A Learning Model for Forecasting the Future of Information Technology

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Abstract

System-theoretic accounts of the epistemological processes underlying knowledge acquisition have been shown to apply to both individual human behavior and social development processes, and to enable algorithms to be developed for computer-based systems modeling. Such accounts are applicable to the upper levels of the hierarchy of autonomous systems to provide models of socio-economic behavior. In this paper they are applied to the development of information technology, and used to account for past events and predict future trends in relevant industries such as computing and genetic engineering. Underlying all developments in information technology is a tiered succession of learning curves which make up the infrastructure of the relevant industries. The paper provides a framework for the industries based on this logical progression of developments. It links this empirically to key events in the development of computing and genetic engineering. It links it theoretically to a model of economic, social, scientific and individual development as related learning processes with a simple phenomenological model. It uses this model to account for past developments in information technology and extrapolates it to predict future trends.

1 Introduction

Advances in computing science and molecular biology are two of the most important phenomena of our age. They are each representative of the development of information science as a new foundation for human knowledge. They are both predictive sciences that can model natural processes: the reasoning and evolutionary processes of living systems, respectively. They are also both expressible operationally as normative sciences that can generate new technologies that modify and go beyond natural processes: electronic computing to extend reasoning and genetic engineering to extend evolution, respectively. At a fabrication level the two technologies have much in common: microelectronic device manufacture is the control of information structuring semiconductor material at a molecular level to create non-living knowledge processors; genetic engineering is the control of information structuring organic molecules at a molecular level to create living systems. Together the two technologies illustrate the massive extent of information science, encompassing the furthest reaches of human rationality and the ultimate foundations of life, and bringing both into the technological domain, subject to human control and design.

1.1 Autonomous Technology and the Life World

Many writers have speculated upon the impact of computing and genetic engineering on our society, culture and value systems (Wiener 1950, Bell 1973, Mowshowitz 1976, Weizenbaum 1976, Carney 1980, Cherfas 1982). The impact is now being felt and many commentators are attempting to analyze its nature and project its trends (Toffler 1980, Dizard 1982, Krimsky 1982, Brod 1984, Turkle 1984, Glover 1984, Nossal 1985). However, the majority of such speculation and analysis offers one-sided perspectives relative to two key distinctions. The first perspective assumes that the major impact is of information technology on society rather than society on information technology. This takes for granted Ellul's (1964) view of technology as autonomous, and fails to question why the technology itself has arisen out of the processes of society. The second perspective assumes that the future may be projected as an extrapolation of processes begun in the past. This takes for granted the causal models fundamental to physical science and fails to recognize the higher level goals that lie behind information technology developments seen as part of the teleology of society.

These one-sided perspectives are valid and lead to meaningful conclusions relative to their presuppositions. They are appropriate to the analysis of technological dependencies for purposes of industrial and government planning, for example, that one must have adequate capabilities for semiconductor device manufacture or DNA cloning before one can develop computer or genetic engineering industries. However, they are not appropriate perspectives from which to evaluate the future development of information technology which involves relations between information processing, society, values, culture and creativity. These last four are phenomena of the life world (Schutz & Luckman 1973) and embedded in its processes. To understand their relations to information technology we must view it also as a phenomenon of the life world embedded in its processes, both generated by them and generating them (Blum & McHugh 1984). If we treat technology as autonomous we forget its roots:

> *"Technology is the human's achievement, not his failing—even though the use he chooses to make of it may be fallen indeed. If the products of human techne become philosophically and experientially problematic, it is, I would submit, because we come to think of them as autonomous of the purpose which led to their production and gives them meaning. We become, in effect, victims of self-forgetting, losing sight of the moral sense which is the justification of technology. Quite concretely, the purpose of electric light is to help humans to see. When it comes to blind them to the world around them it becomes counterproductive. The task thus is not to abolish technology but to see through it to the human meaning which justifies it and directs its use." (Kohak 1984)*

1.2 The Need for Teleological Models in Forecasting

Information technology is directed by the processes of society at least as much as it impacts them. Up to its present 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 social change. The perspective that views only the impact of computing on society misses the major dynamics of information technology during the past forty-five years. In particular, technological forecasting is unlikely to be a basis for any except very short-term projections of the future of computing and genetic engineering. The social objectives that determine the economic pressures on these industries are satisfied by selecting from the pool of available technology of the most effective technologies to satisfy market requirements. The inertia of social development is very much greater than that of technological change and long-term forecasts are most accurately based on social objectives rather technological extrapolation.

Viewed as a causal chain the development of information technology is highly indeterminate. Technological forecasts for computing are notoriously difficult (Gaines 1984a), and the younger industry of genetic engineering has developed at a startling pace (Cherfas 1982). Projections of the technologies 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.

> *"The world is overwhelmingly complex for every kind of real system... Its possibilities exceed those to which the system has the capacity to respond. A system locates itself in a selectively constituted 'environment' and will disintegrate in the case of disjunction between environment and 'world'. Human beings, however, and they alone, are conscious of the world's complexity and therefore of the possibility of selecting their environment—something which poses fundamental questions of self-preservation. Man has the capacity to comprehend the world, can see alternatives, possibilities, can realize his own ignorance, and can perceive himself as one who must make decisions."*

This model seems to underlie De Bono's (1979) views of the role of computers:

> *"By great good fortune, and just in time, we have to hand a device that can rescue us from the mass of complexity. That device is the computer. The computer will be to the organization revolution what steam power was to the industrial revolution. The computer can extend our organizing power in the same way as steam extended muscle power... Of course we have to ensure that the result is more human rather than less human. Similarly we have to use the computer to reduce complexity rather than to increase complexity, by making it possible to cope with increased complexity."*

Wojciechowski (1983) sees the coupled dynamics of complexity processes and information technology as the most recent manifestation of the growth of the knowledge construct in human society, the infrastructure of information acquisition, storage, processing and dissemination that is part of our culture and supports individual and social knowledge processes. He has developed an ecology of knowledge and proposed a set of laws underlying the dynamics of knowledge processes and their role in society (Wojciechowski 1986). He notes that, while attempts at complexity-reduction are a major social dynamic, the overall complexity of the life-world is increasing and that most human problems are now humanly generated:

> *"Contrary to past epochs, from now on the future of humanity, and ideed the very survival of the human race, is in its own hands. Man will have a future if he is capable of envisaging a positive course for himself and planning for it. The capacity of dealing with the future entails the ability to cope with the present and future problems." (Wojciechowski 1986)*

The conceptual framework established by Luhmann and Wojciechowski provides foundations for a model of information technology and its role in society. This paper gives substance to these models of society and information technology by extending the notion of a personal scientist modeling the world (Shaw 1980) to that of a society learning a technology, a communal scientist

(Shaw & Gaines 1986). This enables Marchetti's (1981) concept of society as a learning process to be used in order to model the development of information technology:

> *"The concept of a learning society, with its implications on the ecological Volterra equations, represents a very powerful tool in organizing social behavior and hints to the possibility of a unified theory for genetic evolution, ecology, sociology and economics."*

2 The Modeling Hierarchy

In analyzing the architecture of modeling systems, Klir (1976, 1985) proposed an epistemological hierarchy accounting for the main components of any modeling systems and their inter-relations. Gaines (1977) gave a mathematical formulation of the general problem of modeling as a relation between order relations at different levels of the hierarchy. Gaines & Shaw (1981) gave a general interpretation of this hierarchy as generated by levels of distinction and showed how it was instantiated in psychological terms. The hierarchy has proved a valuable conceptual tool in analyzing a wide variety of modeling systems both in terms of their ontological presuppositions and their epistemological processes.

The notion of a distinction itself is a primitive concept underlying the representation of knowledge (Gaines & Shaw 1984b, 1985). It is a sufficient primitive to give foundations for systems theory including the notion of a system itself (Gaines 1980). In its psychological form, as a personal construct (Kelly 1955, Shaw 1980), the notion has been used to derive very effective techniques for knowledge transfer from experts to expert systems (Shaw & Gaines 1983a, Boose 1985). In the context of the development of information technology, the fundamental role of distinctions as determining the nature of knowledge is best put by Brown (1969):

> *"The theme of this book is that a universe comes into being when a space is severed or taken apart...By tracing the way we represent such a severance, we can begin to reconstruct, with an accuracy and coverage that appear almost uncanny, the basic forms underlying linguistic, mathematical, physical and biological science, and can begin to see how the familiar laws of our own experience follow inexorably from the original act of severance."*

Their foundational role in knowledge acquisition is evident in the hierarchical representation of distinctions in a modeling system shown in Figure 1. It is important to note that this hierarchy does not introduce any additional primitives beyond that of making a distinction. The levels of the hierarchy are the results of distinctions that we make. Thus, in Klir's (1976) terminology:

- The source system is distinguished as those distinctions that the particular modeling system makes—it is a distinction about distinctions defining the construct system of an individual;
- The data system is distinguished as those distinctions that have been made about a particular event—a distinction about distinctions defining an event.
- The generative system is distinguished as a set of distinctions that also defines an event—these are model-generated rather than event-generated—it is the match between the model-generated and event-generated distinctions that determines the degree of approximation of the model to the world—this is a distinction about distinctions among distinctions that defines goodness of fit;

- The structure system is distinguished as a set of distinctions that compare models—is is the order relation of simplicity/complexity on models that determines the preference for the simplest model that is an adequate approximation to the world—this is a distinction about distinctions that defines our preference for simple models;
- The meta system is distinguished as a set of distinctions that specify the basis of these comparisons.
- The meta-meta system, and higher levels, are distinguished as sets of distinctions that specify further relations among the distinctions on the level below.

Note that the upper levels of modeling are totally dependent on the system of distinctions used to express experience through the source system.

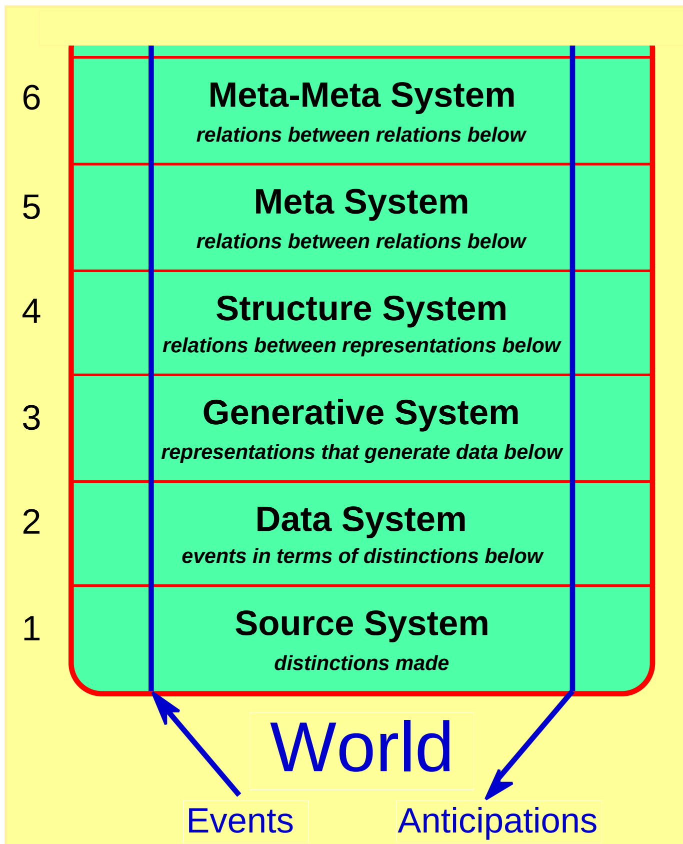

Figure 1 Epistemological hierarchy of a system modeling a world

Distinctions are not just static partitions of experience. They may be operations: actions in psychological terms; processes in computational terms. Whether a system finds a distinction in the world, imposes it passively as a view of the world, or imposes it actively as a change in the world, is irrelevant to the basic modeling theory. It makes no difference to the theory whether distinctions are instantiated through sensation or action. We can make a distinction passively or actively. We can sense some condition already in the world or we can act to establish some condition in the world. In system-theoretic terms there is no intrinsic distinction between prediction and control. In scientific terms the predictive goals of scientific investigation and the normative goals of technological change are basically indistinguishable. In biological terms, a living system may discover a comfortable niche, create one, or combine the two processes.

2.1 Learning in the Hierarchy

The hierarchy of Figure 1 accounts for learning processes as the modeling of events enabling adequate prediction and action. A modeling schema results from distinctions about distinctions at each level in the hierarchy. In prediction the key distinction is to what degree a level accounts for the information flowing through it and hence this distinction may be termed one of surprise (Gaines 1977), in the sense used by the economist Shackle (1955). Surprise goes in opposition to the degree of membership (Zadeh 1965, Gaines 1983) of a predicted event to an actual event and the expected surprise is a form of entropy. Surprise at the lowest level of the hierarchy corresponds to distinctions being inadequate to capture events; surprise at the next level to inadequate variety to experience events; at the next level to inadequate approximation to predict events; at the next level to inadequate simplicity to explain events; at the next level to inadequate comprehensiveness to account for events.

The formal theory of modeling is one in which models are selected at each level down the hierarchy to minimize the rate at which surprise is passing up the hierarchy. The criteria for model selection independent of the data are generally thought of as being ones of simplicity/complexity: of two models which fit the data equally well choose the simplest. However, notions of simplicity/complexity are not well-defined nor intrinsic to the class of models. The simplicity/complexity ordering is arbitrary and in its most general form is just one of preference. Hence the general modeling schema is one in which surprise flows up the hierarchy and preference flows down. In situations that are mathematically well-defined, such as determining the structure of a stochastic automaton from its behavior, such a model schema gives the correct results (Gaines 1977). Conversely, the success of the schema in stabilizing with regard to a given world defines the characteristics of that world.

Thus the basic modeling schema for learning from experience is one in which surprise flows up the hierarchy and preferences flow down. In primitive organisms only the lower levels of the hierarchy are developed, surprise is generated from experience and preference is genetically encoded. In higher organisms the modeling process generalizes both surprise and preference to cope with novel environments. Human life has developed the upper levels of the hierarchy and detached surprise from experience and preference from its genetic roots. Surprise can flow up from a level without flowing into it from below because the processes at that level have generated novelty. Preference can be generated at a high level detached from both experience and genetic origins and flow down to affect the relations of the organism to the world.

2.2 Psychological Interpretation of the Hierarchy

The loop in Figure 1 from events through distinctions up through the modeling hierarchy and then down again to predictions and actions characterizes what Shaw (1980) has termed the personal scientist. This derives from the epistemological model of man as an anticipatory system developed by Kelly (1955) as a psychology in which the individual modeling the world is seen as man the scientist. Kelly's personal construct psychology (PCP) provides an extensive theory of both normal and abnormal human functioning, which has strong systemic foundations (Gaines & Shaw 1981) and has been operationalized through computer programs (Shaw 1980). PCP models a person as making distinctions about experience termed personal constructs and described as:

> *"transparent templets which he creates and then attempts to fit over the realities of which the world is composed" (Kelly 1955).*

A person’s construction process is a basis for anticipatory and fallible knowledge acquisition:

> *“Constructs are used for predictions of things to come, and the world keeps rolling on and revealing these predictions to be either correct or misleading. This fact provides a basis for the revision of constructs and, eventually, of whole construct systems.” (Kelly 1955)*

The systemic hierarchy of Figure 1 has an analog in psychological terminology as shown in Figure 2. The source level is one of constructs, distinctions made in interacting with the world. The data level is one of experiences, events which happen to us, and we make happen, in terms of the distinctions already made. The generative level is one of hypotheses which are rationalizations of experience. The structure level is one of analogies which are correspondences between these rationalizations. The meta level is one of abstractions which are foundations of analogies. The meta-meta level is one of transcendencies which are accounts of abstractions. Interaction with the world is, therefore, mediated through the construct system to produce experience which is modeled through the higher levels and leads to predictions, decisions and actions again mediated through the construct system.

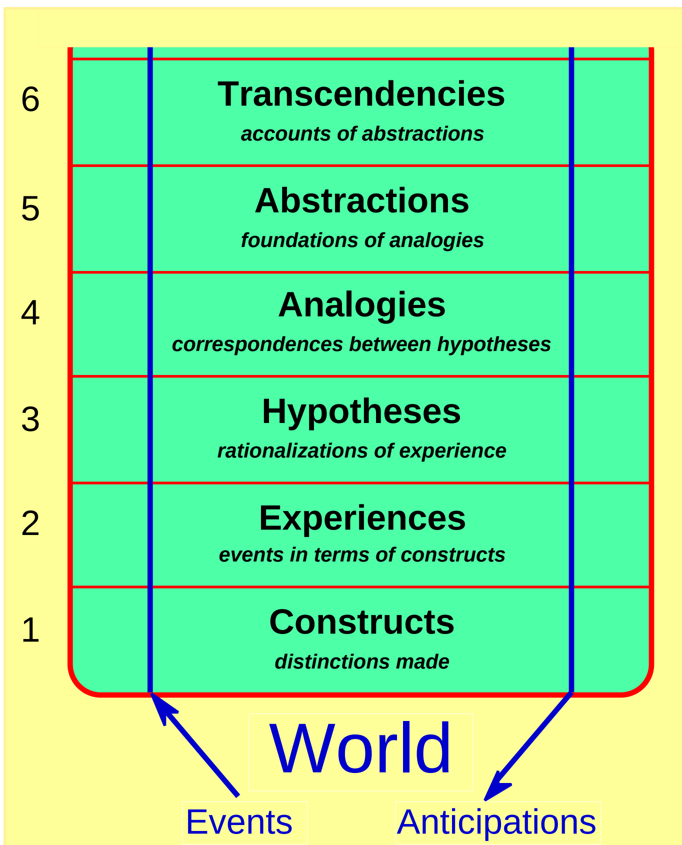

Figure 2 Construction hierarchy of a person modeling a world

Kelly (1955) places the major emphasis of his work on the notion of constructive alternativism, that we have a choice in our construct systems at every level in the hierarchy and that real-world problems may often be solved by exercising this choice. Note that this should not be interpreted as an idealist position that ascribes all phenomena to our interpretation of them. Since the construct hierarchy also leads to decision and action, changes in it may equally affect the real world. Kelly and Brown are both neutral to any philosophical stance such as idealism versus realism; it is the distinctions which a philosopher makes that determines his stance and these can be analyzed in terms of the modeling hierarchy. Kelly saw his theory as reflexive and the only fundamental principle, apart from that of a construct itself, being that of constructive alternativism.

2.3 Roles, Groups and Societies as Cross-Sections of the Hierarchy

The anticipatory processes of the modeling hierarchy may be extended to the operation of society by viewing groups of people as larger cross-sections comprising multiple individuals (Shaw & Gaines 1981). This concept may be given deeper significance by considering the inductive inference process underlying knowledge acquisition and modeled in the hierarchy. Whereas the deductive logical inference that underlies the operation of conventional computers is well-understood and well-founded, the inductive inference that underlies human learning is not. Deduction guarantees to take us from valid data to valid inferences, but the inferences are thereby part of the data—no new knowledge is generated. Induction takes us from valid data to models of that data that go beyond it—by predicting data we have not yet observed, and by giving explanations of the data in terms of concepts that are unobservable. Induction generates new knowledge but, as Hume (1739) pointed out over 200 years ago, the process is not deductively valid and it is a circular argument to claim that it is inductively valid.

Philosophers have continued to debate Hume's arguments and search for justification of the inductive process. Goodman (1973) proposed that we accept the circularity but note that it involves a dynamic equilibrium between data and inference rules as shown in Figure 3: "A rule is amended if it yields an inference we are unwilling to accept; an inference is rejected if it violates a rule we are unwilling to amend." Rawls (1971) in his theory of justice terms this a reflective equilibrium. Recently Stich and Nisbett (1984) noted flaws in Goodman's argument and repaired them by proposing that the equilibrium is social not individual: "a rule of inference is justified if it captures the reflective practice not of the person using it but of the appropriate experts in our society." This argument arose in the context of the explanation of the authority of experts in society, but it is also significant in suggesting that the basic system underlying knowledge acquisition has to be taken as a society rather than an individual.

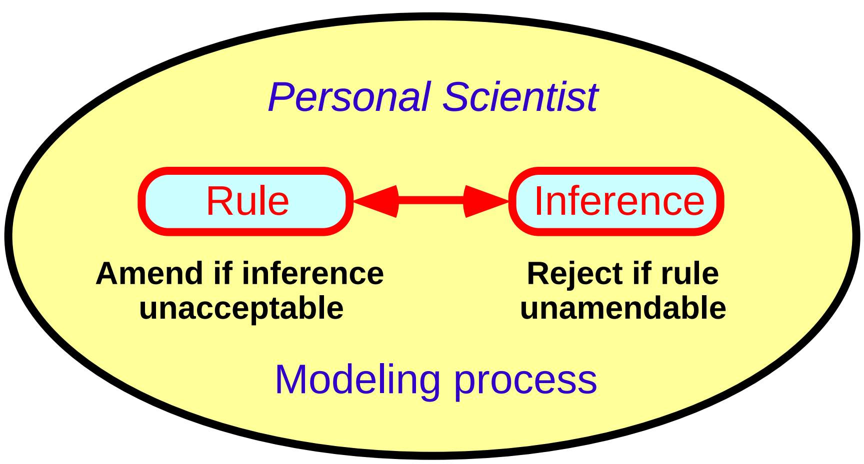

Figure 3 Reflective equilibrium in inductive inference

The extension of the modeling hierarchy to social processes is straightforward since Figure 1 presents a general modeling schema and applies as much to groups of people, companies and societies as it does to the roles of a person. The epistemological hierarchy of a person is a cross-section of the epistemological hierarchy of the society generating their life-world. Pask's (1975) concept of P-Individuals as the basic units of psycho-socio-processes allows roles, people, groups, organizations and societies to be treated in a uniform framework (Shaw & Gaines 1981, 1986). An individual is defined in cognitive terms as a psychological process (Pask 1980) and more complex psychological and social structures may be defined similarly by taking into account the possibilities of timesharing, process switching and distributed processing with psychological processors. For example, one person may assume many psychological roles (process switching), whereas a group of people working together may act as a single goal-seeking entity and hence behave as one process (distributed processing).

2.4 Representation of Skills in the Hierarchy

In the analysis of technology the skills to achieve goals in the world are the crucial capabilities of the modeling system. Figure 4 shows the basis for action at different levels in the modeling hierarchy.

- At level one, the activation of a construct may be linked directly to a primitive act, another construct. This corresponds to reflex actions and stimulus-response connections. In system-theoretic terms this level might be implemented by conditional probability calculations giving confirmation-theoretic inductive inference.
- At level two, constellations of experience may be linked to complete action sequences through rules derived from similar experience. In system-theoretic terms this level might be implemented by fuzzy production rules giving generalization-based inductive inference.
- At level three, a generative model of experience, may be used to compute an optimal action sequence. In system-theoretic terms this level might be implemented by a state-based modeling scheme giving model-based inductive inference.
- At level four, a variety of alternative models may be compared as a basis for selecting one appropriate to the required goals. In system-theoretic terms this level might be implemented by a category-theoretic functional analysis scheme giving analogical inductive inference.
- At level five, generalized abstract models may be used as templets from which to instantiate one appropriate to the required goals. In system-theoretic terms this level might be implemented by a category-theoretic factoring scheme abstracting the mathematical form of an analogy and giving abstractional inductive inference.
- At level six, the entire process described may be transcended through a recognition that it is based on distinctions being made at various level, and an attempt to rationalize these distinctions and create new ones. In system-theoretic terms this level might be implemented by a distinction-based analysis scheme giving what might be termed transcendental inductive inference.

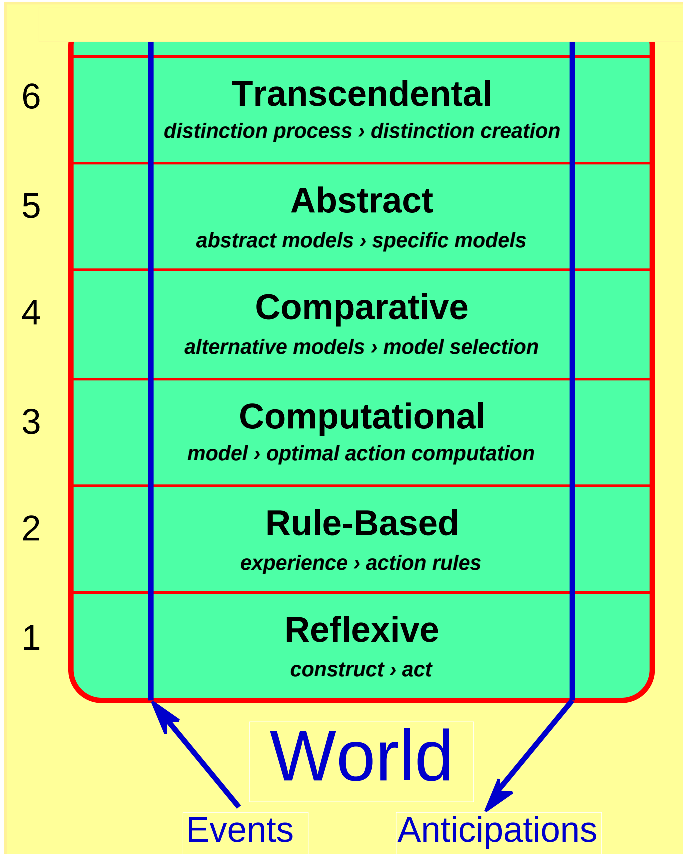

Figure 4 Action hierarchy of a system modeling a world

It is an interesting comment on the state of the art in computer science that it has proceeds "middle-outward" in its representation of the knowledge involved in skills at different levels of the hierarchy. Information technology has been primarily concerned with level three activities, and is only now beginning through expert system developments to emulate level two activities. The primitive sensation-action modes of learning at level one require the large-scale parallel processing essential to the emulation of human vision and locomotion, and will be developed as part of the next generation of robotic systems. The higher level functions of levels four and five are being studied in artificial intelligence but require developments in mathematics and system theory for their full realization.

2.5 Language and Culture in Knowledge Acquisition

The creation of new knowledge takes place through the surprise/preference flows within the hierarchy and it is these processes that determine the rate of technological invention and product innovation. The human capability for an entire society to act as a distributed knowledge acquisition system is dependent on the role of communication processes in coordinating activity at a given level of the hierarchy across different people. This communication process whereby each person does not have to undertake all aspects of the inductive process but can share the results of such processing by others supports what is generally termed the culture of a society. People use language for much of this communication but they also have in common with other animals the capability to communicate cultural information without the use of language.

Mimicry is an important mechanism for knowledge acquisition as is reinforcement through reward and punishment.

The human development of language enables coordination to take place in a rich and subtle fashion that greatly enhances, but does not replace, the more basic mechanisms in common with other species. It is particularly important at the upper levels of the hierarchy where direct expression is difficult. From an individual point of view, language is a way of by-passing the normal modeling procedures and interacting directly with the system at any level. In particular it can directly affect the preference system. Even when language cannot mediate the direct transmission of knowledge it may be used to achieve the same effect by the indirect support of other mechanisms, for example, one can describe a good learning environment, or a behavior in sufficient detail for mimicry. Language is essential to much of human learning, and our interaction with the knowledge construct (Wojciechowski 1983, Gaines & Shaw 1983b) is just as important as our interaction with the world (Shaw & Gaines 1983b, 1984, Gaines & Shaw 1984a). The evolutionary pressures would be very strong in selecting genes giving the capability for a species to act as a single distributed individual, combining autonomy and cohesion through enhanced linguistic communication. Linguistic transfer of knowledge is the most important process for the dissemination of information, for example in technology transfer.

Figure 5 shows the cultural support for knowledge acquisition at different levels in the modeling hierarchy.

- The reflexive knowledge at level one has no verbal component and comes directly from experience, often that of mimicking the behavior of others. This level has been termed informal to correspond to Hall’s (1959) definition of cultural transmission of behavior of this type.
- The rule-based knowledge at level two is usually transmitted by reinforcement of behavior, verbal rules, or is induced from the patterns of knowledge at level 1. This level has been termed formal to correspond to Hall’s definition of cultural transmission of behavior of this type.
- The computational knowledge at level three is usually transmitted by technical explanation, or is induced from the patterns of knowledge at level two. This level has been termed technical to correspond to Hall’s definition of cultural transmission of behavior of this type.
- The comparative knowledge at level four is usually transmitted by simile and metaphorical analysis, or is induced from the patterns of knowledge at level three. Hall does give a name to this level but the term comparative captures his own activity of highlighting the features of one culture by contrasting it with others.
- The abstract knowledge at level five is usually transmitted through mathematical representation, or is induced from the patterns of knowledge at level four.
- The transcendental knowledge at level six is usually transmitted by general system-theoretic analysis, or is induced from the patterns of knowledge at level five. Many mystical and consciousness-raising techniques may be seen as attempts to communicate knowledge at this level when formal analysis is impossible. It involves moving outside the framework established at the lower levels. Pope (1984) has given examples of this process in a wide range of cultures.

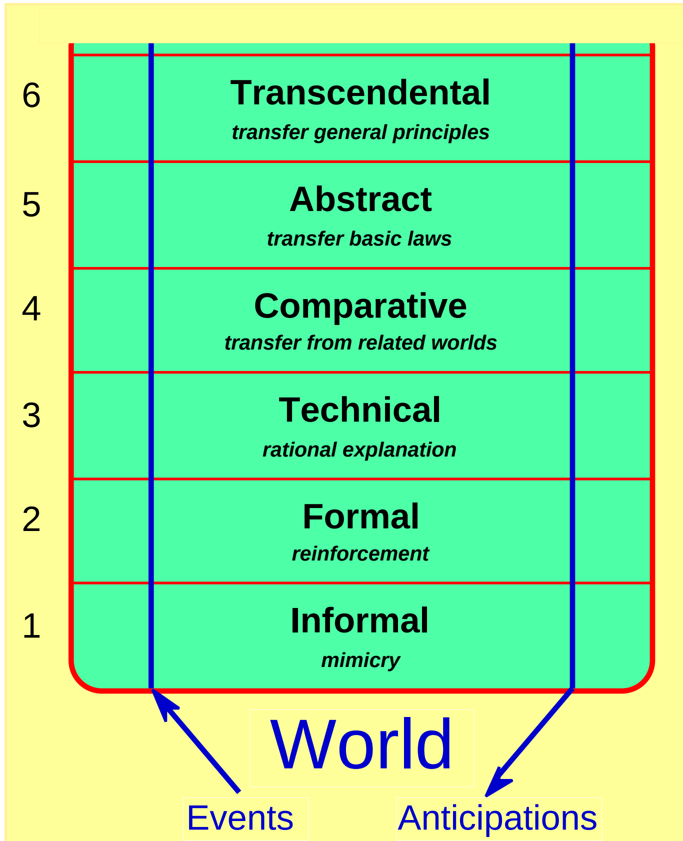

Figure 5 Cultural transmission hierarchy of people modeling a world

3 Phases of Learning

The systemic model of individual and social learning processes given in the previous section may be used to model the processes of technological development and diffusion in society as a whole and in particular industries. In economic terms it bridges between the micro-economic processes of the individual inventor, researcher, product innovation, development engineer, marketer, salesman, and so on, and the macro-economic processes of the development of a major industry. It brings the basic knowledge processes together with the psychological factors that affect the attraction of different phases of product development to people with differing personalities.

The most significant factor in determining the large-scale effects of the detailed learning process described are the information flows required to establish high-level skills in a technology. Learning from experience requires increasing information flows to build up each level of knowledge in the hierarchy. The inductive process at one level is dependent on the results of the inductive process at the level below and hence the rate of development of knowledge at the higher levels of the hierarchy is initially extremely slow. However, were it not for the higher-level inductive processes the lower levels would become overloaded with excessive detail very rapidly. The modeling hierarchy represents an evolutionary adaptation to a world in which a small number of generative principles can account for an extremely wide range of experience.

As learning accumulates at the higher levels it makes information acquisition at the lower levels decreasingly necessary. When a level is able to account for all the information it receives then no surprise flows up from it and any information flow from it can be discarded. Our civilization is itself a learning system with this overall structure and the societies, organizations and people within it form linked substructures. Viewed in this way, the flow of information through language may be seen as a way of passing knowledge between the substructures, and the accumulation of knowledge in libraries and databanks may be seen as a way of preserving it across time. Language and the knowledge construct are the side-effects of a learning civilization based on a distributed system of autonomous, interacting learning units.

If we examine sub-structures of knowledge that are somehow complete in that they give an adequate basis for a certain class of actions, then the same considerations apply. At the beginning the learning process is very slow because it has no foundation other than creative action, that is search procedures and experimentation directed by curiosity, the drive for novelty. When one person makes a creative breakthrough their knowledge is at level one and can be communicated to others only informally by aiding them in mimicking the breakthrough procedure. The originators have little basis for communicating through language except in aiding mimicry by saying what they do as if they were observing themselves. The communication of knowledge in this way after breakthrough leads to a phase of replication.

When more experience is gathered of breakthrough-like situations, inductive inference at level two enables rules to be stated which generalize the experience. Natural language plays an important role here because it facilitates the expression of generalizations as apparently vague statements using fuzzy quantifiers. The explanations that can be given based on rules appeal to past experience, and this phase is one of empiricism. The rules are a linguistic form of reinforcement stating that it is good to do some things and bad to do others, and their empirical content is shown in that “why?” questions have to be answered in terms of “because we did it and it did, or did not, work.”

As further experience leads to the accumulation of the rules, their numbers become excessive in terms of memory and application. Fortunately, they also make possible the inductive inference of generative models that reproduce the rules but are far more condensed in form. This condensation involves encoding the information in a form that is usually remote from experience and requires the development of technical languages for its expression. As these languages are not directly related to experience it becomes important to be very precise in their use in order to communicate correctly. The explanations that can be given of the rules generated are now based on technical languages and appeal to models. This phase may be termed one of theory because of the disconnection between experience and technicality. Note that the theory is not deep from a scientific point of view in that it does not appeal to fundamental laws or basic principles, but it is adequate from a technological point of view in that it is concise and correct.

The next phase is complex because it has multiple branches. An adequate theory solves the problem within a given domain and one effect is to reduce research interest in that domain as noted by Crane (1972). However, as a variety of theories develop, the learning process at level four becomes significant leading to interest in foundations, reductionism, and the use of one theory as a metaphor to speed up the development of another. This metaphorical process has occurred many times in extending human knowledge and is embedded in the structure of language (Lakoff & Johnson 1980). In technological terms, as the use of the models enables more and more action to be subsumed under a more and more concisely encoded rules it becomes feasible to incorporate these encoded rules in mechanisms and hence to enter a phase of automation.

Finally, the technology enters a mature phase where the theory is well-established and well-founded in relation to other areas. The learning process continues at level five as a search for further condensation into basic laws, and at level six where the complete process of knowledge acquisition can now be examined to draw out systemic principles that are applicable to wide domains of human processes.

This sequence from breakthrough through replication to empiricism, theory, automation and maturity (BRETAM) is fundamental to the analysis of the development of major new technologies and their associated industries, such as computing and genetic engineering. The following sections analyze the phenomena associated with it in greater detail.

3.1 Learning Curves

A simple mathematical model may be applied to the learning process described in the previous section by noting that it involves two conflicting processes: needing to have knowledge in order to acquire more; and slowing down in the acquisition as there is less and less left to acquire. This can be approximated to the first order as a systemic process in which the rate of growth is related to: the amount already accumulated; and also to the amount remaining to accumulate. The differential equation of such processes is dominated by a term of the form:

$$dx/dt = ax(b-x)/b \qquad (1)$$

where a is a rate constant and b is the peak attainable. Integrating this gives:

$$x = \beta e^{\alpha t}/(\lambda + e^{\alpha t}) \qquad (2)$$

where λ is a constant of integration, which is the standard symmetric S-shaped logistic curve. If other phenomena occur which perturb the dynamics of Equation 1 then the symmetries of Equation 2 may be distorted but the basic shape remains the same.

The logistic curve has been found to be a useful phenomenological model of the introduction of any new knowledge, technology or product which follows a “learning curve” in which growth takes off slowly, begins to climb rapidly and then slows down as all the information has been assimilated. Such curves arise in many different disciplines such as education, ecology, economics, marketing and technological forecasting (Van Dujin 1983, Stoneman 1983). It has also been noted in many disciplines that the qualitative phenomena during the growth of the logistic curve vary from stage to stage in a similar sequence to the BRETAM analyzed above (Crane 1972, De Mey 1982).

From Equation 2, if we take the amount of knowledge necessary for a mature technology to be 1, then the 0.1, 0.25, 0.5, 0.75 and 0.9 points are equally spaced in time along the logistic curve. These points can be roughly correlated with the significant phases in knowledge acquisition analyzed previously as shown in Figure 6 where the BRETAM sequence is superimposed on the logistic learning curve. When less than 0.1 of the knowledge is available little can be achieved and we are in a breakthrough period where most projects attempted will fail through lack of some critical information or skill. However, at around the 0.1 level some form of recognizable breakthrough becomes possible and we move into a phase of replication in which the breakthrough activity is noted and mimicked widely with little understanding. This leads to increasing experience and knowledge based upon it and when the 0.25 level is reached sufficient information is available for a phase of empiricism in which design rules are formulated based on experience. At the 0.5 level sufficient information has been accumulated for deeper patterns to be discerned, and 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 0.75 level the theories have become accepted as the normative basis for further progress and an automation phase commences in which they are used for design and to search out the residual knowledge. Above the 0.9 level a phase of maturity is entered when the knowledge is expected to be available and used routinely.

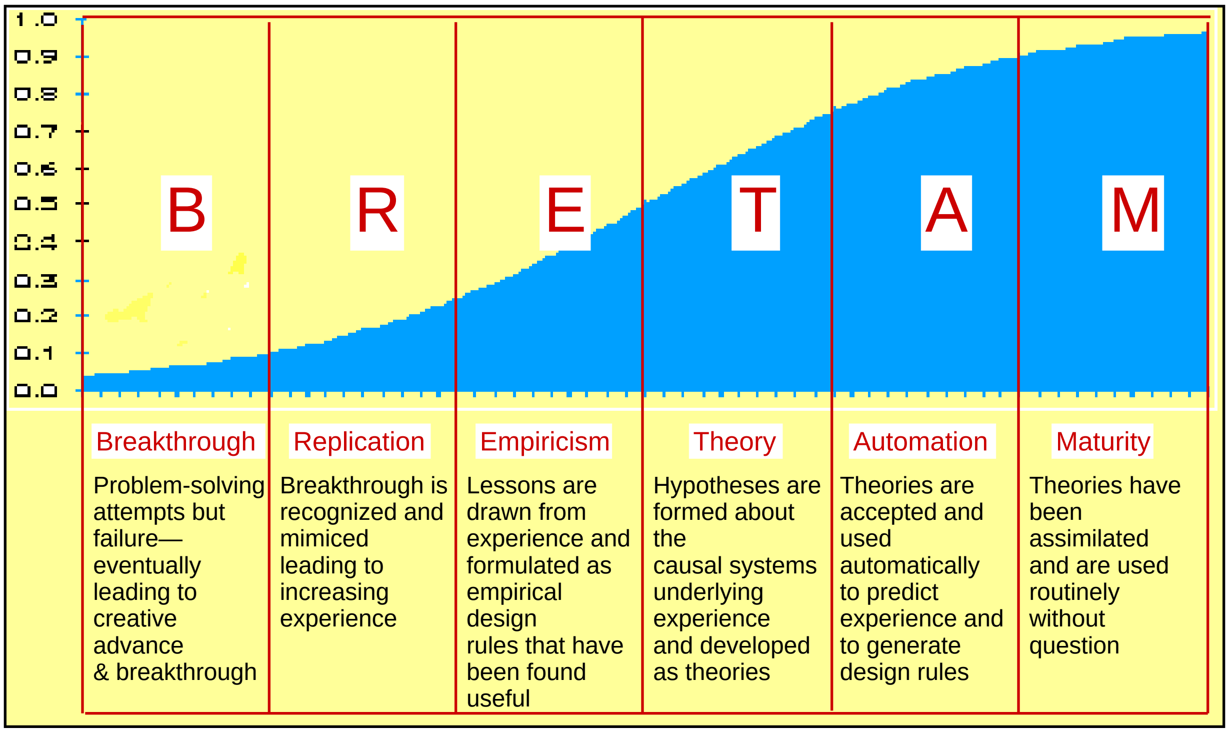

Figure 6 Phases of learning superimposed on a logistic learning curve

This is a very tidy description of what is essentially a random process with many local peculiarities but strong global trends. One problem with using it predictively is that the asymptotic final level can only be estimated in retrospect, and attempting to determine the form of a logistic curve from data on the early parts is notoriously sensitive to error (Ascher 1978). However, fitting logistic curves to historic data gives a very precise account of the development of major technologies such as the successive substitutions of one form of energy production for another (Marchetti & Nakicenovic 1979).

3.2 Tiers of Learning, Invention, Research, Innovation and Product Lines

The BRETAM learning sequence shown in Figure 6 represents the phases of knowledge acquisition involved in a specific technology as a linear sequence. However, it does not make apparent the impact of developments in one technology on those in another or the changes in people, locations and applications involved in the technology. The development of one technology is often the prerequisite for a breakthrough in another so that the BRETAM sequences of related technologies tend to be linked together. These linkages become strongly emphasized because of the personalities and roles of the people involved at different stages of the sequence and the socio-economic effects of a developing technology.

It has been noted previously (Gaines & Shaw 1984d) that major differences in people result from different emphasis on the levels of the epistemological hierarchy. The core constructs (Kelly 1955) that determine the dynamics of the individual and manifest as “drive” and “motivation” may be predominantly at one level of the hierarchy. Some individuals are concerned primarily with experience not assimilable at level one, with extreme novelty where appropriate constructs do not yet exist. They are inventors of modes of experience. Their emphasis on novelty may make it difficult for them to operate in tight organizational structures and it is difficult to manage the promotion of breakthroughs. These tend to occur unexpectedly by their very nature.

Some individuals are primarily concerned with the assimilation of novel constructs at level one. They are the generators of new experience and gravitate towards research positions where facilities are available to replicate breakthroughs and refine them. Some individuals are primarily concerned with the assimilation of experience at level two. They are innovative designers who formulate rules for product development and gravitate towards companies willing to undertake the risk of product innovation. Some individuals are primarily concerned with the assimilation of theory at level three. They design products ranges that are well-founded on principles enabling integrated systems to be developed and supported as long-term product lines. They tend to gravitate towards industry majors who take a strategic position towards supporting a large customer base requiring product continuity.

These personal and industry phenomena lead to the successive stages of the BRETAM sequence being associated with different individuals, functions within companies, and types of company. For those concerned with any phase of the BRETAM sequence there is the equivalent of a switch of attention when a particular technology enters the next phase. The breakthrough person will look for other breakthroughs but probably never find another. The research team will switch to alternative projects as will product innovation teams and product line teams. Thus social dynamics are superimposed on the basic learning sequence.

The overall effect is that BRETAM sequences for a sequence of technologies, each of which is a prerequisite for the breakthrough of the next, tend to get stacked in a regular formation as shown in Figure 7. The base technology which initiates the tier is a prerequisite to the next level technology, which is a prerequisite to the technology above, and so on. The focus of attention in research, product innovation, and so on, shifts from one technology to another in each successive phase of the learning sequence:

- Invention is focussed at the BR interface where new breakthrough attempts are being made based on experience with the replicated breakthroughs of the technology below.
- Research is focussed at the RE interface where new recognized breakthroughs are being investigated using the empirical design rules of the technology below.
- Product innovation is focussed 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 technology below.

- Established product lines are focussed at the TA interface where they can rest on the solid theoretical foundations of one technology and the automation of the technology below.

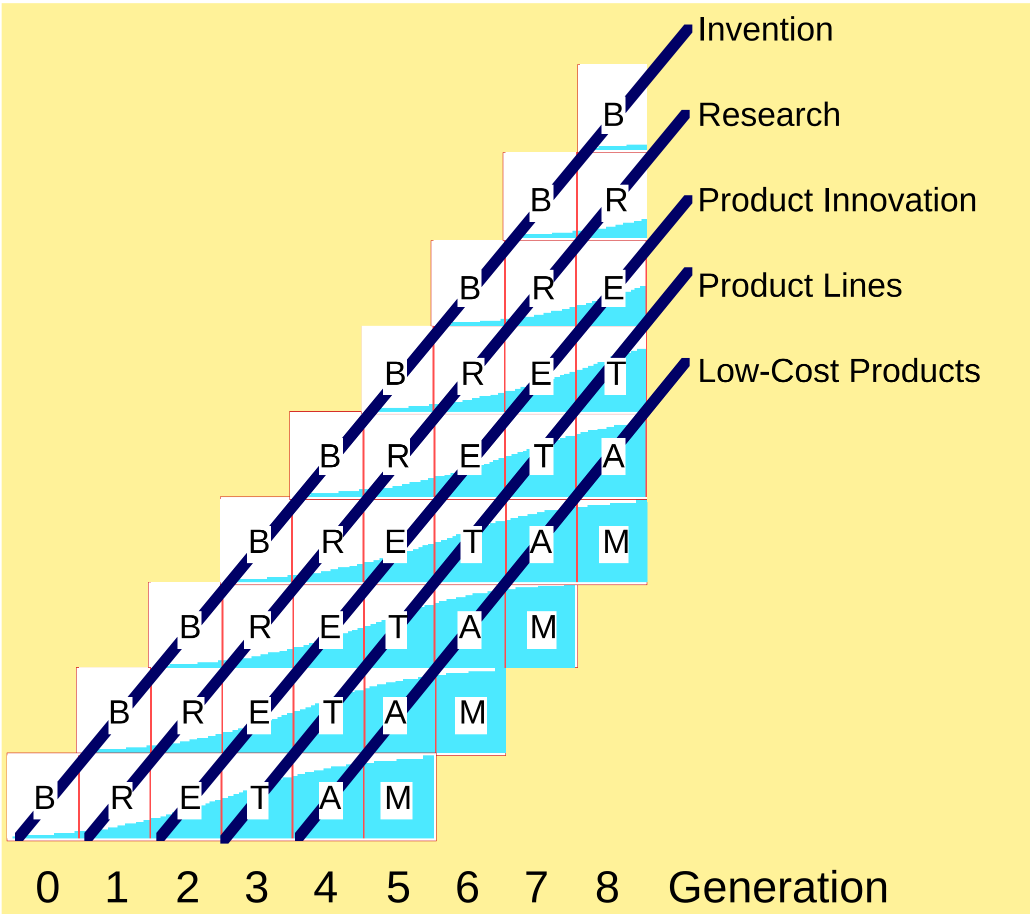

Figure 7 Tiers of learning curves defining generations of technology

From a macroscopic viewpoint the generic technology from which all the others derive defines an industry, and the phases of the learning curves define generations of technology within that industry. Note how product innovation occurs about two generation periods after the initial breakthrough, and product lines are three generation behind the breakthrough. This is the delay between invention and innovation noted by Schumpeter (1939) and linked to the phenomena of Kondratiev long-waves in the economy (Freeman 1984).

In terms of the overall industry, knowledge acquisition proceeds as a succession of learning curves each building upon one another, and it is the envelope of these that we see as the improving performance of the technology in time. This is what has happened in the base technology underlying computing where relays were replaced by vacuum tubes in the 1940s, by transistors in the 1950s, by integrated circuits in the 1960s, and so on. Each new technology has had its own learning curve, and hardware-based performance parameters such as speed of operation have shown a steady improvement based on the envelope of these learning curves (Ayres 1968).

Note how the horizontal BRETAM sequence becomes replicated in a vertical BRETAM structure representing the stages of development of all the differing technologies in a given generation. This replication is complete by the fifth generation which is often seen as the one in which the industry itself reaches maturity. For example, Drucker (1978) compares the development of the electricity industry with that of the information industry, making the analogy that “information is energy for mind work.” He remarks 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.” It was the invention of the light bulb that led to the use of electricity as a universal form of energy.

4 Application to Information Technology Industries

Information technology is interesting in providing examples of well-documented learning processes that exhibit the phenomena of Figure 7 (Gaines & Shaw 1984c). For example, the electronic computer 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.

4.1 The Birth of the Computer Industry: Social Need and Electronic Device Technology

There is a simple systemic model of the development of the computer industry. The precursors necessary to the birth of a new industry are a social need and a technology capable of satisfying it. The need allows a market to be generated. The technology allows products to be created for that market. For computers the enabling technology was electronics. The key operational concepts of a digital computer date back at least to Babbage, Lovelace and Boole in the nineteenth century (Goldstine 1972). However, the mechanical technology of their time could not support a digital computer with adequate operations, storage capacity and speed.

The social need for computation in Babbage's time was navigation and its support through astronomical calculations themselves supported by the calculation of tables of logarithms. The enabling technology of electronic devices dates to the early 1900s with De Forest's development of the triode vacuum tube (Shurkin 1984). However, it was not until the outbreak of World War 2 in 1940 generated the need for rapid calculation of ballistic trajectories that the social requirement for computation became sufficiently urgent. Mechanical device technology in the ball and disk differential analyzer had been taken to its limit and was inadequate. The pressures created by the urgent need to find an alternative technology supporting computation led to the use of vacuum tubes in the design of ENIAC by Mauchly and Eckert (Stern 1981).

Thus the initial breakthrough for computing was in electronic device technology (EDT) and it is interesting to see how well a simple, one-dimensional learning curve model for the substitution of different electronic technologies accounts for generation changes in computing:

- 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 1949 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.
- The sixth generation will start in 1988 with ultra large-scale integration and some 10 million transistors on a chip;
- The seventh generation will start in 1996 with grand-scale integration and 1,000 million on a chip.

This definition of generations in terms of hardware works well for the zeroth through second generations because of the distinct qualitative changes involved. However, as Rosen (1983) notes in his analysis of computer generations it blurs thereafter and "we are faced with an anomalous situation in which the most powerful computers of 1979-1980, the CDC Cyber 176 and the CRAY 1, would have to assigned to the second and third generations, respectively, while the most trivial of hobbyist computers would be a fifth-generation system." The reason for this anomaly is that the substitution effects of one form of technology for another along the horizontal BRETAM curve are gradual and do not generate hard boundaries. The enabling effects of changing technologies giving the vertical BRETAM sequence are far more dramatic: 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.

The pattern is one of improvements in the basic technology allowing new developments to occur in the architecture and applications of systems based on it. What is missing from the model of computing developing through successive generations of electronic device technology (EDT) 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—a version of Figure 6 specifically for computing.

4.2 Tiers of Learning in Computing Technologies

Figure 8 shows the BRETAM tiers for the computing industry. The breakthrough in EDT leading to the zeroth generation is placed at 1940 about the time of the Atanasoff and Berry experiments with tube-based digital calculations. Experience was gained with COLOSSUS and ENIAC during the next eight years leading to a spate of empirical designs in the 1956-63 period, theoretical foundations for logic minimization and automata theory, automation with computer-aided design tools, and culminating into maturity with the 4004/8008 microprocessor chips in 1971/1972. The number of devices on a chip follows Moore's law in doubling each year through the second and third generations, and has continued to double every 1.5 years through the fourth and fifth generations (Robinson 1984). Automation has reached the extreme level where silicon compilers allow a designer to implement his ideas directly in EDT with little further human intervention (Fields 1983). However, our knowledge of EDT is now largely accumulated and future developments will be quantitative in speed, size and cost rather than qualitative in enabling new breakthroughs. Radical changes will come only from the way in which we use EDT or from alternative basic technologies such as volumetric rather than planar devices, optical processing or organic devices (Tucker 1984).

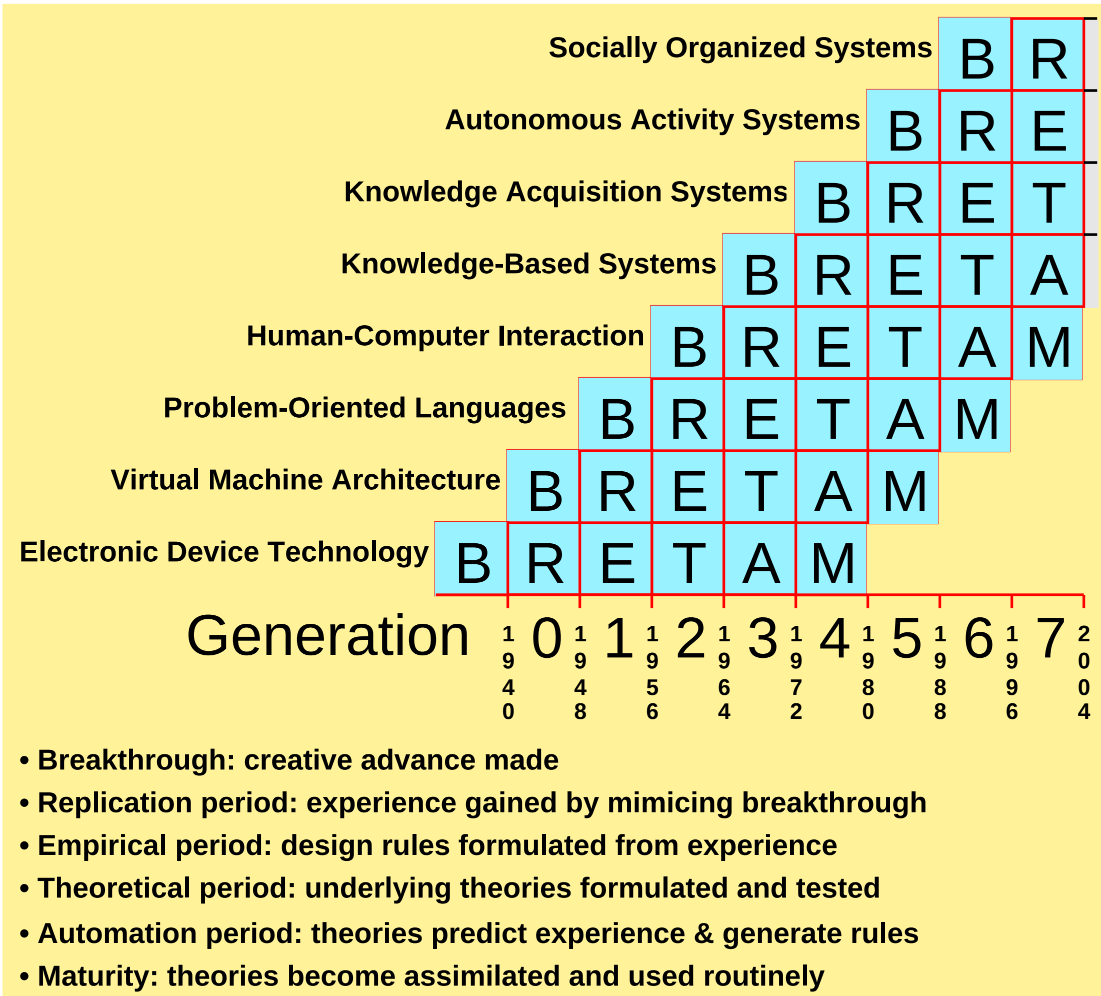

Figure 8 Eight generations of computers and their underlying technologies

The first breakthrough generating a computing infrastructure was the introduction of the stored program concept which led to the transition from the ENIAC to the EDVAC designs. The key concepts were discussed by Mauchly in his paper of 1947 and the first implementations were the BINAC and EDSAC machines in 1949. Mauchly (1947) recognized the significance of stored programs in enabling the machine instruction set to be extended, noting that subroutines create “a new set of operations which might be said to form a calculus of instructions.” This was the key conceptual breakthrough in computer architecture, that the limited functionality provided directly by the hardware could be increased by stored programs called as subroutines or procedures, and that the hardware and these routines together may be regarded as a new virtual machine. This is the foundation of the development of a variety of forms of virtual machine architectures (VMAs, Weegenaar 1978) that separates out computing science as a distinct discipline from other areas of electronic applications. The use of subroutines to give access to arithmetic and operating system capabilities was followed by the development of machine architectures dependent on traps to procedures emulating missing hardware and led to theories such as those of semaphores, Petrinets and the logic of databases underlying diverse architectural concepts. In the fifth generation era the virtual machine technology has become a mature foundation for advanced system design in human factors and knowledge engineering (Gaines 1984c).

The next level of breakthrough was to bridge the gap between machine and task through the development of problem-orientated languages (POLs). Their foundations in the first generation were subroutine libraries providing VMAs closer to the problem requirements, notably floating point arithmetic and mathematical functions. Work on the design of FORTRAN in 1954 and its issue in 1957 marks the beginning of the second generation era with languages targeted to specific problem areas of business data processing, text processing, database access, machine tool control, and so on. A 1968 paper on the coming fourth generation notes that “programming today has no theoretical basis” and calls for a scientific basis in the next generation (Walter, Bohl & Walter 1968). Sure enough the theory linking POLs to the underlying VMAs developed during the fourth generation era, for example, that of abstract data types and initial algebras (Goguen, Thatcher & Wagner 1978). In the fifth generation era the application of experience, design rules and theory to the automation of software production has become the top priority (Balzer, Cheatham & Green 1983).

The binary VMA-POL relationship bridges the gap between the computer and its application. However, the computer industry is based on the triadic relationship between computer, application and person, for example, programmer, system analyst or user. The next level of breakthrough was to bridge the gap between the computer and the person with the development of interactive computers. The move from batch-processing to direct human-computer interaction (HCI) was made in 1963/1964 with the implementation of MIT MAC, RAND JOSS and Dartmouth BASIC systems (Gaines & Shaw 1983a). The study of such systems led to design rules for HCI in the 1970s (Hansen 1971) and theoretical foundations have started to emerge in the 1980s (Gaines & Shaw 1984e). The improvement of HCI is a major priority in the Japanese fifth generation development program (Karatsu 1982).

The third element in the triadic relationship between computer, application and person is that between the application and the person. It is one of knowledge-processing, the human capability to store information through its inter-relations and make inferences about its consequences. The breakthrough in knowledge-based systems (KBS) dates from the development of DENDRAL (Buchanan, Duffield & Robertson 1971) for inferring chemical structures from mass-spectrometry data and MYCIN (Shortliffe 1976) for the diagnosis of microbial infections in the early 1970s. It led to a spate of expert system development in the fourth generation era of the 1970s (Gevarter 1983), and pragmatic design rules for knowledge engineering in the current fifth generation era (Hayes-Roth 1984). The utilization of their massive VLSI production capability (Gaines 1984a, Galinski 1983) for the support of KBS through LISP (Bawden et al 1979) and PROLOG (Clark & Tarnlund 1982) machines is the other major priority in the Japanese fifth generation development program (Moto-oka 1982).

Defining the upper levels of the infrastructure becomes more and more speculative as we move into the immediate past of our own era and look for evidence of learning curves that are at their early stages. It is reasonable to suppose that the level above the representation and processing of knowledge in the computer will be that of its acquisition, breakthroughs in machine learning and inductive inference systems (IIS). Two breakthroughs in this area have been Lenat's AM learning mathematics by discovery (Davis & Lenat 1982) and Michalski's inductive inference of expert rules for plant disease diagnosis (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).

One may speculate that 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 autonomous activity systems (AAS). It is possible to see the nascent concepts got this breakthrough in the adoption of the goal-directed programming paradigms of logic programming languages such as PROLOG. When, in a robot, a goal specification is expanded by such a programming system into a sequence of actions upon the world dependent on conditions being satisfied in that world, then the behavior of such a system will deviate sufficiently from its top-level specification, yet be so clearly goal-directed, as to appear autonomous. However, to achieve significant results with such systems we need to add perceptual acts to the planning structures of a language such as SIPE (Wilkins 1984) and develop logic programming languages that cope with the resulting temporal logic (Allen 1984) —in these developments the sixth generation breakthrough will come to be recognized.

One may speculate further that interaction between these systems will become increasingly important in enabling them to cooperate to achieve goals and that the seventh generation era commencing in 1996 will be one of socially organized systems (SOS). The social reflective equilibrium model outlined in the earlier part of this paper gives some indication of the need to embed knowledge science, applying to both human and machine intelligence, within a socio-cultural framework. It is reasonable to suppose that current theoretical work in this area will form the basis of a technological breakthrough within the next decade.

However, it is also reasonable to suppose in the light of past forecasting failures in computing technology that these speculations will be greatly in error. The projected breakthroughs may not occur or may occur much earlier. The recognized breakthroughs may be in completely different areas. It is even possible that building an adequate forecasting model based on the premises of this paper may undermine the very processes that we model. If we come to understand the dynamics of our progress into the future then we may be able to modify the underlying process—to make the next steps more rapidly when the territory is better mapped.

4.3 Invention, Research, Innovation and Product Lines in the Computing Industry

The lines of invention, research, product innovation and product lines for the development of the computing industry are shown on the BRETAM infrastructure in Figure 9, and it is interesting to relate them to events in each generation. In particular note that the delay between invention and product innovation in the computer industry is about 16 years, and that between invention and product lines is about 24 years.

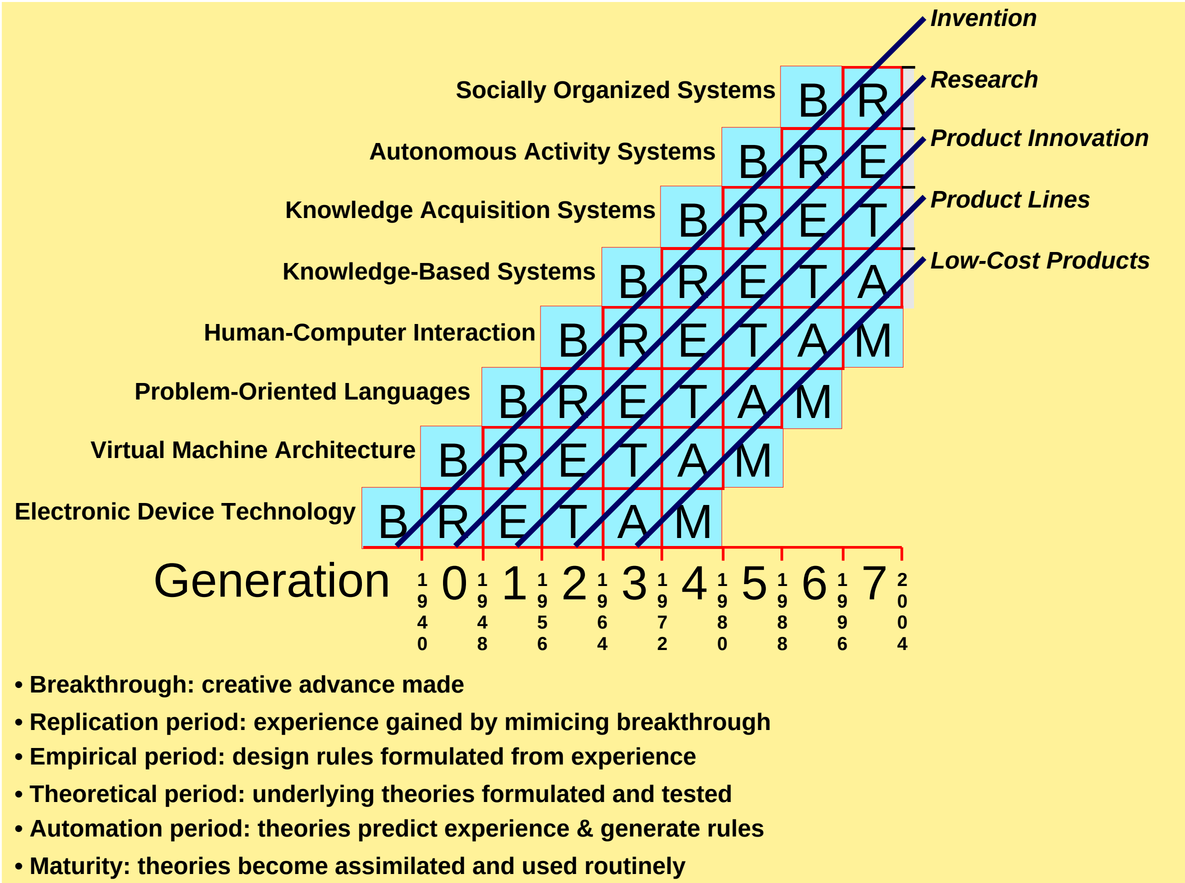

Figure 9 Invention, research, innovation and product lines through generations of computers

In the zeroth generation (1940-47):

- (BR) recognition of the potential of EDT led to the breakthrough to the stored program and virtual machine architecture.

In the first generation (1948-55):

- (BR) recognition of the capabilities of subroutines to extend the VMA led to the breakthrough to the problem-orientated language;
- (RE) research focussed on increasing the capabilities of the VMA to take advantage of advances in hardware development, e.g. index registers in the Manchester University Mark I.

In the second generation (1956-63):

- (BR) recognition of the advantage of making the POL directly control the machine led to the breakthrough to direct human-computer interaction;
- (RE) research focussed on increasing the capability of POLs to take advantage of advances in VMAs, e.g. the block structure of ALGOL60;
- (ET) experience with the potential of the VMA led to the product design innovation of virtual memory hardware in the ATLAS computer.

In the third generation (1964-71):

- (BR) recognition of the knowledge engineering possibilities of HCI led to the breakthrough to knowledge-based systems;
- (RE) research focussed on the improvement of the HCI through the development of interactive languages, e.g. Dartmouth BASIC;
- (ET) experience with the POL ALGOL60 led to the innovative VMA of the Burroughs B6500 computer;
- (TA) the emulation capability of the VMA led to the design of the IBM360 product line of mainframes.

In the fourth generation (1972-79):

- (BR) recognition of the knowledge acquisition possibilities of KBS led to the breakthrough to inductive-inference systems;
- (RE) research focussed on the natural representation of knowledge through the development of HCI, e.g. the Xerox Star direct manipulation of objects;
- (ET) experience with the HCI using the POL BASIC led to the innovative product of the Apple II personal computer;
- (TA) the simplicity of the POL RPG II led to the design of the IBM System/3 product line of small business computers.

In the fifth generation (1980-87):

- (BR) recognition of the goal-seeking possibilities of IIS is leading to the breakthrough to autonomous-activity systems in robotics;
- (RE) research is focussed on learning in KBS;
- (ET) the advantages of the non-procedural representation of knowledge for HCI led to the innovative designs of the Visicalc spread-sheet business product and the LISP machine scientific product;
- (TA) the ease of HCI through a direct manipulation POL led to the Apple Lisa/Macintosh product line of personal computers.

In the sixth generation (1988-95):

- (BR) the recognition of cooperative goal-seeking possibilities of AAS will lead to the breakthrough to socially-organized systems in robotics;
- (RE) research will focus on goal-seeking in robots learning about their environment; (ET) innovative products will use inductive inference to set up KBSs;
- (TA) expert systems will become established product lines.

In the seventh generation (1996-2003):

- (RE) research will be focussed on the social interaction of autonomous robots;
- (ET) innovative products will be based on goal-directed autonomous robots;

- (TA) learning systems will become established products, e.g. an encyclopedia that generates new knowledge from inferences based on combining entries.

It is interesting to examine the Japanese fifth and sixth generation computing programs in the light of this analysis:

- The fifth generation program made knowledge-based systems and the human-computer interface its main priorities and commenced in 1982 (Moto-oka 1982, Gaines 1984b). This places it at the ET interface and on the line of product innovation rather than research or invention. This is consistent with the achievements of the program at ICOT to date in developing high-speed PROLOG and relational database machines (Kawanobe 1984).
- The sixth generation program makes the human capabilities to learn by inductive inference in knowledge-based systems its main priority and will commence in 1986 (STA 1985, Gaines 1986). This places it between the RE and ET interfaces and hence between the research and product innovation lines. This is consistent with the stated intention of this program to encourage innovative research in computing in Japan (STA 1985).

4.4 The Business Cycle and the Computing Industry

Figure 8 shows the generations of computers and all the associated technological structure linked into a consistent eight year cycle. The literature on computer generations specifies a variety of starting dates and time scales for the generations, anywhere between five and ten years. Withington’s (1974) analysis which separates hardware, software, applications and organizational effects, allocates eight years to generations two through four but puts the starting dates two years later than ours. The boundaries of each generation are naturally somewhat fuzzy and depend on whether one counts from the initial availability or the widespread use of the technology.

The model of the development of computing presented here is partially based on a collection of key events in computing. When this collection was started it seemed reasonable to regard “generations” as convenient demarcations of the history of computing and to be dubious about there being any underlying cyclic mechanism. However, as more data were gathered the discrete nature of each era became more and more pronounced, both subjectively in relation to recollections of the ethos of those eras, and objectively as in relation to the critical events at the boundaries.

One interpretation of the timing of the generations is that they relate to the underlying business cycle of capital equipment purchase, the Juglar cycle originally identified in the nineteenth century (Juglar 1889) and apparent as a definite eight year cycle through to the current times (Lewis 1978). The peaks in the Juglar cycle correspond to our eight year boundaries from 1940 through 1980; the USA statistics show the 1964 peak as being in 1967 due to purchases to support the Viet Nam war but the next peak is in 1972 on target showing the dominating effect of world trade cycles rather than national events (Van Dujin 1983).

It is possible to speculate further on the causal linkages between the trade cycles and innovation in computing. The slump in purchasing following a peak leads to cut-backs in research and development investment so that the next generation of products tends to be based on the innovations made prior to the preceding peak. There are also longer term trends and cycles in invention and innovation that underlie the development of complete waves of new technology over periods of about fifty years, some six Juglar cycles.

Marchetti (1981) projects the current long-wave as having a learning curve in inventions from the 0.1 level in 1951 to the 0.9 level in 1989, and in their application as product innovations from the 0.1 level in 1987 to the 0.9 level in 2003. This corresponds to the creative era of computing being the first through fifth generations and the social impact era as being the sixth and seventh generations. The exodus of KBS researchers from the universities to industry is symptomatic of this transition (Business Week 1984). It is also analogous to the transition to widespread impact between the fifth and sixth generations of technology in the electricity industry quoted previously from Drucker (1978)

4.5 The Growth of the Genetic Engineering Industry

The biological application of information technology which has led to the development of the genetic engineering industry is a rather more recent phenomenon than computing and it is not yet possible to establish the detailed infrastructure of the industry. However, there is historical documentation on the development of both the science of molecular biology (Allen 1975, Judson 1979, Glass 1982, De Pomeray 1985 Gribbin 1985,) and the resultant industry (Cherfas 1982, Prentis 1984, Nossal 1985, Kahn 1985), and already a number of significant parallels have emerged.

Miescher first isolated DNA in 1869 and one of his students, Altmann, named it as nucleic acid. Miescher also speculated on the mechanism of heredity and in 1892 suggested that the information was carried in large organic molecules where the repetition of a few chemical configurations could encode a complex message, "just as the words and concepts of all languages can find expression in twenty-four to thirty letters of the alphabet", but named proteins rather than DNA. This parallels Babbage's attempt to develop a mechanical computer in 1834 and Lovelace's development of the concept of programming it. The concepts of the early information technology pioneers were remarkably advanced but the mechanical and chemical sciences of the nineteenth century could not support them.

Turing's (1936) paper on computable numbers gave scientific foundations to the notion of computing well before the machinery to reify it was developed. This is paralleled by Schrodinger's (1944) book on the nature of life which analyzed the foundations of genetic encoding in molecular structures well before the decoding of DNA. In both cases these theoretical developments were a great stimulus to the scientific and technological pioneers to give meaning to the theory through practice, to invent or discover a physical model for the mathematics.

The breakthrough in molecular biology was Watson and Crick's discovery of the double helix model of DNA in 1953. This gave the architecture of the genetic process and is comparable to the Mauchly and Von Neumann concepts of computer architectures in 1946. It took a further thirteen years for the details of the genetic code to be worked out, and hence the programming mechanism by which DNA specifies proteins to be understood. This brought molecular biology to an advanced state as a predictive science by the mid 1960s. The breakthrough into a normative technology came in 1970s with the development of cutting enzymes that allowed the structure of DNA to be changed and controlled, and hence genetic engineering to begin to emerge as an industry. In the 1980s the conceptual models to mediate between the specifications of required organic structure and the genetic structures to produce them are being developed—the problem-orientated languages of biological information engineering.

The next stages of development in information technology, both in computing and biology, are ones that emphasize the recursiveness of the model presented in this paper. As computing developments the techniques of artificial intelligence, and genetic engineering develops techniques for changing the structure of life, the human species is modifying its knowledge acquisition processes both through the artefacts that mediate it and through the brains that have been its primary dynamics. It has been suggested in this paper that there is a single system underlying all these phenomena: the anticipatory processes of a living system targeted on its survival. The model proposed is not yet adequate in detail to carry the full weight of this global conjecture, but it is already useful in providing a rationale for developments in information technology, and suggesting future directions.

5 Conclusions

Information technology may be viewed as autonomously impacting society. However, it may also be viewed as a product of society, created through its needs and molded by its values. From this second point of view, the development of information technology may be modeled as a succession of social learning processes arising out of the need to cope with an increasingly complex world. This paper has given a system-theoretic accounts of the epistemological processes underlying knowledge acquisition, and has shown that these apply to both individual human behavior and social development processes. Such accounts are applicable to the upper levels of the hierarchy of autonomous systems to provide models of socio-economic behavior.

The knowledge acquisition model has been applied to the development of information technology, and used to account for past events and predict future trends in relevant industries such as computing and genetic engineering. Underlying all developments in information technology is a tiered succession of learning curves which make up the infrastructure of the relevant industries. The paper has provided a framework for the industries based on this logical progression of developments. It has linked this empirically to key events in the development of computing and genetic engineering. It has linked it theoretically to a model of economic, social, scientific and individual development as related learning processes with a simple phenomenological model. It has used this model to account for past developments in information technology and extrapolated it to predict future trends. Only now in the fifth generation and beyond are computing systems becoming able to interact with people at the levels of the higher processes of the mind. Thus, their major impact is yet to come.

As a parting remark, let us note that the understanding of the processes of knowledge, induction and problem-solving that are necessary to the development of future generations of computers is equally applicable to human development. The tools of humanity change the world and humanity itself. If we view the development of computing as a symptom of a changing basis for civilization then we can begin to gain some glimpses of the future. If we view it as autonomous technology causing problematic and unwanted change then the future will continue to be opaque.

Acknowledgements

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