped the...", or can the word "watch" fit the sentence

"the old man hobbled across the room and picked up the valuable...from the mahogony table"?

There was a strong tendency for the more elaborated sentences subsequent to be better recognised. This, and other related findings, led Craik and Tulving to suggest that what is critical is

not simply the presence or absence of semantic coding, but the richness or elaboration with

which the information is encoded.

In the literature on the cognitive psychology of memory, the levels of processing approach led to a rather arcane debate about the mechanisms involved in producing the striking effects observed in the experiments. We need not concern ourselves with this level of theory. Some sense of the complexi�ies involved can be gained from Mayes & Mcivor (1980)

The relevant point for the present discussion is that both empirical and theoretical underpinning for the idea of cognitive tools is evident in this work.

One further finding from this literature is worth highlighting. That is the enactment effect. _ohen (1981) showed subjects a series of objects. Under one condition they were asked to perform an action on each object. For example, they might be shown a match and then asked to "break the match". Subsequent recall was significantly higher if the instruction to break the match was actually carried out rather than simply being read. Other studies have confirmed that the enactment effect is is large and robust (Nilsson & Cohen, 1988). As Craik and Tulving put it: people remember what they *did*.

3 Cognitive Tools and Instructional Theory

Glaser and Bassok (1989) have discussed the various instructional approaches that have emerged from the main thrust of work in cognitive science over the last few years: the concentrated work on competence, on the study of the growth of expertise in complex domains such as medical diagnosis, geomeuic proofs and computer programming. How do cognitive tools fit in?

3.1 The Development of Competence

One line of insuuctional development is based on the study of the way in which expert perfortrumce differs from that of novices. It is widely agreed that knowledge acquisition proceeds from a declarative form to a procedural, compiled form. As performance becomes more expertlike and fluent so the component skills become automatised. Thus, conscious attention is no longer required to monitor the low�level aspects of performance and cognitive resources are available for more strategic levels of processing. Thus the computer tutors developed by Anderson and co�workers (Anderson et al, 1984; Anderson et al, 1985; Lewis et al, 1988) for learning LISP, for producing geomeuSy proofs, and for solving algebraic equations are all based on this 'expertise' view of teaming, and on the model of Fitts and Posner (1967) that described the development of skill as progressing from a declarative, verbal knowledge initial stage, through an intermediate stage of associative learning, to a final autonomous stage of compiled knowledge. Anderson's ACT* theory (Anderson, 1983) can be seen as an elaboration of this. Essentially Anderson argues that initial declarative knowledge must be applied in solving problems if the development to subsequent stages is to occur. The process of knowledge compilation will occur in two ways: first, proceduralisation will result from comparing problem states before and after generating the solution, and then building the production rules on which the automatisation of the skill will be based. Cotnposition is the building of larger and larger units of production, or to use other terminology, the building of feedback loops around larger and larger units of behaviour. Based upon this progression towards expertise through problem solving practice, Anderson has derived insubuctional methods which concentrate on giving declarative knowledge about problem solving strategies and which closely monitor the student's performance. One method used for achieving an efficient interpretation of declarative knowledge is the use of analogy to previously experienced examples.

Glaser (1990) makes the interesting point that the instructional strategies to be found in Anderson's intelligent tutoring systems are strongly reminiscent of Skinnerian shaping and successive approximation schedules in programmed instruction. Thus the tutor's close monitoring of the developing skill, the immediate feedback during problem solving, the requirement to minimise errors, and the gradual shaping of performance by the accumulation of components are, from an instructional viewpoint, almost identical to the procedures of programmed learning. This strongly suggests that the philosophy of intelligent tutoring is really orthogonal to the cognitive tool approach to learning. It is possible to argue, however, from our definition of cognitive tools as tasks which simply engage the learner in an analysis of some domain, that the essential use of problem solving to achieve learning underlies both approaches. In fact, most intelligent tutoring can be seen as an attempt to teach the learner how to perform some specific analytical or problem solving technique, such as programming or geometry. The cognitive tools approach is concerned with the kind of learning that flows from the performance of the skill, once it has been acquired.

3.2 Metacognition

A second instructional approach can be identified as that which concentrates on self�regularory strategies. This also can be derived from studies on expert performance since experts develop high�level skills for monitoring their own performance. There is also a strand of work from developmental psychology which emphasises the need for metacognitive skills to underpin successful learning. Several cognitive instructional programmes have now been designed which aim to develop these executive control strategies, in reading comprehension, in writing and mathematics. There are two important general concepts from developmental psychology which underpin this approach.

1. Learning is self�directed. The need to make sense of one's environment is absolutely as natural as breathing. Thus there is intrinsic motivation for generating explanations, and the skill in doing this is a fundamental component in learning. Cognitive experimentation, the trying out of new hypotheses, seems crucial here.
2. Cognitive development occurs through the internalisation of cognitive activity originally experienced in social contexts. This leads to an emphasis on cooperative learning. The learner is exposed to alternative viewpoints that challenge initial understanding. This is a rationale for "Reciprocal Teaching" (Vygotsky, 1978).

Glaser (1990) describes other instructional methods which we can classify as being directed towards metacognitive control skills. In these approaches, problem solving is taught by making explicit such processes as generating alternative hypotheses, evaluating likely outcomes, and keeping track of success.

This approach represents a radically different view of the learner from that of the procedural skills approach. Here, the learner is seen as intrinsically motivated to seek and explore explanations. Cognitive tools will capitalise on such intrinsic motivation by engaging the learner in a challenging task. Presumably there is also the expectation that the learner will become aware of the effectiveness for learning of pursuing the kind of thought processes stimulated by the cognitive tool task, and will start to apply them even without the 'tool'. This is the 'learning how to learn' argument

3.3 The Mental Models Approach

A different conceptualisation of the learner is to be found in White & Frederiksen's (1986) account of the progression through increasingly sophisticated and elaborate mental models that will characterise the learner's gradual mastery of a new domain. They argue that learners should first be exposed to models that make contact with their intuitive naive models of phenomena. Thus an effective learning environment will be one which offers models which are designed to allow more complex models to be transformed from them. Each model will allow the learner to interact at an appropriate level of complexity. It is not simply an incomplete version of an expert but is a model specifically designed for transformation. It is obviously important to devise problems which will trigger a change of model. This approach assumes that the domain is sufficiently well analysed, and the stages to expertise sufficiently well understood. The underlying assumptions here are interestingly different from those above. Thus, the mental models approach assumes that the optimal route to understanding entails conceptual discontinuity: the goal of the instructional strategy is to encourage this to occur in the leamer. It implies a curriculum approach, presenting a sequence of conceptualisations. A cognitive tools version of this, on the other hand, would have to devise tasks which encouraged the learner to progress through such conceptual stages without explicit guidance. This seems a very challenging requirement, and it is hard to think of any current examples, but it seems plausible that a combination of the cognitive tools and mental models approaches might lead to some particularly interesting solutions.

4 Cognitive Tools in Practice

4.1 Hypermedia as a Cognitive Tool

It is usually assumed that hypermedia itself embodies a particular kind of instructional theory. This is probably an implicit version of the metacognitive approach and assumes that providing a rich environment for exploration, in which a learner can move fluently between different levels of detail, can offer the learner a powerful environment for picking up knowledge. In particular it is assumed that active exploration encourages the learner to learn the high level skills of asking questions, creating hypotheses etc

Nevertheless, it is possible to see hypermedia as quite well suited to the support of each of the above kinds of instructional strategy. It is, for example, perfectly possible to employ hypermedia as an effective vehicle for programmed instruction, or in its more modem guise, as a guided curriculum. Zellweger (1989) has described the concept of a path in hypertext, and has shown how path mechanisms can solve the problems of disorientation and cognitive overhead. When a reader is lost in hyperspace, it should be possible to recognise a nearby path. There is no reason why hypertext should offer the browsing paradigm as the major mode of interaction. Paths allow the author to impose a sequence. The expressive power of a path is determined both by the sequencing model and the characteristics of the entries that can appear along the path. Just as in later forms of programmed instruction, a branching path contains branches that can be made contingent on the student's choice and a conditional path can be made contingent on his or her perforrnance. Zellweger extends this idea to something more lice a programming paradigm.

As we will see below in the description of StrathTutor, hypermedia systems are perfectly well suited to the generation of problems. Of course, there are many issues that are raised here: about control, about modelling, about representation, and others. Nevertheless, it is easy to devise forms of hypermedia that will engage the learner in an analytical approach to the contenL Hammond's (1991) 'knowledge jigsaw task' is a good example.

4.2 StrathTutor

StrathTutor has been described fully elsewhere (Mayes et al, 1988a; 1990a; l990b). To make the argument that it can serve as a cognitive tool, however, certain features need to be highlighted. In StrathTuror links are computed on the basis of attribute coding, from a set of up to 60 attributes predefined by the author for the particular domain. Each designated 'hotspot' of text and/or graphics is so coded. The system computes the 'relatedness' of all remaining unseen frames to the current frame ('frame' is arbitrarily set at the size of a single screen) or hotspot. Each frame can be represented as a profile of attributes, summed across all hotspots in that frame. StrathTutor demonstrates that fixed links between objects such as individual graphics or fragments of text are not necessary to generate a hypertext system, if by hypertext we mean the provision of such links at run time. Thus, each frame is separate, united with its underlying knowledge but independent of all other frames until a link is formed at run time. A frame may be deleted and the system will still operate without the need to remove links now undefined. Similarly, a frame together with its attributes may be added and the system automatically takes it into account when links are generated.

The learner can choose to navigate by accepting the 'related' frames offered by the system, or can proceed to access named frames. Details of the way in which StrathTutor achieves this computation are given in Kibby and Mayes (1989). The browsing in StrathTutor is encouraged to take place in conceptual space, rather than in the spatially organised network of conventional hypertext, with fixed links. There is, however, a traditional hypertext feature whereby some hotspots are explicitly linked to windows presenting explanatory material. Nevertheless, a much more important feature of this system is the opportunity it offers learners to try out hypotheses about the meaning of attributes and the relationships between them. Every frame that is presented by StrathTutor represents a problem to be solved; the learner is continually being challenged to 'make sense' of the underlying computation, which is based on the knowledge description of the domain produced by the author.

The learner may click on a hotspot, meaning "tell me more about this" and the system will simply provide a new frame. The learner now has to solve � problem: what is the connection between the previous material and this? In fact StrathTutor provides a menu choice of Why show this frame? which will, when chosen, display a list of the attributes in common between the two frames, or the hotspot and the new frame. Often the links will remain obscure; only as the learner becomes immersed more deeply in the content and the nature of the relationships between nodes, by 'second guessing' the system, will any understanding of some links be possible at all. When the learner is beginning to obtain a glimmer of understanding of the way in which certain attributes relate, say the attributes of erosion, weathering and deposition in the domain of glaciation, then he or she can 'interrogate' the system by setting up that combination of attributes for a 'guided tour' of all frames that are coded with that particular subset. This rnay be regarded as giving the learner the opportunity to "navigate with concepts". A series of scenarios is then presented, each of which the learner must attempt to understand as an illustration of that particular combination of attributes.

An insight into StrathTutor's essential role as a cognitive tool can be gained by considering each frame as a scenario in which the learner must attempt to identify the attributes represented. If wee consider each attribute as a node in the underlying conceptual space then the frames or scenarios are ways of representing some of the links. Each scenario is a little hypermedia system of its own, which the learner must unravel in order to proceed with the task.

Thus the instructional approach embodied in SrrathTutor is one of learning by challenge. Despite its conventional frame�based appearance it can clearly be seen as a problem generating system. This is achieved in two ways in StrathTutor: first, by allowing the learner to interrogate the system with combinations of attributes which are beginning to make sense. In this manner the learner is probing the system with hypothetical 'links' and asking the system to confirm the nodes, by presenting just those frames having that particular subset of attributes. Secondly, Ike StrathTutor 'quiz' invites the learner to play a kind of game, in which he or she tries to identify the areas across the two frames which have maximum overlap in attributes. The game�playing aspects of this are made explicit by offering the learner a "bullion score" of gold and silver points based the number of attributes in common between the two hotspots identified Here the learners are matching themselves against the author who created the attribute tags on each hotspot. Only by engaging at the conceptual level with the domain in question can the game be 'played' at all. This, surely, is the essence of a cognitive tool approach. Embedded within a kind of hypermedia specifically devised as a learning system, are tasks which the learner must perform by carrying out an analysis of the material at a conceptual level. This analysis leads inevitably to deep learning.

Finally, the case for cognitive tools is also a justification for the old adage that the best way to learn something is to try to teach it. In the present context we might say that the best way to gain deep understanding of some domain is to author it in a CAL system. In our work with StrathTzxtor, by far the most significant gains in understanding, and thus in learning, have been observed in the authoring process, where people have to devise and assign atuibutes to the presentational material. This task makes very similar demands to those of building knowledge bases from, or of making explicit the semantic organisation of, some body of to�be�learned information, which forms the rationale for other cognitive tool approaches to be found in this Volume. In order to teach something its underlying conceptual suucture must be made visible, and accessible to the learner. Any computer�based task for elucidating such structure will perform the essential role of a cognitive tool for learning. Authors who we have studied in the process of building a StrathTutor hyperbase have all reported that they have been required to think more analytically about the subject matter than ever before. In a real sense their understanding of the material has been advanced by the performance of the task. This is the case for cognitive tools.

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