HOW DO EXPERTS ACQUIRE EXPERTISE?

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Abstract: The role of the expert in the knowledge processes of society is analyzed and shown to be that of managing the inductive dynamics of knowledge acquisition. Experts trade the skills based on their knowledge for access to problems providing them with new material for the inductive process. The formation of expertise is functional in general because it leads to division of labor in the management of knowledge acquisition. The development of an individual expert is a random process brought about by strong positive feedback loops in the social process, for example, that a proto-expert with superior performance is brought more problems and hence has a greater opportunity to learn and improve that performance. A diversity of such positive feedback processes operate in the professions and sciences with little relation between them except their overall effect in promoting the formation of expertise. Sociological evidence for the existence of these effects is discussed, and simulation studies showing the quantitative phenomena are described.

INTRODUCTION

Knowledge acquisition and transfer processes in human society are complex and poorly understood (Gaines 1987a). Expert systems add a new component to these processes by enhancing an expert's capability to transfer knowledge in a usable form. However, taking part of the social process of knowledge transfer and embedding it in technology makes it necessary to have a more overt understanding of what an expert is, and does. It also raises questions about the possibly changing role of the expert—what will the expert do once the expertise is captured—who is accountable for the advice given by the expert system?

This paper is the second in a series addressing the problems of developing knowledge support environments for the development, application and validation of knowledge-based systems. The first paper (Gaines 1987a) analyzes the foundations of knowledge-based systems. A distributed anticipatory system formulation of knowledge acquisition and transfer processes is presented which provides scientific foundations for knowledge engineering. This paper builds on this formulation to present a model of experts as managers of knowledge acquisition and transfer processes in particular domains, trading the transfer of their existing knowledge for the access to new problems that will enable them to acquire more. The third paper (Gaines 1987b) develops an architecture for knowledge-based systems, integrating knowledge acquisition, application and validation.

THE NATURE OF EXPERTISE

Hawkins (1983) has abstracted from experience at Schlumberger in developing mineral exploration expert systems and proposed a model of human expertise relevant to expert systems. His model is summarized in figure 1:

- The expert first elicits data about the problem from the client;
- He develops a minimal model that accounts for the data provided;
- He generates advice based on the model and feeds this back to the client;
- The client may accept the advice, or query it and, possibly, the model;
- The queries lead to further data elicitation, and repeat of the modeling/advice/query cycle.

Thus, in Hawkins' model, the client plays an active role in further developing the model by providing more data until he or she is satisfied with the model and consequent advice. Thus, expert advice giving and taking is part of a cycle of negotiation around a process of model formation.

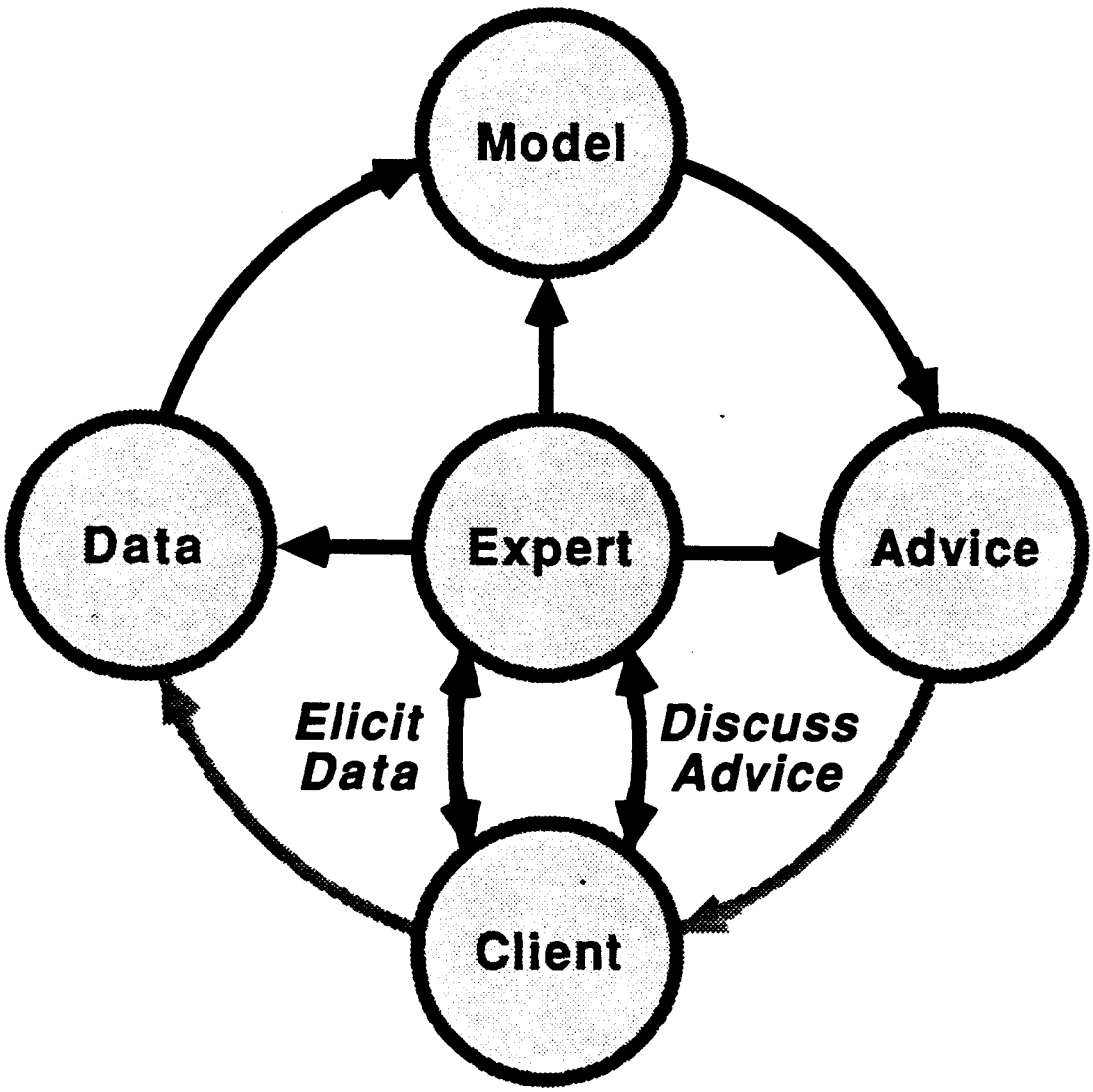


Fig.1 The negotiation cycle in expert consultation

This model of the expert-client interaction as the negotiation of a mutually acceptable model may be given formal foundations in mathematical modeling theory. Figure 2 shows a general hierarchical modeling process (Gaines 1987a) based on Klir's analysis of model formation (Klir 1985):

- At level one, *constructs* are those distinctions that the particular modeling system makes, a language for describing of the world;
- At level two, *data* are descriptions of actual case histories in terms of the constructs, an account of experiences of the world;
- At level three, *hypotheses* are the means of regenerating particular case histories from generalized accounts, rationalizations of the world (often called *models*);
- At level four, *analogies* are similarities between differently generated generalized accounts, correspondences between models;
- At level five, *abstractions* are accounts of a wide range of models, underlying foundations of analogies;
- At level six, *principles* are systemic foundations for abstraction, accounts of abstractions.

Rasmussen (1985) has noted the importance, and analyzed the roles, of such hierarchical knowledge representation in individual and organizational decision making.

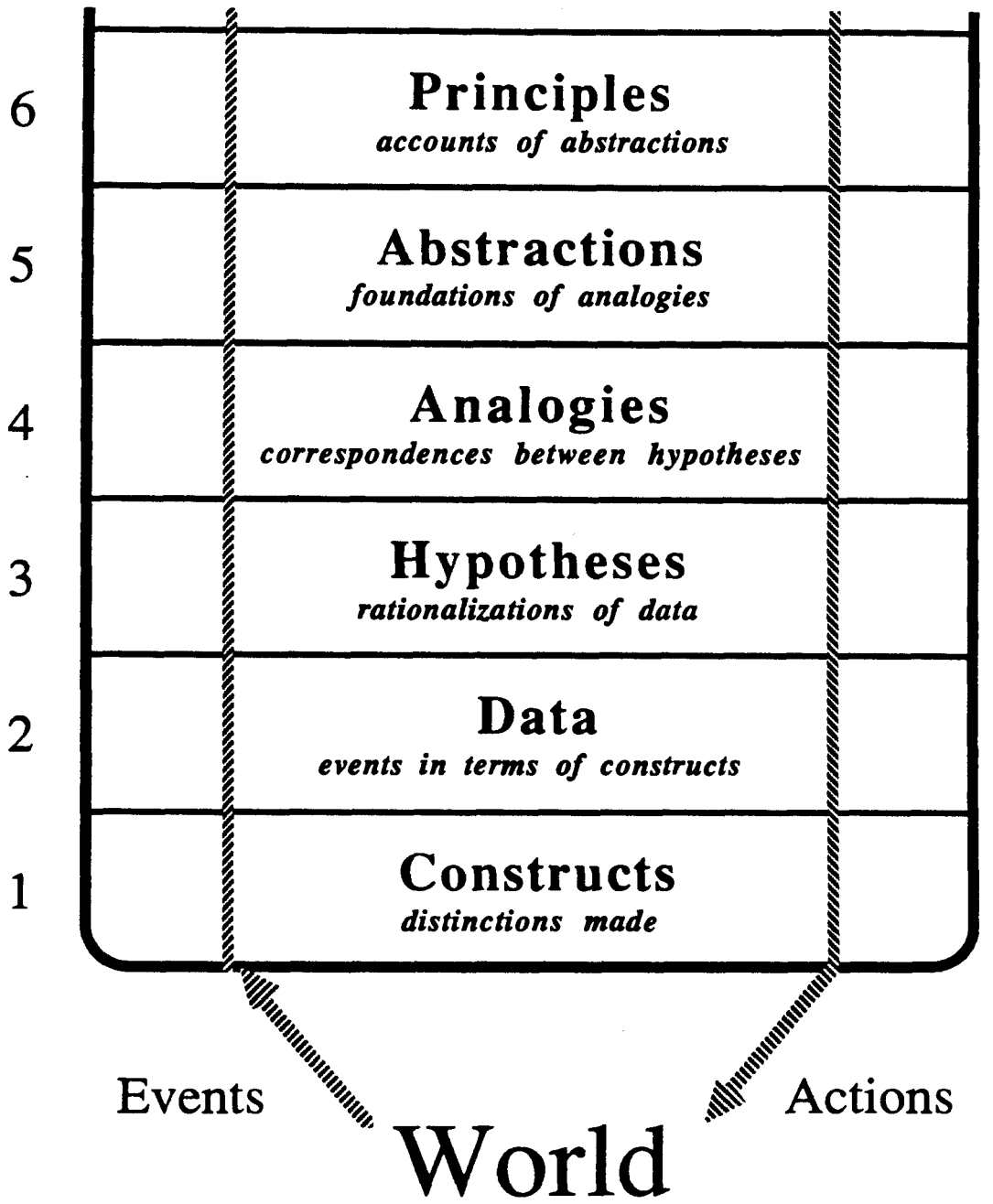


Fig.2 General hierarchical modeling process

Modeling may be evaluated by the degree to which a level accounts for the information flowing through it. This may be measured as the *surprise* at an actual event in relation to one predicted, and the expected surprise is a form of entropy (Gaines 1977). The formal theory of modeling is one in which selections are made at each level down the hierarchy to minimize the rate at which surprise is passing up the hierarchy. The criteria for 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. 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. It should be noted that the

modeling is an active process also—constructs 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. Figure 2 encompasses both the expert's model-formation and model-application processes.

Hawkins' (1983) studies exemplify the roles of each of these levels in expert behavior and in the negotiation between expert and seeker of advice. In particular, he illustrates the significance of shared constructs between expert and user, and the potential for 'data' from falsely constructed events to invalidate expertise. What the basic modeling theory does not account for, however, is these types of social interaction, the relation between experts and users, the assumptions that an expert makes about the problem situation, the relation between experts and society. Indeed, it does not account for the concept of an 'expert' except as a particularly well-validated modeling system, leaving open the question as to how one system becomes better validated than another.

The following section extends the basic modeling theory to encompass social processes and the formation of expertise.

SOCIAL PROCESSES IN THE FORMATION OF EXPERTISE

The weakness of the account of modeling given in Figure 2 is that it accounts for only a minor part of the knowledge acquisition processes of an individual. Most of our knowledge does not come from forming models of events in the world, but rather from the social transfer of others' knowledge by a variety of cultural processes, some formalized in education but many very informal. However, the account can be extended to encompass such cultural knowledge acquisition if one notes that human civilization as a whole is representable as a general modeling system having no sources of knowledge other than its combined, cumulative experience of the world (Gaines 1987a).

The modeling schema of Figure 2 applies as much to groups of people, companies and societies as it does to the roles of a person. The modeling processes of an individual may be viewed as a cross-section of those of the civilization of which they are part. The modeling processes of society may be viewed as carried out by a distributed system of sub-processes in individuals. Cultural processes of knowledge transfer are then just various modes of communication between such sub-processes. The distributed system analogy nicely accounts for a variety of psychological and social phenomena: one person may assume many psychological roles (process switching), whereas a group of people working together may act as a single modeling entity and hence behave as one process (distributed processing).

These concepts may be formalized by considering the inductive inference process underlying knowledge acquisition. 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. 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 formal justice as induction from informal moral behavior terms this a *reflective equilibrium.*

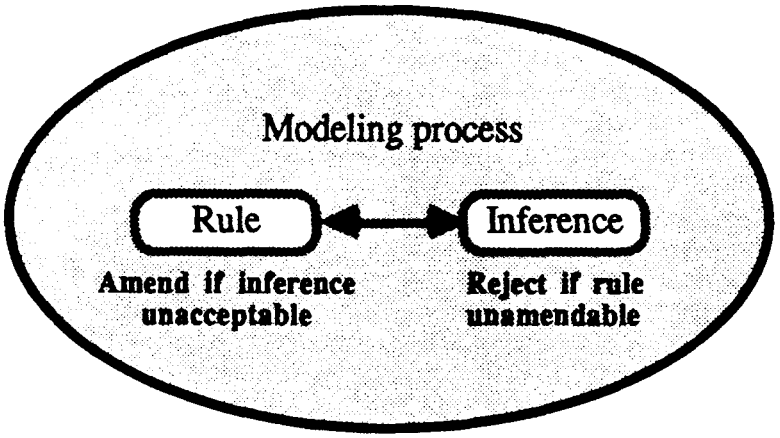


Fig.3 Reflective equilibrium in inductive inference

Stich and Nisbett (1984) noted flaws in Goodman's argument in that individuals do not necessarily behave rationally in their own behavior relative to known good practice. They 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 gives an operational definition of the role of experts within an overall knowledge acquisition system as referential sub-systems managing a domain of the knowledge acquisition process. It also leads to an concept of the role of expert systems in society, as making the referential process more overt and widely available. It is noteworthy that professional development books concerned with good practice emphasize the importance of balancing experts' authoritarian roles as referential sub-systems with their entrepreneurial roles as knowledge acquirers (Schön 1983).

The hierarchical model of Figure 2 can also be used to give a theoretical framework for the socio-cultural transmission of knowledge. The left hand side of Figure 4 shows the feedback loops between events and actions at each level of the hierarchy:

- At level one, *reflexive* feedback links the activation of a construct directly to a primitive act, another construct;
- At level two, *rule-based* feedback links constellations of experience to complete action sequences through rules derived from similar experience;
- At level three, *computational* feedback uses a generative model of experience to compute an optimal action sequence;
- At level four, *comparative* feedback compares a variety of alternative models in order to one appropriate to the required goals;
- At level five, *abstract* feedback uses generalized models as templets from which to instantiate one appropriate to the required goals;
- At level six, *transcendental* feedback takes the entire process described, recognizes that it is based on distinctions being made at various level, and attempts to rationalize these distinctions and create new ones.

The acquisition of knowledge by direct inductive inference, learning a task by attempting it, is the only course open to the species as a whole. However, it would be inefficient for individuals to acquire more than a small part of their knowledge in this way, and the right hand side of Figure 4 shows the cultural mechanisms through which individuals acquire knowledge at each level:

- At level one, mimicry through watching expert's perform the task is the main mechanism for transmitting reflexive knowledge.
- At level two, reinforcement through working under expert supervision is the main mechanism for transmitting rule-based knowledge.
- At level three, rational explanation by reading books and interviewing experts is the main mechanism for transmitting computational knowledge;

- At level four, analogical models used to derive knowledge from similar situations form the main mechanism for transmitting comparative knowledge;
- At level five, basic laws used to derive specific models are the main mechanism for transmitting abstract knowledge;
- At level six, systemic principles used to derive specific laws are the main mechanism for transmitting transcendental knowledge.

This plethora of mechanisms for knowledge transmission is further complicated by the possibilities of *managing* the learning situation, for example, one person may route another to a good role model, supervisor, explainer, similar task, or underlying law or principle.

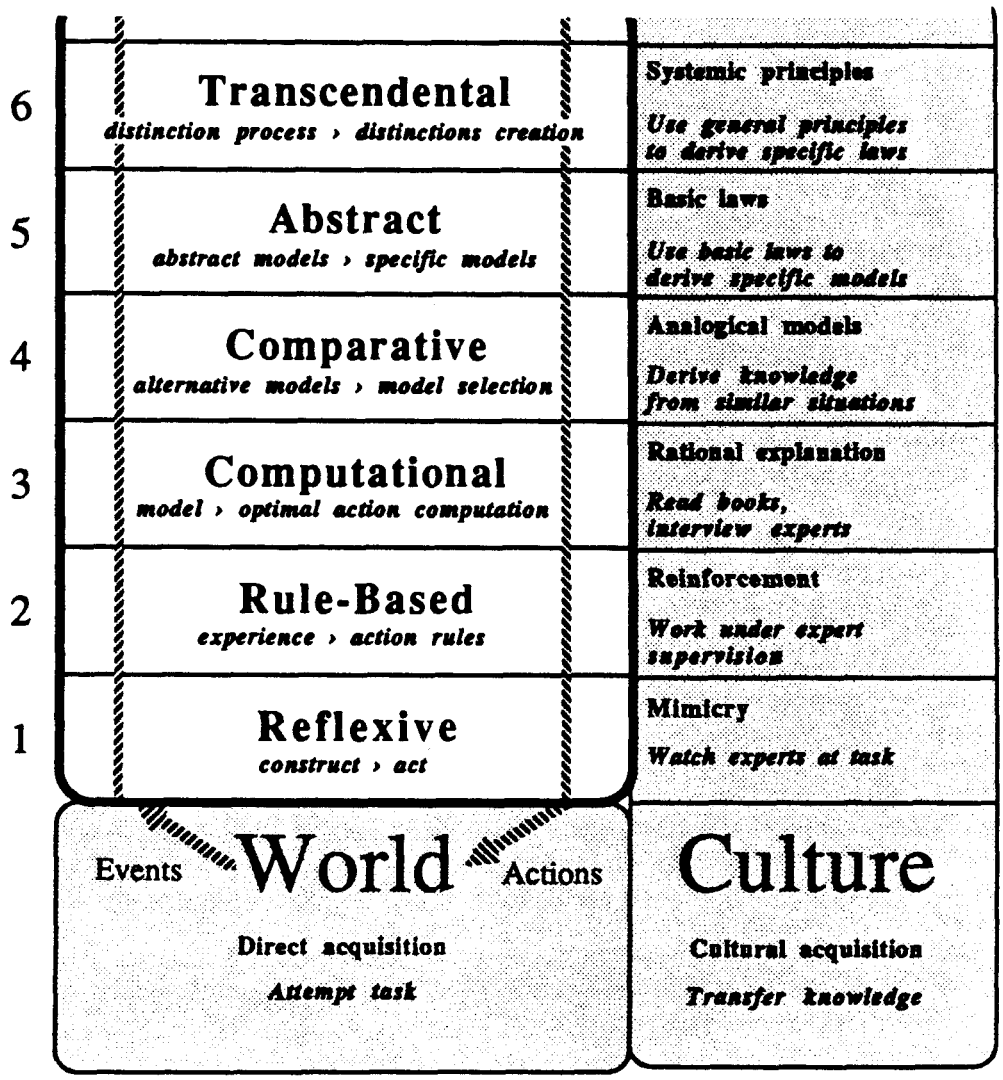


Fig.4 Hierarchy of knowledge representation and acquisition processes

Thus the pragmatic model of expertise developed by Hawkins can be brought into the formal framework of modeling theory by taking society to be a distributed modeling system in which experts are those with responsibility for managing the inductive process in particular domains. However, even this extension does not specifically account for the formation of expertise—how does a particular individual become an expert. The following section shows that positive feedback processes in the management of the various levels of knowledge transmission driven by random processes in society is adequate to account for expertise formation.

EXPERTISE FORMATION BY POSITIVE FEEDBACK PROCESSES

An expert in Stich and Nisbett's account is a modeling system that has particular authority to decide on changes when events violate rules—in terms of Figure 2, are new constructs needed, should the data be rejected, should the hypothesis be changed, and so on. However, this authority is a social construct, not usually one of right in present society, and the ascription of such authority to an individual is part of the larger modeling system's processes in determining which of its sub-processes is effective. Now, to become effective in modeling is, from Figure 4, dependent on many factors: having access to knowledge at the upper levels such as principles, abstractions, analogies and classes of hypothesis; having access to knowledge at the lower level such as adequate construct systems and relevant data from case histories. Such access is itself a social resource, not generally available to all, and there are social mechanisms for allocating such access to individuals. It is the interaction between the criteria for access and the acquisition of knowledge that leads to the formation of expertise.

Sociologists have noted the very strong positive feedback processes in the dynamics of the scientific community (Hagstrom 1965). Merton (1973) coined the term the "Matthew effect" for those features of the reward system in research that were biased towards allocating greater credit for the same discovery to those with an already established reputation. The qualitative effect of such positive feedback processes is to amplify random differences within a population, creating strong distinctions which have no other basis than the feedback process itself. That is, even if all scientists were created equal in their capabilities, some would become experts relative to others because random differences in early performance generated credit that affected resource allocation and gave them greater opportunities to acquire knowledge.

In many areas of expertise where expert systems are expected to play a major role these positive feedback processes are exceptionally strong. In medicine, for example, the key learning resource is access to medical problems, and the 'owner' of such a problem has a keen personal interest in only allowing someone of very good reputation to handle it. The system, including considerations of legal liability, strongly funnels problems to those who are regarded as experts. It is, however, precisely these problems from which new knowledge is generated. Hence the data at level two in Figure 2 is made available primarily to those with already established reputations for having capabilities at level three and above to deal with it. Similar considerations apply to the award of scholarships, invitations to scientific congresses, and so on (Blume 1974). There are many positive feedback loops that seek out expertise and seek to develop it. However, they are also adequate in their own right to create it.

Simple simulation experiments are adequate to show the strength of these phenomena. Figure 5 shows the structure of a simulation in which a user community is represented as an *expert selection automaton* which determines which of two experts, represented by *expert automata*, it will use in the solution of a succession of problems. The rules are: equal learning capability for each expert; a finite number of items of knowledge; each problem requires certain knowledge; if the expert does not have the knowledge necessary it guesses with a probability of success, learning if it succeeds; the community choses the expert for a problem with equal probability initially, gradually biasing the choice according to success or failure; there is no communication of knowledge between experts.

Figure 6 plots: the probability that one expert will be always preferred and shows that this rapidly approaches 1.0—a best expert is determined; the expected knowledge of the better expert and that of the rival—one goes to 100% rapidly and the other is asymptotic to about 36%—there is objective evidence of the superior ability of the chosen expert. Which of the two individuals becomes the 'best expert' is, of course, completely chance.

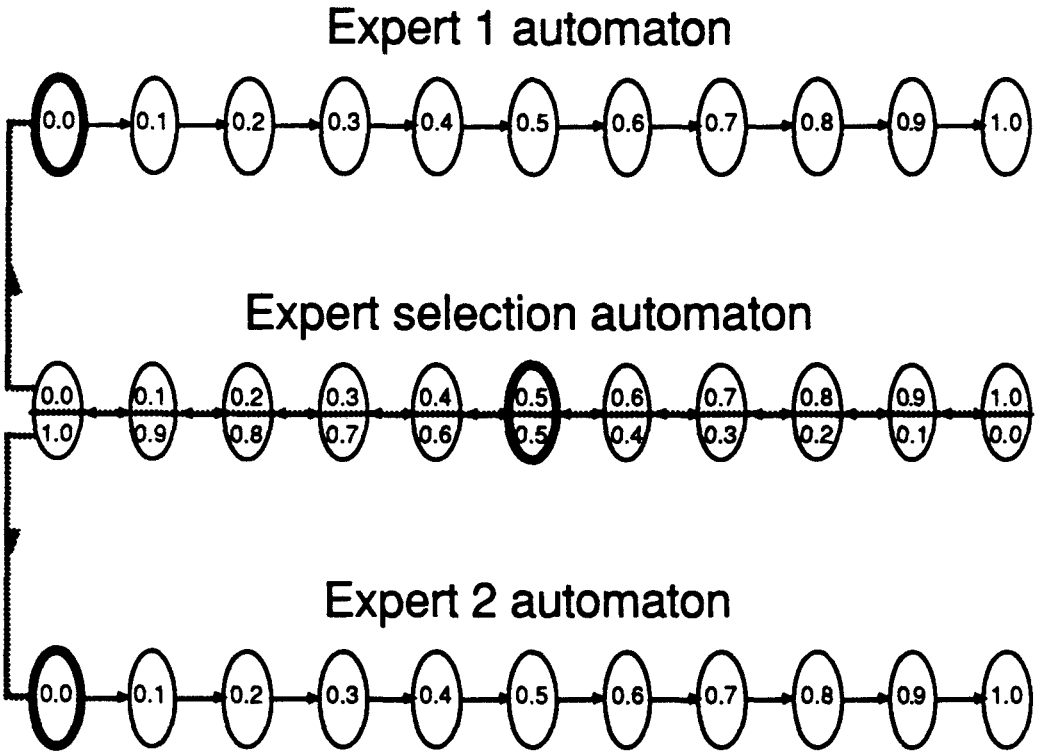
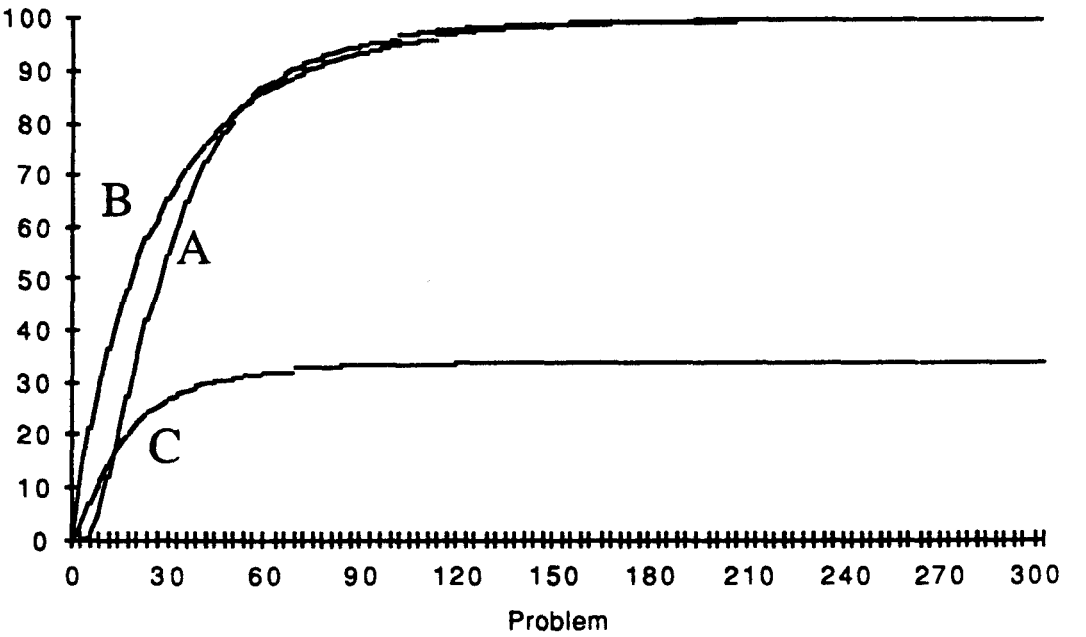


Fig.5 Automata simulating expert selection processes



A: Percentage probability that problem will be given to only one of the two 'experts'
B: Expected knowledge of superior 'expert'
C: Expected knowledge of inferior 'expert'

Fig.6 The effects of positive feedback on the formation of expertise

The simulation can easily be adjusted to take into account differences between the experts: that one starts with greater knowledge; that one learns faster; that one is favored initially (the prima facie credibility or 'well-dressed consultant' phenomenon). Similar simulations have been made of different positive feedback mechanisms, for example, if both experts are given the same problem but the problem difficulty is adjusted upwards if either gets it right—the situation of keeping up in the scientific 'rat race.' Effects have been introduced of the loss of knowledge through inadequate opportunities for its application, the growth of scientific knowledge so that there is always more to be acquired, and differential access to cultural knowledge transfer. All the simulations bear out the expected qualitative result, that a variety of different positive feedback mechanisms in society are adequate to account for differential expertise in a sample with initially equal knowledge and capabilities.

These results are not intended to suggest that individual differences are insignificant, or be a basis for egalitarian ethics. They do demonstrate, however, that the process of expertise formation is a natural systemic phenomenon in a learning society. It is functional because it distributes the processors available to different tasks through global mechanisms with no localized control. The random mechanism is efficient because it does not matter to the overall system which processors are allocated to particular tasks, and it will tend to pick out individual differences in capabilities if they exist. It puts experts into the role of traders who must offer their services to solve problems in order to gain access to those problems in order to increase their knowledge.

In practice, the professional and scientific communities also have strong mechanisms set up to reduce the effects of positive feedback in exaggerating differences, such as the ethical pressure to disseminate knowledge as widely as possible, and mechanisms for doing this through publications and seminars (Whitley 1984). However, much knowledge underlying skilled performance cannot be shared in this way (Nisbett & Wilson 1977) and the positive feedback mechanisms will always exert a strong effect.

SOME PRACTICAL CONSEQUENCES

The popular stereotype of an expert is a fount of knowledge in some domain. If that fount can be captured in an expert system then the role of the person who previously embodied is called into account. Those outside the expert systems industry often ask the question, "why should experts put themselves out of their jobs by allowing their knowledge to be transferred to an expert system." The reply is usually that experts complain about the number of phone calls they have to answer to give advice on trivial problems. They would prefer to have the time to read journals, attend professional meetings, and think more about what they are doing. The model of expertise put forward in this paper gives theoretical foundations for this informal empirical result. The expert is not a static fount of knowledge but a dynamic process for continuously maintaining that fount by managing the acquisition of new knowledge.

The model of the expert's relation to those seeking advice as one of trading it for access to problem-solving, and hence learning, opportunities is also consistent with the actual behavior patterns of experts in relation to expert systems. Divesting the unprofitable trading to focus on the profitable is a sensible strategy, that is, passing to an expert system those standard problems where little learning opportunity is expected. However, the uncertainties about the classification of any problem situation suggest there may be dangers in this approach which could be avoided by adequate design and application of expert systems. The advice giving system should contain rules which indicate problem-solving situations that are beyond the boundaries of its capabilities and refer these to a human expert (in the same way that human experts refer difficult problems to others). It should log actual case histories of advice giving for later review by human experts so that these rules can be validated. It should make provision for feedback as to the results of advice so that learning opportunities are not lost.

The continuity between the modeling role adopted by the expert in Hawkin's model of expert-client negotiation in Figure 1, and the expert's wider modeling role in managing Goodman's reflective equilibrium in Figure 3, suggests that the performance and knowledge acquisition phases of expert systems should not be separated as they are currently. It would be better to think in terms of *knowledge support systems* that integrate knowledge acquisition and advisory roles (Gaines & Shaw 1987). In particular, the model of system-user relations as mutual negotiation rather than authoritarian advice giving is a good model for expert system.

All these considerations are also relevant to questions about the accountability of expert, expert system, and user for the advice. However, that is a side-effect of the social pressures on the inductive process—accountability, and the resultant rewards and punishments, are cultural mechanisms to encourage learning and the appropriate use of expertise. Well designed expert systems will make provision for the clear presentation of the quality of advice, reference to human experts, audit trails, logging, and case history review, because these are necessary to an effective technology—the possible legal consequences of not doing this are just a reminder of what is an effective technology in the domain of knowledge acquisition and transfer.

CONCLUSIONS

The role of the expert in the knowledge processes of society has been analyzed and shown to be that of managing the inductive dynamics of knowledge acquisition. Experts trade the skills based on their knowledge for access to problems providing them with new material for the inductive process. The formation of expertise is functional in general because it leads to division of labor in the management of knowledge acquisition. The development of an individual expert is a random process brought about by strong positive feedback loops in the social process, for example, that a proto-expert with superior performance is brought more problems and hence has a greater opportunity to learn and improve that performance. A diversity of such positive feedback processes operate in the professions and sciences with little relation between them except their overall effect in promoting the formation of expertise. Sociological evidence for the existence of these effects has discussed, and simulation studies showing the quantitative phenomena described.

This model of the nature of expertise provides foundations for knowledge acquisition and transfer processes in expert systems and associated knowledge acquisition tools. It also places expert systems technology within a social context and provides a basis on which social and legal aspects of their use and its implications may be analyzed.

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