FOUNDATIONS OF KNOWLEDGE ENGINEERING

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Abstract

An anticipatory system formulation of human cognitive psychology is presented which provides scientific foundations for knowledge engineering. The formulation gives an operational model of the notion of expertise and the role it plays in our society. It suggests that the basic cognitive system that should be considered is a social organization, rather than an individual. Computational models of inductive inference already developed can be applied directly to the social model. One practical consequence of the model is a hierarchy of knowledge transfer methodologies which defines the areas of application of the knowledge engineering techniques already in use. This analysis clarifies some of the problems of expertise transfer noted in the literature, in particular, what forms of knowledge are accessible through what methodologies. The model is being used as a framework within which to extend and develop a family of knowledge support systems to expedite the development of expert system applications.

1. Introduction

The term *knowledge engineering* was coined by Feigenbaum (1980) to encompass the process of reducing a large body of knowledge to a precise set of facts and rules. Knowledge engineering is now recognized as a fundamental problem in expert system applications, and it is generally seen as a major bottleneck impeding applications to new domains. Guidelines about knowledge engineering techniques have been published (Hayes-Roth, Waterman & Lenat 1983) and the psychological problems of knowledge transfer have been analysed (Welbank 1983). However, no scientific framework for knowledge engineering has been established, and present techniques are based on intuition, experience and empirical results rather than deep foundations.

This weakness is not unreasonable at this stage of the rapid growth of a new technology, but lack of scientific foundations is an impediment to the development of sound engineering principles supporting the application of expert systems. Empirical studies of knowledge engineering raise doubts about the possibility of eliciting expert knowledge using available techniques (Collins, Green & Draper 1985). Collins (1985) studied knowledge transfer processes among scientists and suggests that some knowledge may not be accessible through the expert, not only because he cannot express it, but also because he may not be aware of its significance to his activity. In an earlier study Hawkins (1983) emphasized the severe limitations of expertise and its dependence on critical assumptions which are often implicit.

Much human activity is not accessible to awareness (Dixon 1981), and the problem of knowledge elicitation from a skilled person is well-documented (Nisbett & Wilson 1977, Broadbent, Fitzgerald and Broadbent 1986). Bainbridge (1979, 1986) notes that there is no necessary correlation between verbal reports and mental behavior, and that many psychologists feel that verbal data are useless. However, this remark must be taken in the context of experimental psychologists working within a positivist, behavioral paradigm. Other schools of psychology see the problem not as methodological but as psychological and resulting from cognitive defences that impede internal communication for a variety of reasons (Freud 1914, Kelly 1955, Rogers 1967). Clinical psychologists in particular have developed techniques for making use of verbal interaction to identify underlying cognitive processes, for example through structured interviewing techniques. These can be used to by-pass cognitive defences, including those resulting from automization of skilled behavior.

However, knowledge engineering is an important aspect of advanced computer technology, and neither the pragmatic development of interviewing methods nor the importation of techniques from clinical psychology will in themselves be regarded as satisfactory foundations for an engineering discipline. We need to be eclectic in acquiring knowledge engineering techniques from all possible sources, but we also need to complement our pragmatism with effort to develop scientific foundations for our activities. We cannot be satisfied until we have a precise understanding of the processes underlying expertise, its operation, acquisition and transfer. This is not a simple requirement since it entails understanding the nature of knowledge, its dynamics and application. The foundations of computer technology in the physical sciences are no longer adequate and need extension into the humanities. The philosophy, psychology and sociology of knowledge processes are highly significant to future computing, and we have to operationalize theories and obtain precise answers to questions that have long been regarded as certainly controversial and possibly intractable.

This paper presents a model of knowledge processes in human society that is based on a systemic model of knowledge acquisition with strong mathematical foundations (Gaines & Shaw 1984b, 1985), gives an operational formulation of expertise as an essential component of the inductive process (Gaines 1977), and models the dynamics of knowledge transfer in a way that encompasses both human social processes (Shaw 1985) and the application of technology (Shaw & Gaines 1986a).

2. The Knowledge Acquisition Process

The systemic principle behind a cognitive psychological model that provides adequate foundations for knowledge engineering is that the human species is uniquely characterized as a highly anticipatory system, modeling the world so as to increase its probability of survival. This is is the basis of Kelly's (1955) personal construct psychology, and the modeling principle involved can be given strong formal foundations. 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* is a basic concept underlying the representation of knowledge (Gaines & Shaw 1984b, 1985). It is sufficient primitive to give foundations for systems theory including that of a system itself (Gaines 1980). In 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). Its foundational role in knowledge acquisition is evident in the hierarchical representation of distinctions in a modeling system shown in Figure 1. The levels of the hierarchy itself are the results of distinctions that we make so that no additional primitives are introduced—in Klir's (1976) terminology:

- The *source system* is distinguished as those distinctions made by a particular modeling system—it is a distinction about distinctions defining a construct system;
- 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—it 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.

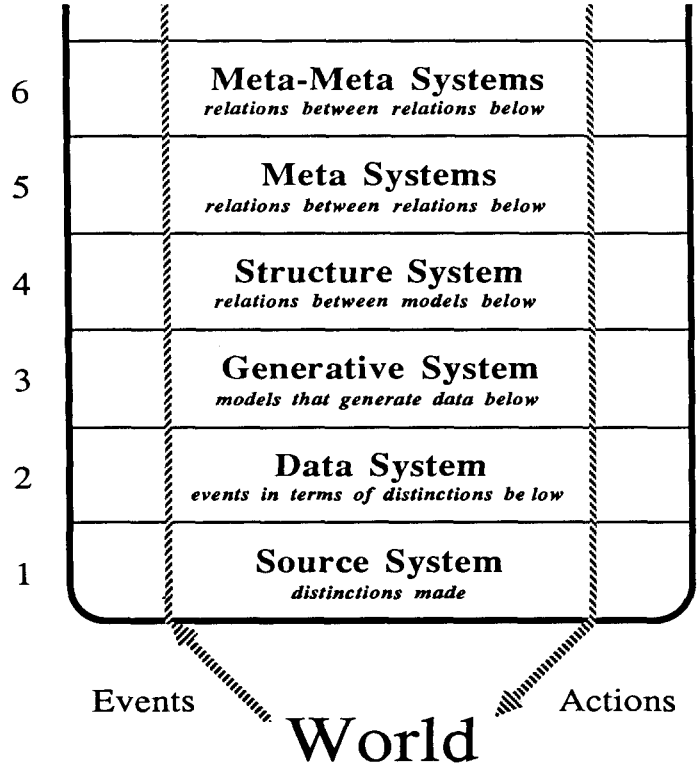

Figure 1 Epistemological hierarchy of a system modeling a world

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

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. In knowledge engineering we have to incorporate both the expert's prediction and control processes.

3 Learning in the Hierarchy

The hierarchy of Figure 1 accounts for knowledge acquisition 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.

4 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*. The systemic hierarchy of Figure 1 has a psychological analog 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.

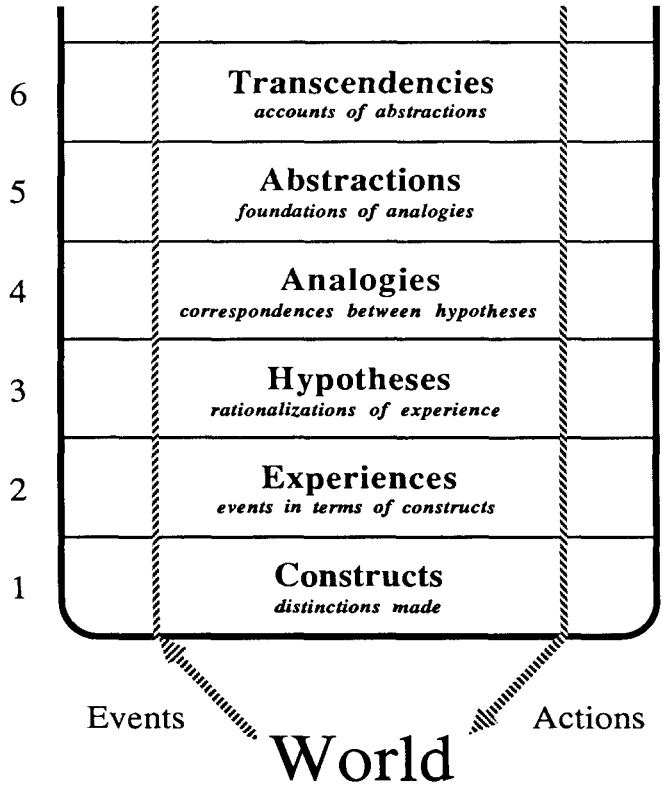

Figure 2 Construction hierarchy of a person modeling a world

5 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 is a society rather than an individual.

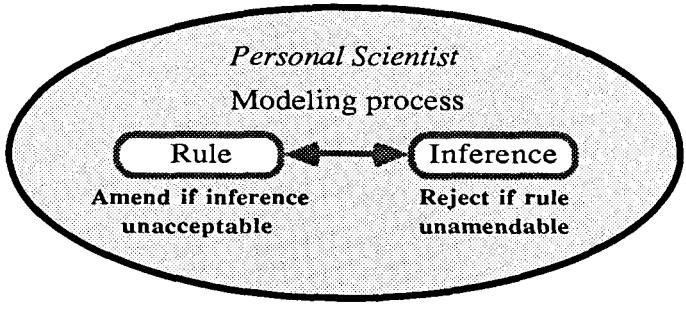

Figure 3 Reflective equilibrium in inductive inference

The extension of the modeling hierarchy to social processes is simple 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, 1986a). 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).

6 Representation of Expert Skills in the Hierarchy

In the analysis of expertise the *skills* to achieve goals in the world are the crucial capabilities of the modeling system, and hierarchical models of skills (Powers 1973, Rasmussen 1983) are naturally subsumed within the modeling formulation. 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. These constellations may be regarded as prototypical schema, or frame-like structures in computational terms.

- 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.

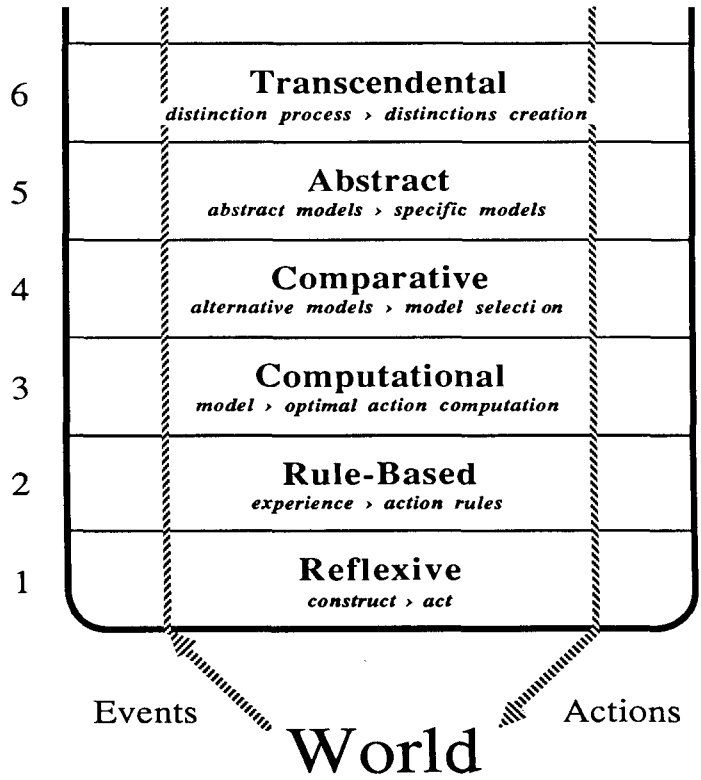

Figure 4 Action hierarchy of system modeling a world

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.

7 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 (Vanderburg 1985). 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. Much skilled activity is not directly accessible through language, but 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 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.

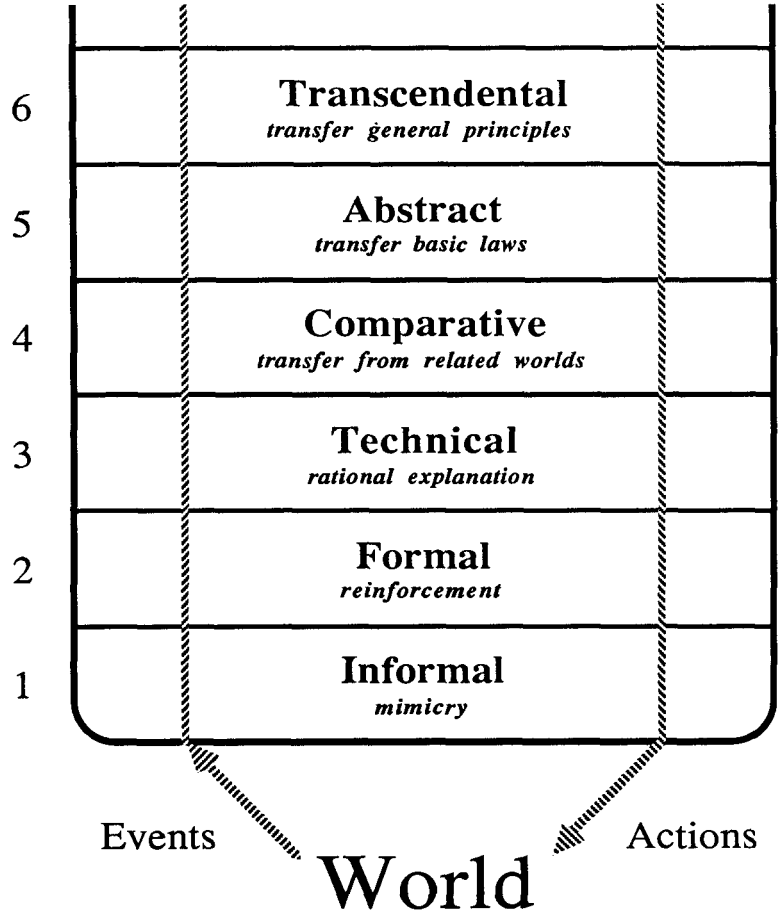

Figure 5 Cultural transmission hierarchy of people modeling a world

8. Conclusions

The anticipatory system formulation of human cognitive psychology outlined in this paper provides scientific foundations for knowledge engineering that lead to some interesting conclusions:-

1. It gives an operational model of the notion of expertise and the role it plays in our society, and hence provides formal foundations for expert systems;
2. Computational models of inductive inference already developed can be applied directly to the social model;
3. It suggests that the basic cognitive system that should be considered is a social organization, rather than an individual;
4. It suggestss that we should consider groups of experts rather than individual experts in developing expert systems;
5. One practical consequence of the model is to define a hierarchy of knowledge transfer methodologies as shown in Figure 6;
6. The hierarchy indicates the areas of application of the knowledge engineering techniques already in use.

This analysis clarifies some of the problems of expertise transfer noted in the literature, in particular, what forms of knowledge are accessible through what methodologies. The model is being used as a framework within which to extend and develop a family of knowledge support systems to expedite the development of expert system applications.

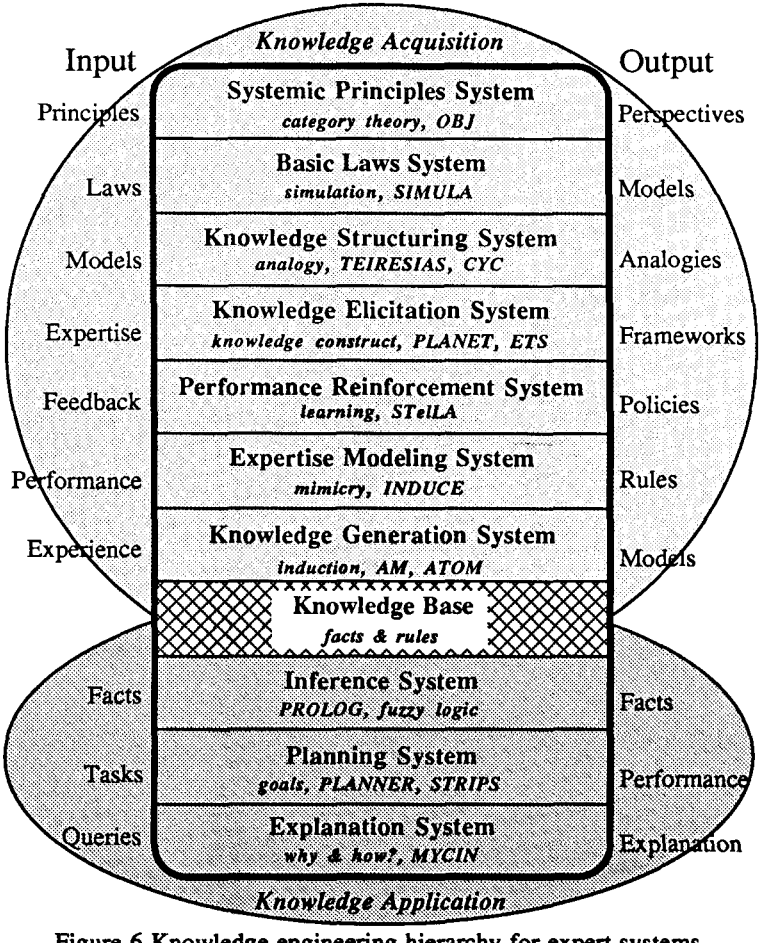

Figure 6 Knowledge engineering hierarchy for expert systems

Acknowledgements

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