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A COGNITIVE SCIENCE ANALYSIS OF EXPERT SYSTEMS AND SIMULATION

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This paper presents a cognitive science framework for the development of knowledge-based systems combining expert systems and simulation. It commences with the construct of a *communal scientist* as a model of a social organization driven by anticipation and then differentiates this into *personal scientists* with diverse relations to people and their internal and external communication. This provides a powerful and general model of society, people, and the roles of people in society. This model extends naturally to the role of conventional media in the knowledge processes of society and the new roles of knowledge-based computing including simulation and expert systems. In particular this framework provides a model of knowledge transfer that enables the processes of knowledge engineering to be automated.

1 INTRODUCTION

Knowledge engineering may be defined as the acquisition, elicitation, structuring and encoding of knowledge for application in inferential, goal-directed, explanatory, decision and action support systems. The term has arisen in the industries concerned with the development of computer-based expert systems. However, the problems of knowledge engineering are not peculiar to computer technology. Most of them have their roots in the systemic principles underlying the dynamics of knowledge processes, and have long been studied in philosophy, psychology, sociology and system theory [4].

The term knowledge engineering has arisen in the context of expert systems developments where one is attempting to solve problems that are not amenable to conventional systems analysis by modeling the human controller or decision-maker rather than the system with which he interacts [8]. However, the concept of knowledge engineering is far more widely applicable. In simulation studies it is usually the deep physical knowledge of the system to be simulated which is significant. Expressing the principles involved, validating their applicability, manipulating them in mathematical form, operationalizing them as computer algorithms—these also are knowledge engineering. In recent years the need to develop systems that combine the *deep* knowledge of simulation with the *how-to-do* knowledge of expert systems has become of increasing importance. We need a framework for knowledge engineering that encompasses both these forms of knowledge, and also covers other forms of knowledge that are neither principles nor rules.

This paper presents a cognitive science framework for the analysis of knowledge-based systems including people, media, simulation and expert systems, and resulting in a practical model for the procedures of knowledge engineering.

2 COGNITIVE SCIENCE FOUNDATIONS

Personal construct psychology [14] provides foundations for cognitive science based on a conventionalist epistemological approach that has deep systemic foundations and is applicable to any anticipatory system [6,18]. This includes social systems and technological systems as well as the individual person. It is a psychology of the individual and many of its applications emphasize the idiosynchratic nature of construction systems. However, personal construct psychology is also a psychology of the individual interacting with the world and embedded in society [24]. It encompasses shared constructs and construction systems, and their generation through experience of the life world. In particular it encompasses those construction systems that are so widely shared and so significant that they are construed as *knowledge*, and treated as having an existence virtually independent of their carriers.

In particular, the early practitioners of knowledge engineering have come to realize that many problems are arising through lack of an adequate conception of the nature of *expertise* [13]. In recent years, with the breakdown of many social structures, interest has increased among sociologists and philosophers in the phenomena of expertise, authority, professions and disciplines [12]. Stich and Nisbett [27] argue for the essential role of expertise and authority in resolving the philosophical problem of justifying predictive modeling despite Hume's criticism that such justification is impossible. They accept Goodman's [10] counter-argument that the justification of both deduction and induction is essentially valid but circular, but argue that the *reflective equilibrium* between rules and inferential practice is essentially socially based and involves the authority of experts.

There are as yet inadequate links between the psychology of the inquiring individual and the social dynamics of knowledge creation. It is these links which would provide the foundations of a science of knowledge engineering.

Epistemological Hierarchy of Communal Scientist

I have previously termed the personal construct model of an individual a *personal scientist* [23] to emphasize that the basic human drive is modeling, hypothesis formation and testing, in order to anticipate the future. However, this is also the drive of human society as a survival-driven system, and one may take the underlying system to be a *communal scientist* as show in Figure 1, interacting with the world, experiencing events, generating actions, and modeling the interaction so as to better anticipate future events.

Mathematical modeling theory provides general theories of the operation and structure of anticipatory systems [4]. Figure 1 shows Klir's [15] *epistemological hierarchy*, a general modeling structure based on successive levels of distinctions:-

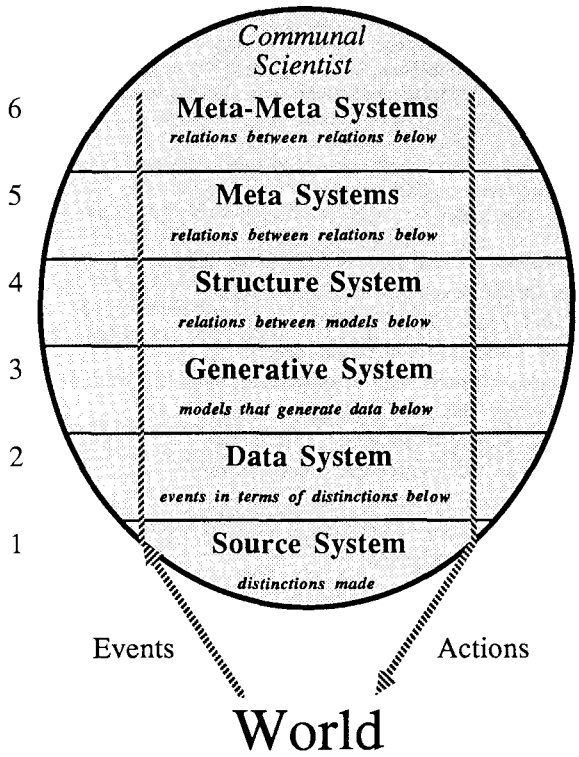

Fig.1 Modeling hierarchy of a communal scientist interacting with the world

- 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—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.

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 [21] 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 [25]. An individual is defined in cognitive terms as a psychological process [22] 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).

Figure 2 shows three personal scientists differentiated within the communal scientist, and also replaces the abstract vocabulary of Figure 1 in a cognitive science context by giving psychological terms to the levels in the hierarchy. Figure 3 shows how the personal scientists may be regarded as *roles* within people, and communal scientists as *groups* coordinating personal scientists in several people. Person A has two personal scientists in internal communication, and Person B has two not in internal communication. Personal scientist 2 of Person A is in communication with 3 of Person B. As an effective anticipatory system, the dynamics of the communal scientist shown will be such that the construct systems of the four personal scientists shown come to give increasingly improved anticipation of events in the world. As this happens it is probable that they will become functionally differentiated, even to the extent of the *fragmentation corollary*, that they become "inferentially incompatible" [14].

It is this fragmentation that leads to the constructs of expertise and authority. One personal scientist is more *expert* than another in a given situation if it is better able to anticipate future events in that situation. The coordination mechanism that is effective for the overall communal scientist may then be construed as giving the expert the *authority* to act in that situation.

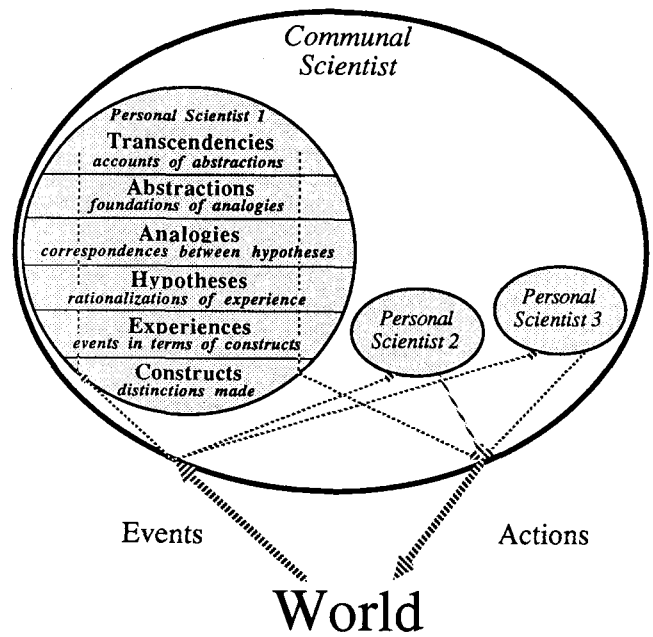

Fig.2 Differentiated personal scientists in a communal scientist interacting with the world

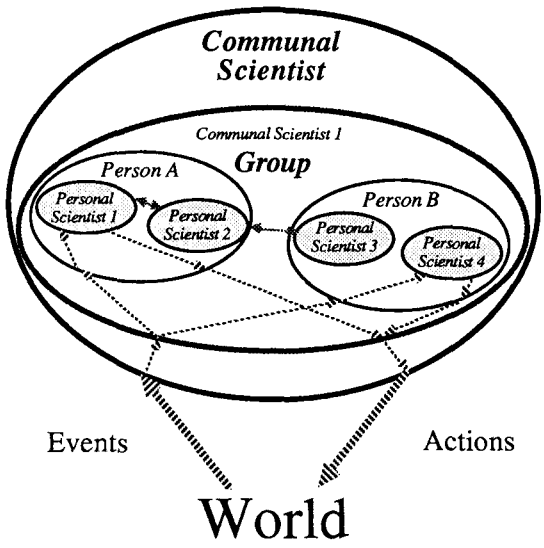

Fig.3 People, roles and groups in a communal scientist

3 REPRESENTATIONAL MEDIA & SIMULATION

Figure 4 shows Person A interacting with the world through a representational medium such as radio or television. The interaction contrasts with that of Person B interacting directly with the world in that it is only *one-way* rather than two-way [7]. Person A can perceive the world through the medium but not influence it. Representational storage media such as film or videotape being used by Person C give similar access that transends time in allowing past events to be experienced but is still one-way. Note how Person C has no necessary interaction with the world—indeed the medium may become the world as far as he is concerned.

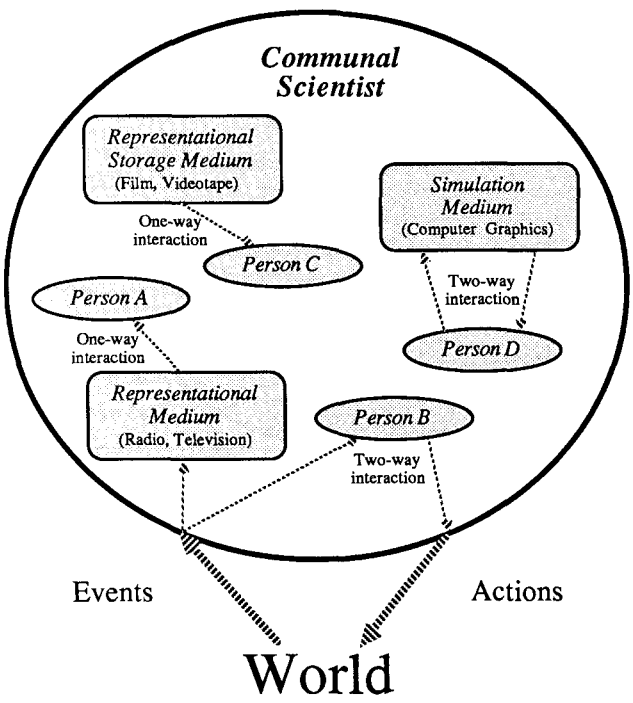

Fig.4 Representational media in a communal scientist

The simulation media based on computer graphics being used by Person D allow two-way access to a simulated world, and as they become more realistic can increasingly replace direct experience [8]. Person D also has no necessary interaction with the real world. The simulated world may be a substitute for such interaction, perhaps a safe training environment as in flight simulation, or perhaps a fantasy replacement as in video games. Computer graphic media in knowledge-based systems can give access to experience in worlds of simulated reality that may, or may not, model real world events.

4 SYMBOLIC MEDIA AND EXPERTISE

The role of symbolic media may also be modeled within a communal scientist and relates with that of experts and their activities in establishing reflective equilibria. Person C in Figure 5 is carrying out a task with help from an expert advisor, Person B who has no other interaction with the task. Person A is carrying out the task with broadcast advice from Person B, that is with expertise mediated through a symbolic medium. However, as with representational media, the mediated communication is one-way whereas the direct communication is two-way [7].

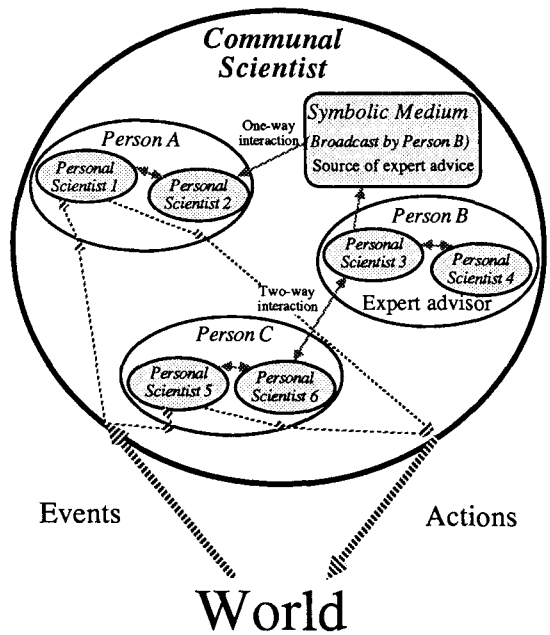

Fig.5 Symbolic media in a communal scientist

Some of the problems of knowledge engineering, of transferring knowledge from experts to expert systems, are also apparent in Figure 5. Personal scientist 4 is the process with the required skill in Person B and has to communicate through 3, an external language process, but sometimes this link may be unavailable [1]. Similarly personal scientist 5 requires the skill in Person C and has to be able to communicate internally with a language process, 6, which itself has to be able to communicate externally with 3; lack of effective communication on either link will prevent knowledge transfer.

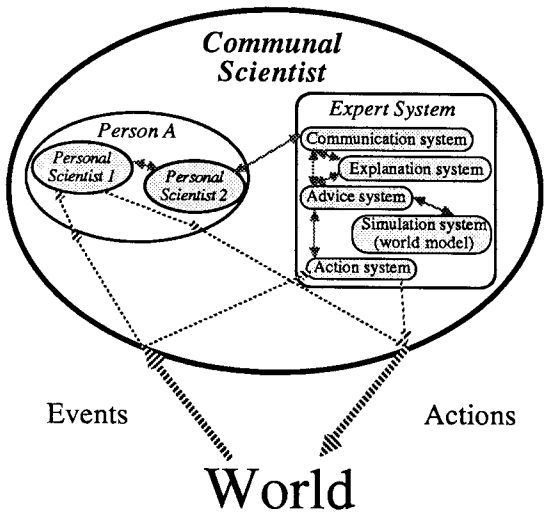

Fig.6 Structure of an expert system within a communal scientist

Combining Expert Systems and Simulation

A symbolic storage medium, such as a book or paper, may replace Person B in Figure 5 to provide advice that is available even when Person B is not. However, the interaction is now essentially one-way. An expert system is a *two-way* symbolic storage medium that encodes the psychological processes of Person B to make his advice available interactively as shown in Figure 6. The expert system has an internal structure of processes that mimic those of its source, Person B:–

- The *advice system* is that satisfying the common stereotype of an expert system in that it uses a *knowledge base* and *inference system* to provide expert advice.
- The associated *communication system* is of critical importance in giving access to the advice. Its role is somewhat neglected in the secondary expert system literature but the primary literature on successful developments emphasizes the effort required to establish effective communications, e.g. TEIRESIAS [3].
- The *explanation system* is one of the most important developments in computing technology and its availability distinguishes some of the pseudo expert systems now being marketed from true ones. The concept of explanation in itself presents philosophical difficulties [16] as advice may be explained at many different levels in many different terms. The basic mechanism in current expert systems is to backtrack through the processes of inference used in generating the advice and present the user with the knowledge used at each stage.
- The *simulation system* shown is absent in many of the current generation of expert systems. They are based on mimicking the behavior of an expert and lack the deep knowledge of the underlying processes on which that behavior is based. Advice from such systems can become obsolete if the world changes in unanticipated ways, for example, if a new drug becomes available in a medical treatment context. A major development in expert systems is to integrate models of the world that may be used to simulate the effects of actions on the world [8].
- The *action system* shown is also uncommon currently since the expert systems are being used as advisors rather than active participants. However, it is a logical extension of the technology and consistent with previous applications of computer-based systems in control and automation.

5 KNOWLEDGE ENGINEERING

All the sub-systems in Figure 6 have equivalent roles within a person and our knowledge of the psychology of the person is applicable to the understanding and development of the computer-based processes within expert systems. The communal scientist model provides the foundations for understanding society as an anticipatory process. It also provides the foundations for a technology of knowledge-based systems. For example knowledge transfer processes underlying the development of expert systems can be represented in the inductive system hierarchy of Figure 1. Figure 7 shows the feedback processes at different levels of this hierarchy to provide a model for knowledge acquisition in both people and expert systems. The levels have been labeled in terms of Hall's [11] forms of cultural transmission, and the right hand side indicates the way in which knowledge is transfered at each level. Without cultural transmission the only way a task can be learnt is by primitive inductive acquisition based on attempted performance, a slow and uncertain process.

The first level of cultural transmission is the *informal* where knowledge is acquired by mimicry; the second is *formal* where knowledge is acquired by the reinforcement of reward and punishment; the third level is *technical* where knowledge is acquired from its overt expression as rational explanation often in symbolic media; the fourth is *comparative* where knowledge is acquired by analogies with related worlds; the fifth is *abstract* where knowledge is acquired by using the fundamental laws underlying expertise; and the fifth is *transcendental* where knowledge is acquired from the general principles underlying it.

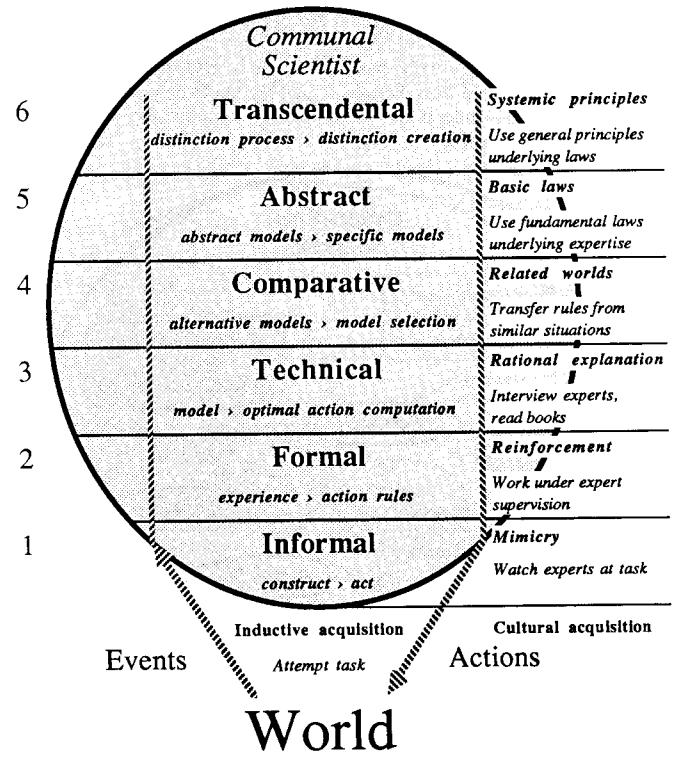

Fig.7 Sources in the cultural transmission hierarchy of a communal scientist with applications to knowledge engineering for expert systems

Figure 8 puts this hierarchy into terms recognizable in computer science and exemplifies it with systems that have already been programmed for various forms of knowledge processing and acquisition. The lower oval shows an expert system architecture based on a knowledge base of facts and rules. This is used by an inference system to derive the consequences of facts about a particular situation. This in turn is used by a planning system to achieve specified objectives, one of which may be the provision of explanations. The upper oval shows the knowledge transfer processes that may be used to establish the knowledge base following the hierarchy of Figure 7:–

- The *knowledge generation system* implements knowledge acquisition by the raw induction of models from experience without cultural support as exemplified by ATOM [4] and AM [3].
- The *expertise modeling system* implements knowledge acquisition by mimicking an expert's behavior as exemplified by INDUCE [19].
- The *performance reinforcement system* implements knowledge acquisition from performance feedback as exemplified by STeLLA [5].
- The *knowledge elicitation system* implements knowledge acquisition by interviewing experts as exemplified by PLANET [26] and ETS [2].
- The *knowledge structuring system* implements knowledge acquisition by analogy as exemplified by TEIRESIAS [3] and CYC [17].
- The *basic laws system* implements knowledge acquisition by building physical models as exemplified by simulation languages such as SIMULA [20].
- The *systemic principles system* implements knowledge acquisition by derivation from abstract principles as exemplified by the category-theoretic language OBJ [9].

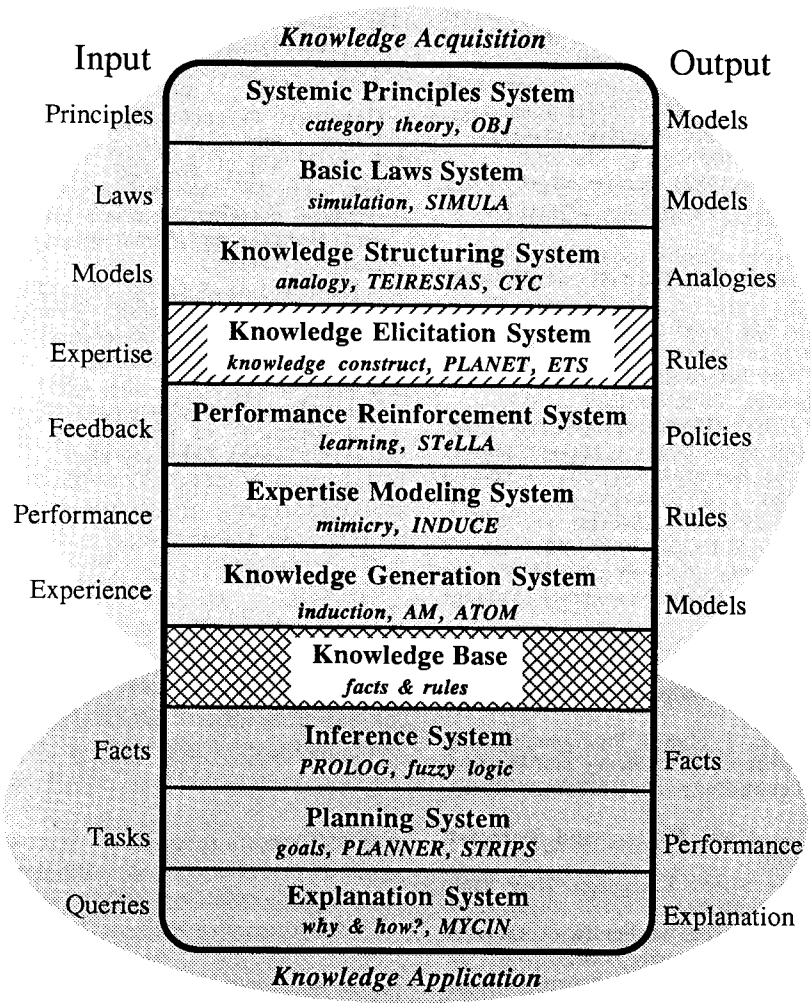

Fig.8 The knowledge engineering hierarchy

6 CONCLUSIONS

This paper has presented a cognitive science framework for the analysis of knowledge-based systems including people, media, simulation and expert systems, and resulting in a practical model for the procedures of knowledge engineering. Commencing with the construct of a *communal scientist* as a model of a social organization driven by anticipation and then differentiating this into *personal scientists* with diverse relations to people and their internal and external communication provides a powerful and general model of society, people, and the roles of people in society. This model extends naturally to the role of conventional media in the knowledge processes of society and the new roles of computer-based simulation and expert systems. In particular it provides a model of knowledge transfer that enables the processes of knowledge engineering to be analyzed and automated.

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