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FROM TEACHING MACHINES TO KNOWLEDGE-BASED SYSTEMS: CHANGING PARADIGMS FOR CAL

by

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ABSTRACT

The future of computer-assisted learning is analyzed in terms of the interplay of information technology and education as phenomena in the life world, both supporting the knowledge transfer processes of our society. The infrastructure of information technology shows patterns of learning curves through the generations of computing that have been reflected in the foci of attention in CAL. Only in the present fifth generation era of knowledge-based systems can information technology begin to offer direct support to the educational process.

INTRODUCTION

Advances in technology have raised many expectations in education and fulfilled few. We are right to be suspicious that the glitter of advanced technologies such as artificial intelligence may not be an indication of pedagogical gold. However, as technology moves into the realms of the mind, it not only offers more of direct relevance to education but has also come to need access to the intellectual foundations of the educational process. The transition from information-processing to knowledge-processing is a very difficult one for the computer industry. The electronic and software engineering foundations of information processing are no longer adequate. The underlying disciplines for the study of knowledge are philosophy, psychology, linguistics, neurology, sociology, anthropology and education—none of which are particularly well represented in the design divisions of computer companies.

This paper traces developments in information technology leading up to knowledge-based systems and suggests that we have commenced a major new cycle of development analogous to the original invention of computing. It relates this to the shifting paradigms for CAL: from the early teaching machines through student modeling and learning environments to knowledge-based systems. It gives a systemic framework for these shifts in terms of transitions from *control-theoretic*, through *identification-theoretic*, and *ecology-theoretic* to *system-theoretic* modes of thought. These perspectives allow the next stages of research, development and applications in computer-assisted learning to be extrapolated.

Finally, the reverse relationship is examined—what has educational theory and practice to offer innovators in artificial intelligence? Slow progress in the development and application of expert systems has directed attention to the problems of knowledge acquisition and transfer. The *knowledge engineering* necessary to transfer knowledge from an expert to a computer system parallels the *pedagogical engineering* necessary to transfer knowledge from a teacher to a student. Much of what we know about the educational process is directly applicable to the development of knowledge-based systems. The knowledge needs to be more explicit and operational before it can be programmed, but satisfying that requirement will be advantageous to both education and computing. In particular, it makes computer-assisted learning (perhaps re-designated yet again as *computer-assisted knowledge transfer*) a central concept for the new generation of knowledge-based systems.

EDUCATIONAL SYSTEMS IN THREE WORLDS

Computer-assisted learning is an application of information technology to education whose role and significance can best be evaluated within the total context of the educational system and its role and significance in society. Education and computing both involve major interactions with people, technology and knowledge, and it is easy to confuse the different aspects of the inter-relationships involved. It is useful to elucidate these interactions by distinguishing phenomena in the *three worlds* of physical objects, subjective experience and statements-in-themselves (Popper 1968)—here termed the material, mental and logical worlds, respectively. Figure 1 shows the relations between a student and various relevant sub-systems involved in education in terms of these worlds.

The material world is one where:

- our perspective is *epistemological*;
- distinctions exist through the necessity of physical *actuality*;
- truth is by *correspondence* to some 'reality', and inference is *causal*.

In this world, from an educational perspective:

- a student has direct experience of the *physical world*, learning from this and relating his or her educational experience to it;
- *teaching aids* support the student's knowledge acquisition processes;
- *information technology* provides new possibilities that have the potential to have far greater impact than any past teaching aids, including books;
- students interact with the material world through direct *experience* of physical entities, and much of their knowledge comes from inductive processes based on such experience.

The mental world is one where:

- our perspective is *psychological*;
- distinctions exist through the choice of human *agents*;
- truth is *performative* in maintaining role integrity, and inference is *conventionalist*.

In this world, from an educational perspective:

- the educational system is part of our *culture* which is itself a dynamic entity, changing as our society develops;
- *teachers* have the responsibility to manage a substantial part of the student's knowledge acquisition processes;
- *domain experts* have the authority to manage particular islands of knowledge;
- students interact with the mental world through *discourse* with people, and much of their knowledge comes from such cultural transmission.

The logical world is one where:

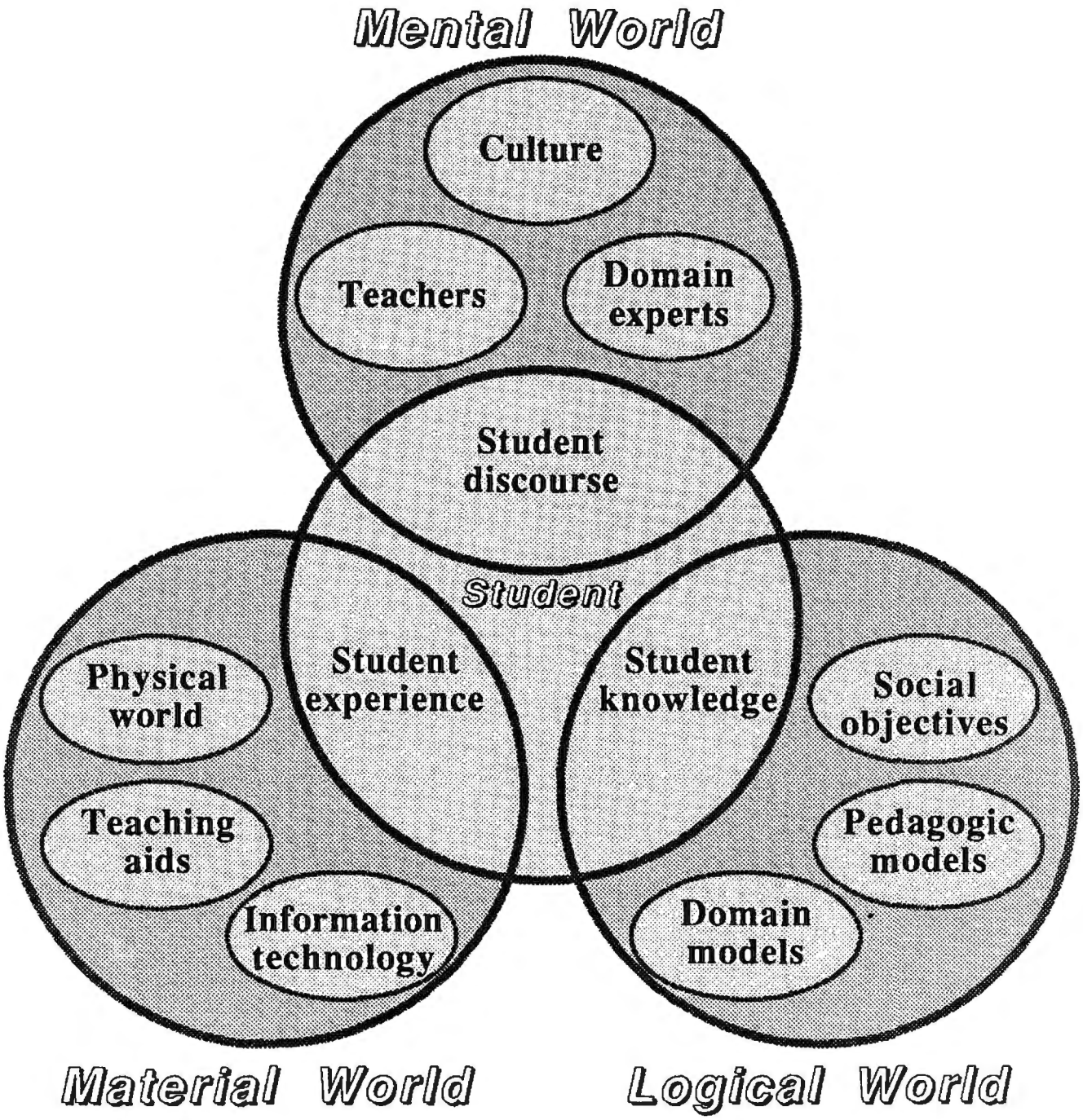
- our perspective is *ontological*;
- distinctions exist *in themselves*;
- truth is by *coherence* in some system of relations, and inference is *structuralist*.

In this world, from an educational perspective:

- the educational system is guided by *social objectives* which are the explicit expression of the planning processes in our society;
- *pedagogic models* guide the management of the student's knowledge acquisition processes;
- *domain models* express the structure of particular islands of knowledge;
- students interact with the logical world by acquiring *knowledge structures* within it, and the educational system is concerned with managing the acquisition process.

In evaluating the role of information technology in education we have to take into account the relations it bears to all the other entities shown. It is a technology arising out of

Perspective: 'psychology'
Key concept: 'agency'
Distinctions defined: 'by choice'
Truth: 'performative'
Inference: 'conventionalist'



Perspective: 'epistemology'
Key concept: 'actuality'
Distinctions defined: 'by necessity
Truth: 'correspondence'
Inference: 'causal'

Perspective: 'ontology'
Key concept: 'abstraction'
Distinctions defined: 'in themselves'
Truth: 'coherence'
Inference: 'structuralist'

Figure 1 Students, education, computing, knowledge and society

our culture and having a high, but little understood, social impact in its own right. It can provide simulation to mimic experience of the physical world. It can be regarded as an extension of existing media as teaching aids, subsuming many past media, greatly extending them in some ways, and not yet providing as good facilities in others. Its extensions include the capability to simulate some aspects of the mental processes of teachers and domain experts, and to make social objectives, domain models and pedagogic models operationally implementable.

These considerations suggest that information technology is of major significance for the educational system, but that analysis of its potential depends on an understanding of the technology and its social role, and a more detailed model of knowledge processes and their role in information technology. The next two sections discuss these considerations.

INFORMATION TECHNOLOGY IN SOCIETY

Many writers have speculated upon the impact of computers on our society (Wiener 1950, Bell 1973, Mowshowitz 1976, Weizenbaum 1976). The impact is now being felt and many commentators are attempting to analyze its nature and project its trends (Toffler 1980, Dizard 1982, Brod 1984, Turkle 1984). However, the majority of such speculation and analysis offers one-sided perspectives relative to two key distinctions:

- First, that the major impact is of computing on society rather than society on computing
  – this takes for granted Ellul's (1964) view of technology as *autonomous*, and fails to recognize the *social shaping* of technology through the processes of society (MacKenzie & Wajcman 1985);
- Second, that the future may be projected as an extrapolation of the past
  – this takes for granted the *causal* processes fundamental to physical science and fails to recognize the *teleological* processes underlying developments in computing.

These one-sided perspectives are appropriate to the analysis of technological dependencies such as the impact of low-cost, high-speed data analysis techniques on structural design. However, they are not appropriate perspectives from which to evaluate the relations between information technology, society, and education. These are phenomena of the life world (Schutz & Luckmann 1973) and embedded in its processes. To understand their relations we must view information technology also as a phenomenon of the life world embedded in its processes, both generated by them and generating them (Kohak 1984, Blum & McHugh 1984).

Viewed as a causal chain, the development of information technology is highly indeterminate. Technological forecasts for computing are notoriously inaccurate (Withington 1974, Gaines 1984a). Projections of the technology over more than a few years are meaningless. Each month the technical press contains a number of major surprises. The causal model is not appropriate to a phenomenon governed by social needs and hence directed by the goals of society. The past is not an adequate determiner of the future in these circumstances—a teleological model that views society as moving towards some future situation is more appropriate to the processes of the life world. The cascade of sub-goals generated in order to create that future situation accounts for the activities of the past, generates those of the present and determines those of the future. The determinacy, however, is that of a goal-seeking, adaptive system—it predicts the necessary achievements but not the means by which they will be achieved.

Computing technology is directed by the processes of society at least as much as it impacts them. Up to its present fairly primitive stage, its development has been governed by existing social processes and the dominant value system. It is only just beginning to become an agent for change. The perspective that views only the impact of computing on society misses the major dynamics of computing technology during the past forty-five years. The

social needs underlying computing result from increasing world population and integration leading to an increasingly complex society. In *Trust and Power* Luhmann (1979) postulates complexity-reduction as the fundamental motivation for all our social institutions. We assume roles to simplify our interactions with one another. We use technology to simplify the natural world, creating man-made environments that we can understand and control. In *Future Positive* De Bono (1979) suggests that computer technology was developed to aid us in coping with the increasing complexity of society. The computer is to the organisation revolution what steam power was to the industrial revolution. The computer extends our organizing power in the same way as steam engines extended muscle power. In the *Control Revolution* Beninger (1986) suggests that the information society is just the latest stage of social response to a nineteenth century crisis of control.

The role of information technology in education can be put in perspective by analyzing the development of the technology, particularly the changing paradigms of control involved, and relating this to the changing paradigms of computer-assisted learning.

INFORMATION TECHNOLOGY LEARNING CURVES

In coming to understand information technology, it is important to realise the electronic computer itself is only one component in an elaborate and highly differentiated infrastructure. This infrastructure has grown through a succession of generations of computers, each of which represents a major change in computing technology (Gaines 1984b). During the eight year span of each computing generation, revolutionary changes have taken place that correspond in magnitude to those taking place over some seventy years or more in the aircraft industry. The first generation commenced in 1948 and we are now in the fifth generation spanning 1980 through 1987.

The growth of the infrastructure of computing technology may be seen as the recursive application of the basic process underlying social and individual development, that of learning (Gaines 1986b). Marchetti (1981) has shown that treating society as a learning process leads to simple explanations of socio-economic processes such as business cycles and technology substitution. The introduction of any new knowledge, technology or product follows a logistic learning curve in which growth takes off slowly, begins to climb rapidly and then slows down as all the information has been assimilated (Van Dujin 1983). The slow growth at each end of the curve is due, initally, to the need to have knowledge in order to acquire more, and, finally, to the difficulty in acquisition as there is less and less left to acquire.

It has been noted in many disciplines that the qualitative phenomena during the growth of the logistic curve vary from stage to stage (Crane 1972). If we take the amount of knowledge necessary for a mature technology to be 100%, then the 10%, 25%, 50%, 75% and 90% points are equally spaced in time along the logistic curve. These points mark significant phases in knowledge acquisition:

- when less than 10% of the knowledge is available, little can be achieved—we are in a pre-*breakthrough* period where most projects attempted will fail through lack of some critical information or skill;
- at around the 10% level some form of recognizable breakthrough becomes possible—we move into a phase of *replication* in which the breakthrough activity is noted and mimicked widely with little understanding;
- replication leads to increasing experience and knowledge based upon it—when the 25% level is reached sufficient information is available for a phase of *empiricism* in which design rules are formulated based on experience.
- at the 50% level sufficient information has been accumulated for deeper patterns to be discerned—a phase of *theory* commences in which causal rules are derived that allow further experience to be predicted and design rules to be derived.

- at the 75% level the theories have become accepted as the normative basis for further progress—an *automation* phase starts in which they are used for design and to search out the residual knowledge;
- above the 90% level a phase of *maturity* is entered—knowledge is expected to be available and used routinely.

This learning curve model may be applied to the substitution of different electronic device technologies as a basis for computing. It then distinguishes the generations of computers in terms of the technology in use:

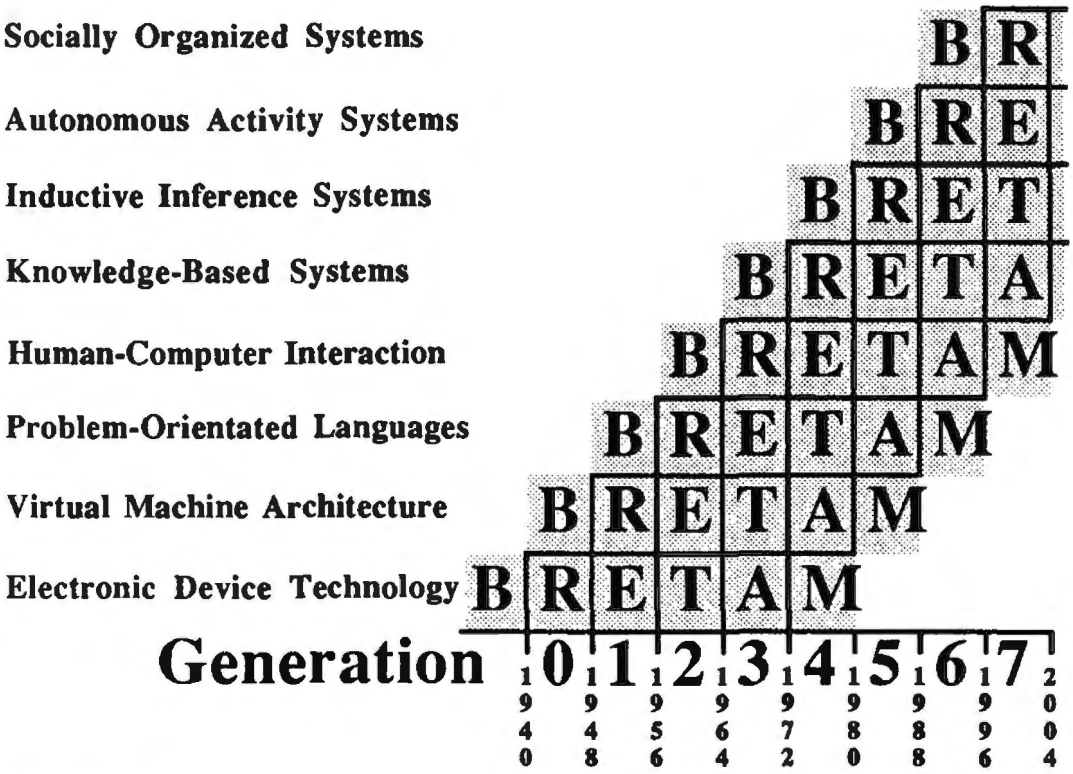
- the zeroth generation started in 1940 with the relay-based Bell Complex Number Computer followed in 1941 by the Zuse Z3;
- the first generation started in 1948 with the vacuum tube-based BINAC in the USA and EDSAC in the UK;
- the second generation started in 1956 with the transistor-based Bell Leprachaun followed in 1959 by the RCA 501;
- the third generation started in 1964 with the IBM 360 family using some integrated circuits;
- the fourth generation started in 1972 with the use of large-scale integration in the main memory of the IBM 370/158 and in the Intel 8008 8-bit microprocessor;
- the fifth generation started in 1980 with the use of very large-scale integration by IBM to put the 370 processor on a chip followed by the HP-9000 in 1981 with 450,000 transistors on a chip;
- projecting the 8-year cycle of generations has the sixth generation starting in 1988 with ultra large-scale integration and some 10 million transistors on a chip;
- projecting further has the seventh generation starting in 1996 with grand-scale integration and 1,000 million on a chip.

INFORMATION TECHNOLOGY INFRASTRUCTURE

The definition of generations in terms of electronic device technology captures some important aspects of computing technology such as cost decreases, size decreases, power increases, and so on. However, it fails to account for the qualitative changes that have given computing its distinct character in each generation. The change from mechanical to electronic devices made it possible to store programs as data and enabled the use of computers as a general-purpose tool and then the development of programming language compilers. The transistor made reliable operation possible and enabled routine electronic data processing and then interactive timesharing. Integrated circuits reduced costs to the level where computers became commonplace and made possible the personal computer dedicated to a single user. What is missing from the model of computing developing through successive generations of electronic devices is the infrastructure that has been built above this. A complete account of the development of the computing industry must be two-dimensional with breakthroughs in key system technologies also represented. Figure 2 shows this infrastructure with the phases on the learning curve of device technology at the base and successive computing technologies above it as the infrastructure.

Now the generations may be defined in terms of major qualitative changes:

- the initial breakthrough in *electronic device technology* leading to the zeroth generation is placed at 1940 about the time of the Atanasoff and Berry experiments with tube-based digital calculations;
- the first generation breakthrough was the introduction by Mauchly and Von Neumann of stored program and subroutine concepts around 1947 which led to the transition from the ENIAC to the EDVAC designs—this detached computing as a separate discipline from electronics by substituting software for hardware in a *virtual machine architecture*;



B • **Breakthrough: creative advance made**

R • **Replication period: experience gained by mimicking breakthrough**

E • **Empirical period: design rules formulated from experience**

T • **Theoretical period: underlying theories formulated and tested**

A • **Automation period: theories predict experience & generate rules**

M • **Maturity: theories become assimilated and used routinely**

Figure 2 The infrastructure of information technology through eight generations of computing

- the second generation breakthrough was to bridge the gap between machine and task through the development of *problem-oriented languages* such as FORTRAN around 1956;
- the third generation breakthrough was to bridge the gap between the computer and the person with the development of interactive time-shared computers in 1964 allowing close *human-computer interaction*;
- the fourth generation breakthrough was in the early 1970s with developments in expert systems based on knowledge-processsing—such *knowledge-based systems* have the capability to store information through its inter-relations and make inferences about its consequence;
- the fifth generation breakthrough was in 1980 with developments in machine learning and *inductive inference systems*;
- the growth of robotics will provide the next breakthroughs in which goal-directed, mobile computational systems will act autonomously to achieve their objectives—the breakthrough into the sixth generation era commencing in 1988 will be one of *automomous activity systems*;
- the interaction between these systems will become increasingly important in enabling them to cooperate to achieve goals—the seventh generation era commencing in 1996 will be one of *socially organized systems*.

The model of the development of computing described above is important in any evaluation of the impact of computing. Each generation represents a revolution in technology with a qualitatively different impact. Each generation subsumes the capabilities of that preceding it, providing very much better facilities at very much lower cost, and adding new capabilities not possessed by the previous generations. The availability of these new capabilities in a generation is linked to the stage of the learning curve for each technology in that generation as shown in Figure 3:

- *Invention* is focused at the **BR** interface where new breakthrough attempts are being made based on experience with the replicated breakthroughs of the technology below;
- *Research* is focused at the **RE** interface where new recognized breakthroughs are being investigated using the empirical design rules of the technologies below;
- *Product Innovation* is focused at the **ET** interface where new products are being developed based on the empirical design rules of one technology and the theoretical foundations of the technologies below;
- *Product Lines* are focused at the **TA** interface where product lines can rest on the solid theoretical foundations of one technology and the automation of the technologies below;
- *Low-cost Products* are focused at the **AM** interface where cost reduction can be based on the the automated mass production of one technology and the mature technologies below.

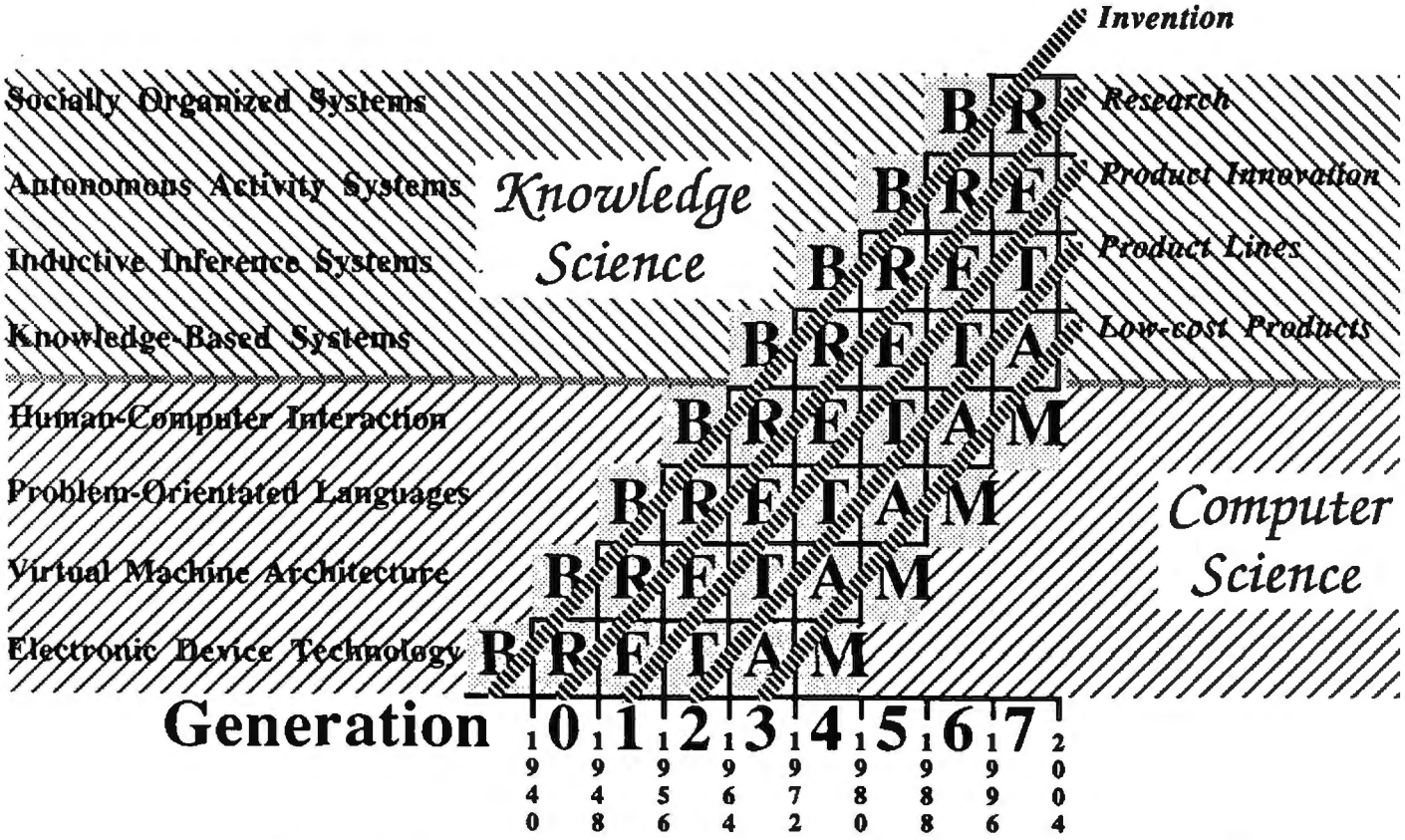


Figure 3 Invention, research, innovation, product lines and cost reduction through eight generations of information technology

For example, in the fourth generation (1972-79):

- **BR**: recognition of the knowledge acquisition possibilities of knowledge-based systems led to the breakthrough to inductive-infererence systems;
- **RE**: research focused on the natural representation of knowledge through the development of human-computer interaction, e.g. the Xerox Star direct manipulation of objects;
- **ET**: experience with the human-computer interaction using the problem-oriented language BASIC led to the innovative product of the Apple II personal computer;
- **TA**: the simplicity of the problem-oriented language RPG II led to the design of the IBM System/3 product line of small business computers;
- **AM**: the design of special-purpose chips allowed the mass-production of low-cost, high-quality calculators.

In the current fifth generation (1980-87):

- **BR**: recognition of the goal-seeking possibilities of inductive inference systems is leading to the breakthrough to automomous-activity systems in robotics;
- **RE**: research is focused on learning in knowledge-based systems;
- **ET**: the advantages of the non-procedural representation of knowledge for human-computer interaction led to the innovative designs of the Visicalc spread-sheet business product and the Lisp-machine scientific product;
- **TA**: the ease of human-computer interaction through a direct manipulation problem-oriented language led to the Apple Lisa/Macintosh product line of personal computers;
- **AM**: the design of highly-integrated language systems has allowed the mass-production of low-cost, high-quality software such as Turbo Pascal.

CAL IN THE INFRASTRUCTURE OF COMPUTING

The model of the development of the infrastructure of the computing industry developed above gives a basis for analysing developments in computer-assisted learning and their changing technological priorities. Product innovation for a particular application such as CAL takes place when technologies have passed through the breakthrough and replication stages and are into the empirical and theoretical phases where design rules are available and theory is becoming available. This corresponds to the trajectory marked product innovation in Figure 3—its relation to developments in CAL is shown in Figure 4.

It should be noted that *product innovation* does not imply *product impact* or *product life*. Innovation fails more often than it succeeds, and the trajectory shown in Figure 4 indicates the focus of attention in CAL developments—the exciting papers at conferences. The trajectory of *product lines* in Figure 3 corresponds to the innovations that have been successful in generating a major market. The low marginal income available for equipment in education makes the cost-reduction phase of the product life-cycle critical, and the *low-cost products* trajectory of Figure 3 corresponds to products having a potentially significant impact.

These considerations show the long timescales for the diffusion of technological innovations into significant educational appplications. There is typically a 16 year gap between invention and product innovation, and a further 16 year gap between innovation and widespread impact. Thus , it is reasonable that there should not have been significant educational effects from information technology until the 1980s, and then initially only in terms of the basic technology such as hand calculators. The impact of developments in languages, interaction and knowledge-based systems is yet to come.

The following sub-sections survey the product innovations indicated in Figure 4 for their impact on developments in CAL.

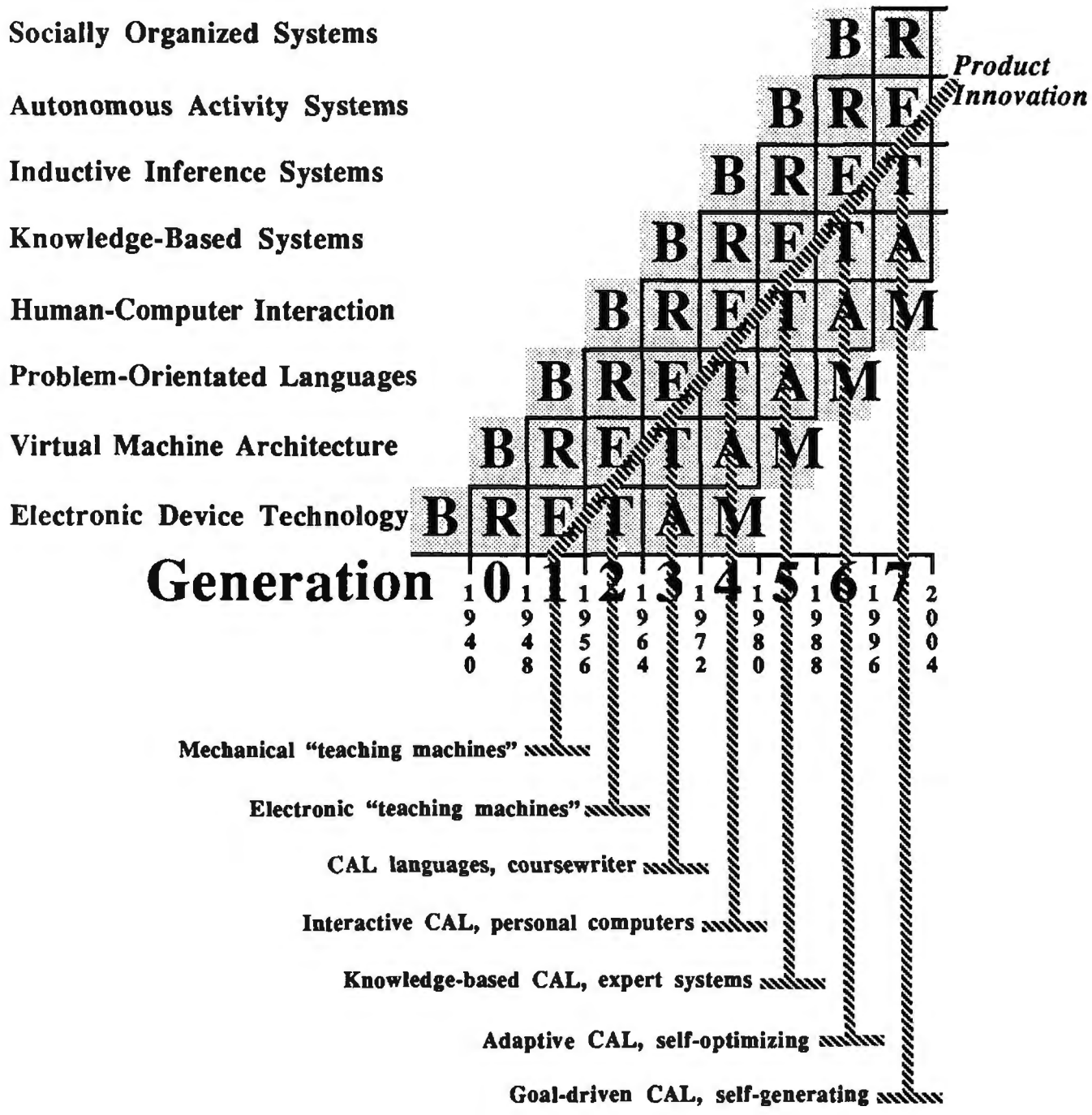


Figure 4 The changing focus of attention in technology for computer-assisted learning

THE PAST GENERATIONS: 1948-1980— A CONTROL-THEORETIC PARADIGM

Pressey's (1926) mechanical systems for teaching and testing were the conceptual precursors of CAL, corresponding to punched card tabulators and sorters as the precursors of computing. In the first generation period, Skinner (1954) linked the application of such systems to reinforcement learning, introducing the *teaching machine* concept that influenced much early CAL.

In the second generation period electronics and transistor technology enabled faster and more reliable teaching machines to be manufactured with some basic branching capabilities. IBM developed such machines in their Typewriter Division and simulated binary arithmetic teaching on a 650 computer controlling a typewriter (Rath, Anderson & Brainerd 1959). Some experiments on the use of computers for teaching were also carried out in universities and military establishments towards the end of this period (Coulson 1962).

The third generation period saw the development of course-writing languages such as Tenczar's TUTOR for PLATO in 1967 (Sherwood 1977), IBM's COURSEWRITER (Maher 1964) and Uhr's (1964) natural language compiler for teaching machines. The initial availability of interactive timesharing system's in this era led to many experiments in on-line teaching such as Suppes' Arithmetic Program at Stanford, but the high failure rates of the equipment and rate of change of the software were not conducive to educational acceptance or success (Suppes, Jerman & Brian 1968). The limitations of typewriter terminals led to the development of graphic displays specifically aimed at educational applications (Bitzer & Slottow 1966). Sophisticated, decision-theoretic theories of the operation of teaching machines were developed (Pask 1961, Smallwood 1962). National interest in computers in education grew strong in this period and studies were made of the feasibility of large-scale applications in education (Bushnell & Allen 1967, Gerard 1967, Gaines 1968, Atkinson & Wilson 1969).

In the fourth generation era the increased speed and reliability of computers made large-scale interactive applications feasible (Bitzer & Johnson 1971, Bunderson 1974), and towards the end of that era the introduction of personal computer with low-cost color graphics such as the Apple II began to make interactive CAL potentially cost-effective in some educational applications (Tagg 1980, Rushby & Anderson 1981).

If we examine the educational paradigm, rather than the technology, through this period we find that it is strongly *control-theoretic*, affected by concepts from cybernetics, and emphasizing the individualized *feedback* possible from teaching machines and interactive computers. The primary advantage of CAL is seen as a transition from the classroom situation where a teacher has to be responsive to consensual needs and average learning rates, insufficently loading some students and overloading others, to an individualized tutorial situation in which the teaching system can track each student's pace. The main differences between systems is in the sources of feedback and how it is used—overall performance feedback or diagnostic analysis—used by the system to adjust the difficulty or type of material, or by the students to evaluate their progress and make their own decisions about pacing, remedial study and sequencing of material. This control-theoretic approach is consistent with trends in industry during the same period and the use of feedback in industrial automation.

THE PRESENT FIFTH GENERATION: 1980-1988— TRANSITION TO A KNOWLEDGE-THEORETIC PARADIGM

The previous section outlines how the focus of attention in CAL has developed through hardware, architecture, software and interaction to bring us to the present era. In the current fifth generation of computing technology many applications routinely use interactive graphic systems, programmed in high-level languages, and based on efficient high-speed architectures

making effective use of very large scale integrated circuits. The first four levels of the BRETAM infrastructure are in place, widely tested in innovative products, and available now in well-supported product lines from major manufacturers. The technology is available for CAL applications and the major cost reduction phase has already commenced for the basic hardware and software.

However, in terms of CAL achievements, there are feelings of anti-climax at this stage. We now have a very high level of computer literacy in education. Nearly all disciplines make some use of the computer and expect students to have basic training in computer applications and elementary programming. Some universities have made student possession of a computer mandatory (Osgood 1987). Most schools have at least one computer laboratory (Becker 1987). The disappointment is with the educational impact, with the lack of imagination in applications, with the qualitative differences that were expected but have not occurred, with the lack of evidence that "computer-assisted learning" changes the way in which students learn, supports new avenues of understanding, and so on (Heaford 1983, Naiman 1987). One can point to major instances of imaginative applications and different approaches to subject matter, but these are not sufficient to counter-balance the overall impression that little has changed—CAL as we know it today, in common with many innovations of the past, has been absorbed into the educational process with little significant impact.

In the introduction to *Mindstorms* Papert (1980) emphasizes the very significant changes that might be expected in an information age:

> "the starship *Enterprise* has a computer that gives rapid and accurate answers to complex questions posed to it. But no attempt is made in 'Star Trek' to suggest that the human characters think in ways very different from the manner in which people in the twentieth century think. Contact with the computer has not, as far as we are allowed to see in these episodes, changed about how people think about themselves or how they approach problems. In this book I discuss ways in which the computer presence could contribute to mental processes not only instrumentally but in more essential, conceptual ways, influencing how people think even when they are far removed from physical contact with the computer...This book is about how computers can be carriers of powerful ideas and of the seeds of cultural change, how they can help people form new relationships with knowledge that cut across the traditional lines separating humanities from sciences and knowledge of the self from both of these."

Papert is talking about the use of information technology not only to transfer information to students but also to change the ways in which they *process knowledge*. This contrasts with the assumptions of the 1960s that computers in education might save labor through automation as was occurring in other 'industries.' He gives an appropriate conceptual framework for CAL as cultural change accelerates and we approach an age in which genetic engineering and space colonization will change our concepts of society, industry and humanity itself.

Even if we focus on less momentous aspects of CAL, there is still a feeling of anti-climax. The computer gives us tremendous capabilities for information processing and presentation at ever decreasing cost, but there is still a barrier to its effective utilization in terms of many educational objectives. The effort and expense to develop courseware, particularly the kind of courseware that represents personal skills in effective teaching, is still too high, and many packages that are technically impressive are weak educationally. However, this is not unreasonable at the present state of the art—education is a process of *knowledge transfer* and knowledge-based system technologies are only now beginning to result in product innovation.

The shading of Figure 3 clarifies this transition to knowledge-based products in the information technology industry. The first four steps in the hierarchy, from electronics through machine architecture and languages to human-computer interaction, are concerned with harnessing the computer as an information-processing tool—the domain of *computer science*. The next four steps, from knowledge-based systems through induction and

autonomy to social organization, are concerned with knowledge processes—with knowledge itself as a tool, its representation, acquisition, active application and distributed organization. This may reasonably be called the domain of *knowledge science*. It is only these later stages of development in information technology that have any significant relationship to the core subject matter of education, that is, to knowledge. The promise has always been there, and this has led to premature expectations and experiments, and hence to some disappointment as each new generation of technology fails to achieve what seems to have been promised. One is reminded of Drucker's (1978) remark in *The Age of Discontinuity* comparing the development of the electricity industry with that of the information industry and making the analogy that "information is energy for mind work" . He notes that if it had been fashionable to speak of generations of generators then there "would have been a 'fifth-generation' or 'sixth-generation' generator before there was any widespread use of electric power."

The first successful innovative products stemming from breakthroughs in knowledge-based systems are *expert systems* which simulate some of the processes of the human mind, knowledge representation and inference, allowing expertise to be encoded for a computer and made widely available (Waterman 1986). This has generated a new industry based on creating expert systems to make the practical working knowledge of a human expert in a specific subject area such as medicine or geology widely available to those without direct access to the original expert. Programs now exist with practical achievements in medical diagnosis, interpretation of mass spectroscopy results, analysis of geological survey data, and other problems where one would normally go to a human expert for advice (Michie 1979, Gevarter 1983, Reitman 1984, Coombs 1984). The initial success of expert system developments and the development of a number of domain-independent software support systems for the encoding and application of knowledge has opened up the possibility of widespread usage.

The focus of attention at the frontier of CAL developments has already switched to knowledge-based systems (O'Shea & Self 1983, Yazdani 1984). *Intelligent tutoring systems* (Sleeman & Brown 1982) encode some of the tutorial capabilities that a skilled teacher would use in presenting material, tailoring it to particular students and diagnosing the deeper causes of individual students' learning problems. In terms of the educational paradigm, rather than the technology, the early studies of intelligent tutoring systems generally go down the same blind alley as control engineering during this era. They adopt an *identification-theoretic* approach in which a student model is presumed to be identified through the interaction, and then used to generate optimal instructional material. This is the logical extension of the control-theoretic approach but it fails in education for the same reasons it failed in industrial control: there is insufficient data in the interaction with which to identify a model; and the optimal control sequence generated is highly sensitive to the accuracy of the model—the correct remedy for the wrong diagnosis may be worse than no remedy at all.

The knowledge-based systems approach might be termed *ecology-theoretic* in Gibson's (1979) sense, in that it regards the subject-domain knowledge as carrying the critical cognitive information, and is far less concerned about the detailed mental processes of the student. The human brain is regarded as a powerful modeling system that will orient itself to knowledge structures if it can be brought into their strong influence. The presentation of the knowledge is the critical variable to optimize, not a model of the student's internal processes. This point of view is more in conformity with educational practice and hence it is also the one that assumes prominence in expert systems developed on the basis of that practice. The emphasis is on the computer as a pluralistic tool, that can make available: text and pictures as in a book; animated images as in movies; simulation as in the laboratory and real-life; note-taking, drawing and annotation as with a notebook; activity and performance logging as with an observer; and advice as with a tutor. That is, information technology is seen as supportive of a wide variety of knowledge apprehension, comprehension and acquisition processes on an individualized basis.

THE COMING SIXTH AND SEVENTH GENERATIONS: 1988-2004— EDUCATION AS A KNOWLEDGE SCIENCE

Sixth generation activities are already being planned worldwide and it is interesting to see the move away from the basic technology and the emphasis on knowledge acquisition, application and processing. The Japanese Sixth Generation Computing System (STA 1985, Gaines 1986a) was issued in 1985 as a report, *Promotion of R&D on Electronics and Information Systems that may Complement or Substitute for Human Intelligence.* Four objectives are specified for promoting knowledge science: innovations in *frontier high technologies*; *economic and cultural advancements*; *contributions to the expansion of human potential*; and *establishing a foundation for creative science.* The proposed research program moves outside the boundaries of information technology and is based on inter-disciplinary interaction with *physiology, psychology, linguistics* and *logic.*

The breakthrough that distinguishes the sixth generation of computing technology has been advances in inductive inference (Davis & Lenat 1982, Michalski & Chilausky 1980). In the current fifth generation era machine learning has become a highly active research area still in its replication phase (Michalski & Carbonell 1983). In the coming sixth generation era we may expect related product innovation affecting education. One possibility is the use of inductive inference to allow real-time student modeling, but, as already noted, such an approach is limited by the paucity of data in current modes of interaction. Its success would require advances in robotic vision and hearing techniques to enable computer-based systems to pick up the cues in facial expression, body language, vocal behavior, and so on, that we use to identify the cognitive and affective states of others.

Where advances can be seen in sixth generation computing developments that are immediately relevant to education is in our understanding and technological support for processes of *knowledge transfer*. The bottleneck in industrial applications of expert systems has been clearly identified as that of transfering knowledge from the expert to the computer (Hayes-Roth, Waterman & Lenat 1983). This has generated a foci of attention in research: first on computer-based tools for expertise transfer (Boose 1986, Shaw & Gaines 1986b); and second on the underlying cultural mechanisms for knowledge transfer in human society (Gaines 1986c). Figure 5 shows a hierarchy of knowledge transfer processes developed from formal foundations in mathematical modeling theory and inductive inference, and applied to distinguish the variety of modes of knowledge transfer and their interaction. The primary learning process is one of direct acquisition based on attempts to solve tasks through interaction with a world, as shown in the lower part of Figure 5. This is applicable to all three worlds: material, mental and logical. This primary process is the only one open to humanity as a species and is distributed across partially autonomous individuals coordinated by cultural communication processes. From an individual perspective it is these communication processes that dominate knowledge acquisition and transfer.

The right hand side of figure 5 shows the cultural communication processes supporting knowledge transfer:-

- At level one *mimicry* by watching experts is the main transfer mechanism.
- At level two *reinforcement* by working under expert supervision is the main transfer mechanism.
- At level three *rational explanation* from interviewing experts and books is the main transfer mechanism.
- At level four use of *analogical models* to derive knowledge from similar situations is the main transfer mechanism.
- At level five use of *basic laws* to derive specific models is the main transfer mechanism.
- At level six use of *systemic principles* to derive specific laws is the main transfer mechanism.

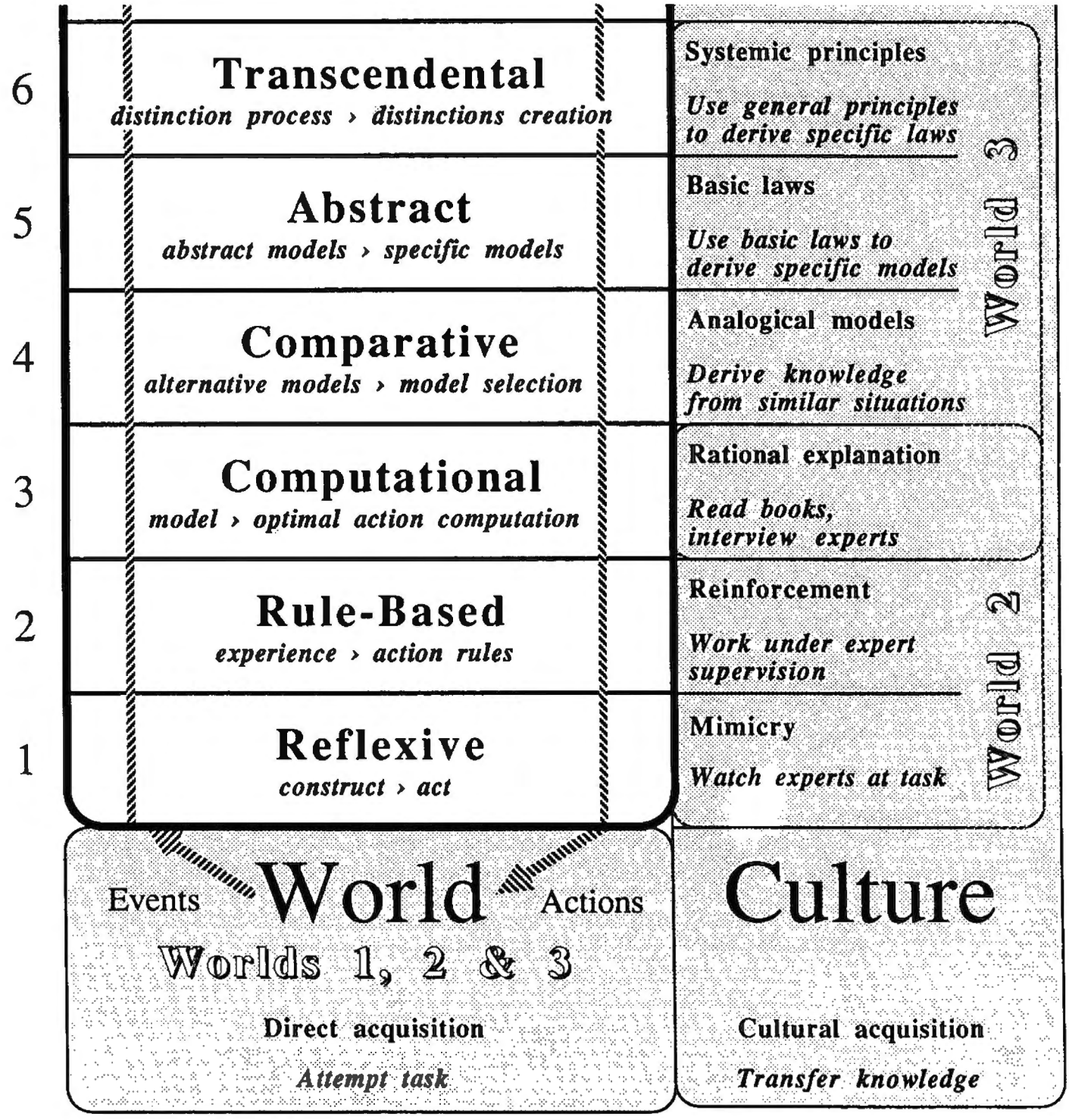


Figure 5 Knowledge representation and acquisition processes

Levels 1 and 2 of cultural transmission, mimicry and reinforcement, belong to world 2, the social environment of subjective experience. Levels 4 through 6, analogies, laws and principles, belong to world 3, the knowledge environment of statements in themselves. Level 3, of rational explanation, bridges both worlds. At each level computational tools have been developed that mimic and support human knowledge transmission processes (Gaines & Shaw 1986, Shaw 1987).

Seventh generation projections are more speculative but it is reasonable to suppose that such learning systems will form the foundation for autonomous goal-driven systems. The fifth through seventh generation emphasis on knowledge-based systems suggests a *system-theoretic* paradigm for CAL—that we seek to understand the complete system that is the human species acquiring knowledge through a plurality of diverse processes, representing it, storing it, processing it, transfering it, applying it to modify the variety of worlds within which human life exists, and using technology to support the system in all these activities. From this point of view, technology is seen as embedded in the life world, and education is seen as the management of a major part of the knowledge transfer processes within that world, including the knowledge about how to create new knowledge and understand the process of creation itself. The system theoretic paradigm subsumes, rather than replaces, the preceding paradigms, combining control, identification and ecological approaches as essential components of an overall system.

CONCLUSIONS

Probably the most difficult task in bringing together advances in educational and knowledge science is to translate between pedagogical and computational jargon. The underlying system principles are the same and the perspectives are complementary—together they give strong foundations for the next generation of CAL—but it is bringing them together that is the problem. There are many systemic analyses in the educational literature that are part of the evolutionary process described in this paper. However, the outstanding example is clearly that of Gordon Pask whose *conversation theory* may be seen as a major attempt to give a systemic framework for knowledge transfer processes (Pask 1975a, 1976, 1980). Pask's work from the early 1950s through to the present time spans the first through fifth generation eras of information technology and CAL, and gives foundations for significant parts of sixth generation knowledge science. It has the remarkable property of being theoretically and empirically well-founded while resulting in practical applications using information technology of every era, from the electro-mechanical uniselectors of Pask's early teaching machines through to recent systems using multiple interactive microcomputers and Lisp machines (Pask 1961, 1975b, Pangaro 1986). Pask's work has influenced many major developments in CAL and has also played a substantial part in expert system development (Bunderson 1974, Coombs & Alty 1984, Gaines & Shaw 1984, Shaw & Gaines 1986a).

The convergence between education and information technology within a framework of knowledge science is worth noting as significant for both disciplines. The operationalization of psychology through the implementation of theory as computational models has generated the new discipline of *cognitive science*, and a similar phenomenon in linguistics has led to *computational linguistics*. Pask's "conversation theory" nicely captures the essence of knowledge transfer, and we might now speak of *conversational science* as encompassing the entire spectrum of cultural processes whereby people transfer knowledge, including those supported by information technology. CAL can then be seen as computer-assisted knowledge transfer with foundations in conversational science, which together with cognitive science, computational linguistics, and other interdisciplinary disciplines, will someday justify the term "knowledge science."

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