A framework for knowledge-based systems unifying expert systems and simulation

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ABSTRACT

We are moving into era of complex information systems, **knowledge-based computing,** in which techniques of human-computer interaction, simulation and expert systems will be integrated using low-cost vlsi, novel machine architectures and advanced software engineering. This paper presents a cognitive science framework for the development of knowledge-based systems. 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 combining simulation and expert systems.

INTRODUCTION

At the 1985 meeting we contrasted simulation and expert systems (ESs) as computer-based technologies for the support of human knowledge processes (Gaines & Shaw 1985). An overview was given of ES developments emphasizing that an ES is not just a static encoding of expertise but rather a dynamic process promoting the acquisition of knowledge. Applications of ESs to industrial control problems were discussed where the links to classical control and simulation could be most readily seen. Simulation and ESs were shown to be complementary technologies in supporting decision and action. They are distinguished in that simulation provides access to simulated experience of the world, while expert systems provide access to knowledgeable discussion about the world.

In March, two months after that meeting, the Japanese announced their sixth-generation computing development program based on the development of **knowledge science** (STA 1985). This program was funded with US$32 million by MITI in June 1985 and will commence mid-1986. The program defines **knowledge science** as:

> "science and technology for clarifying advanced intelligent functions of human beings, i.e. recognition, learning, inference, etc., while developing these functions technically for the construction of various systems." (STA 1985)

The foundations of the research programs come from five scientific areas: physiology, psychology, linguistics, logic and computer science. Simulation plays a major role in making the theories operational, for example, in providing:

> "a model of the information processing function of the brain...a reasonable facsimile of the human cognitive process...modified through the investigation using computer simulation and a mathematical method." (STA 1985)

It is particularly interesting to note the self-reflective nature of the sixth generation program. Human civilization has reached a stage of development where we need to understand human knowledge processes to develop the next state of information technology. However, those knowledge processes are themselves now critically dependent on that same information technology (Wojciechowski 1983). We are involved in a bootstrap operation at the highest level of our intellectual development, generating sixth generation systems based on our understanding of human intelligence but needing such advanced systems also to generate and extend that understanding.

This paper provides a framework encompassing this bootstrap process. It reports advances in the theoretical foundations of the cognitive science underlying the role of simulation and expert systems that were briefly sketched in the final section of last year's paper.

COGNITIVE SCIENCE FOUNDATIONS

Personal construct psychology (PCP, Kelly 1955) provides foundations for cognitive science based on a conventionalist epistemological approach that has deep systemic foundations and is applicable to any anticipatory system (Gaines & Shaw 1981, Mancuso & Adams-Webber 1982). This includes social systems and technological systems as well as the individual person. PCP is a psychology of the individual and many of its applications emphasize the idiosynchratic nature of construction systems. However, PCP is also a psychology of the individual interacting with the world and embedded in society (Shaw 1985). 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.

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 ESs. 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 (Gaines 1977).

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** (Hawkins 1983). 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 (Haskell 1984). Stich and Nisbett (1984) 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 (1973) 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.

Personal and Communal Science

PCP can provide foundations for knowledge science based on a social model. Kelly's (1955) focus was the individual as he was concerned primarily with clinical psychology. However, through his emphasis on the systemic principles underlying anticipation, the psychology he develops is applicable to organizations of individuals acting together as anticipatory systems. PCP provides foundations for social dynamics just as much as it does for individual dynamics. I have previously termed the PCP model of an individual a **personal scientist** (Shaw 1980) 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.

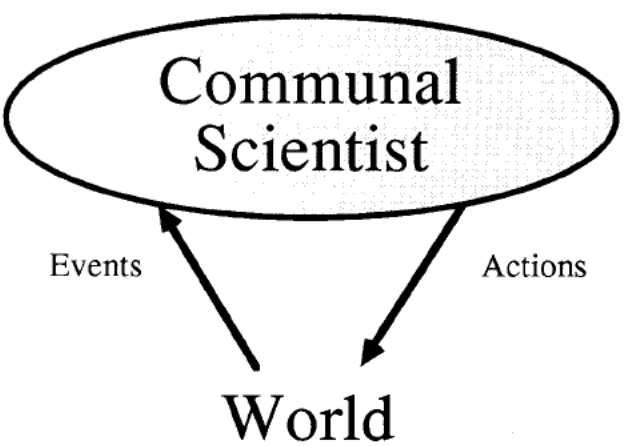

Fig.1 Communal scientist interacting with world

Epistemological Hierarchy of Communal Scientist

Mathematical modeling theory provides general theories of the operation and structure of the types of anticipatory system shown in Figure 1. Klir (1976) has developed a general modeling structure showing the way in which successive levels of distinctions form an **epistemological hierarchy** as shown in Figure 2, and Gaines (1977) has shown this forms the basis for general knowledge acquisition algorithms.

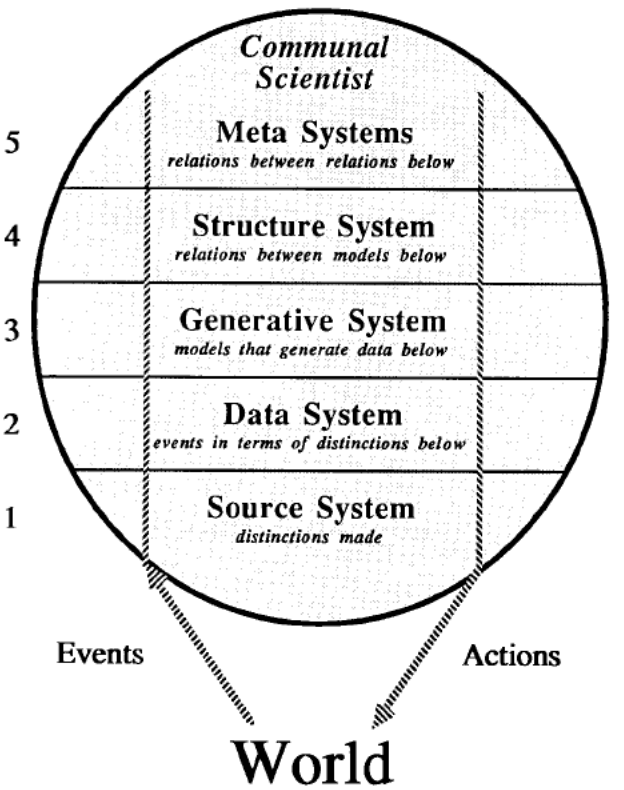

Fig.2 Epistemological hierarchy of system modeling world

In his **conversation theory** Pask (1980) provides foundations for both psychology and sociology by distinguishing knowledge processes from the knowledge processors that carry them out. He terms a set of coherent processes a **P-Individual** (Psychological Individual) and a processor an **M-Individual** (Mechanical Individual). The one-to-one correspondence between P-Individuals and M-Individuals assumed when we confound the person as a psychological entity with the person as a physical entity is very rare. A person as a physical entity may assume many psychological roles and hence support many P-Individuals. A group of people working together as a team may act as a single goal-seeking entity and hence behave as one P-Individual.

In previous papers we have shown that Pask's P-Individuals may be regarded as crosssections of the epistemological hierarchy of Figure 2 and have given examples of people in different roles with disjoint and overlapping construct systems, and groups of people forming a coherent entity, such as a company product executive, distinguished by

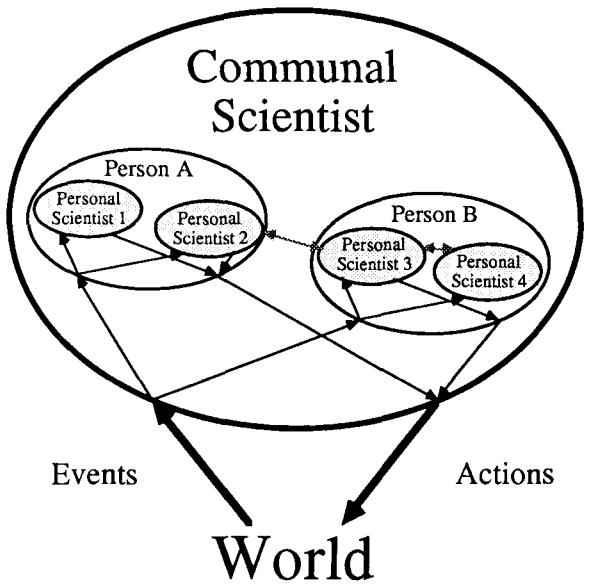

Fig.3 People in communal scientist interacting with world

its compound construct system (Shaw & Gaines 1981, Shaw 1985). Figure 3 shows how a communal scientist may become differentiated into a number of personal scientists (PSs) each interacting with the world and one another. M-Individuals are shown as "persons" grouping together the PSs that are personal roles.

Person A has two PSs not in internal communication and Person B has two PSs with internal communication. PS2 of Person A is in communication with PS3 of Person B. All the PSs are experiencing and acting on the world. As an effective anticipatory system, the dynamics of the communal scientist shown will be such that the construct systems of the four PSs shown come to give increasingly improved anticipation of events in the world. As this happens it is probable that the PSs will become functionally differentiated, even to the extent of the **fragmentation corollary** (Kelly 1955), that they become "inferentially incompatible."

It is this fragmentation that leads to the constructs of expertise and authority. One PS 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 PS the **authority** to act in that situation.

Representational Media and Simulation

As we indicated last year, communications media may be treated as intermediary systems within the communal scientist. Figure 4 shows how representational media such as radio and television contrast with direct experience in providing one-way interaction only. Their advantage is that they can transcend space by providing experience at a distance and, with storage, can transcend time by providing experience of past events.

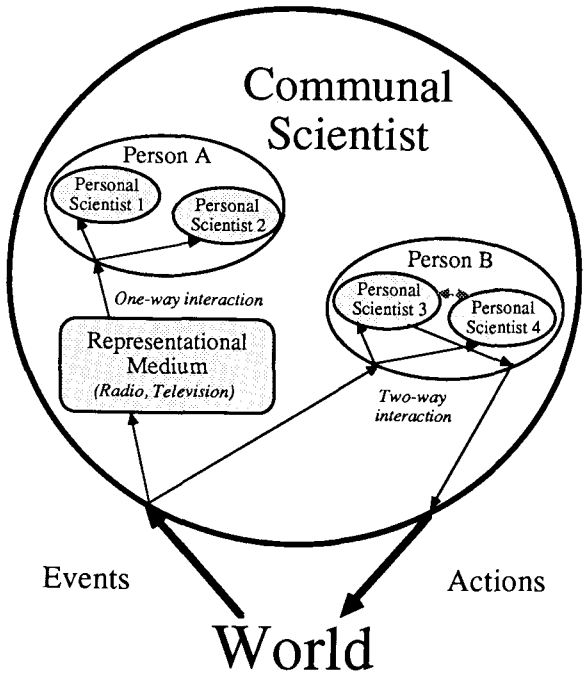

Fig. 4 Representational media in communal scientist

Figure 5 shows how computer-based simulation adds the two-way interaction of normal experience, providing a medium that transcends time and space. Many aspects of the vlsi-based hardware development of fifth-generation technology can be seen as taking this medium towards the speed, capacity and resolution of television and film, and providing the computational power to animate realistic simulation in real-time.

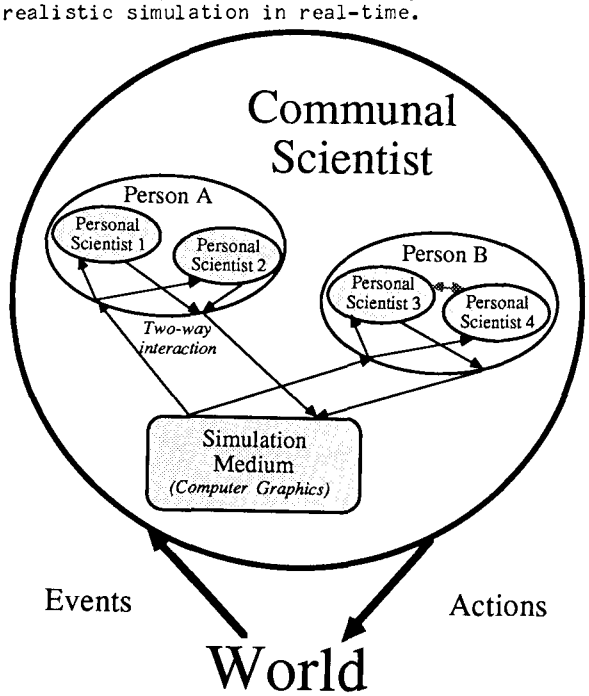

Fig. 5 Simulation media in communal scientist

Symbolic Media and Expert Systems

The development of expert systems and the problems of knowledge engineering may now be analysed in terms of the interactions between PSs in a communal scientist. Figure 6 shows Person B having no interaction with the world but acting only as an **expert advisor** to Person A. PS1 in Person A now has the sole responsibility for interaction and requires access to the knowledge of PS4 in Person B. Note the critical role of both internal and external communications in providing such advice. PS2 in Person A and PS3 in Person B are in communication.

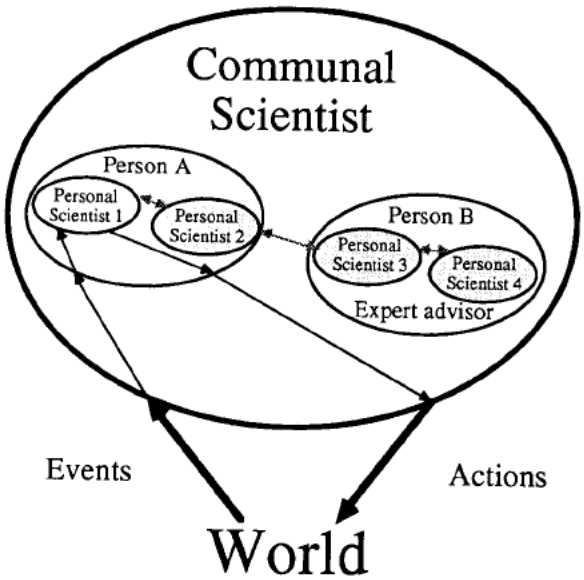

Fig.6 Expert role in communal scientist

If the internal communication between PS3 and PS4 is poor then Person B may not be able to provide effective advice even though he is an expert in doing the task of interest. This is a common situation where a skill has become automatized to the extent that verbal access to it is no longer available (Bainbridge 1979). Person B cannot then advise Person A. He is able to do the task. Person A may be able to modify his construct system through the experience of seeing Person B do the task, that is by mimicing Person B.

If the internal communication between PS1 and PS2 is poor then Person A may not be able to use the advice offered by Person B even though he is able to understand it. This is a common situation where a skill cannot be transmitted verbally. Person B cannot then advise Person A. Again, Person A may be able to modify his construct system by mimicing Person B. Otherwise, he can only acquire the constructs underlying the skill by attempting the task, that is by learning through experience.

Direct access to Person B may not be necessary for his advice to be available to Person A. Person B may be able to externalize his knowledge through a symbolic media such as a broadcast. Figure 7 contrasts the one-way interaction possible through such media with the two-way interaction possible directly between people.

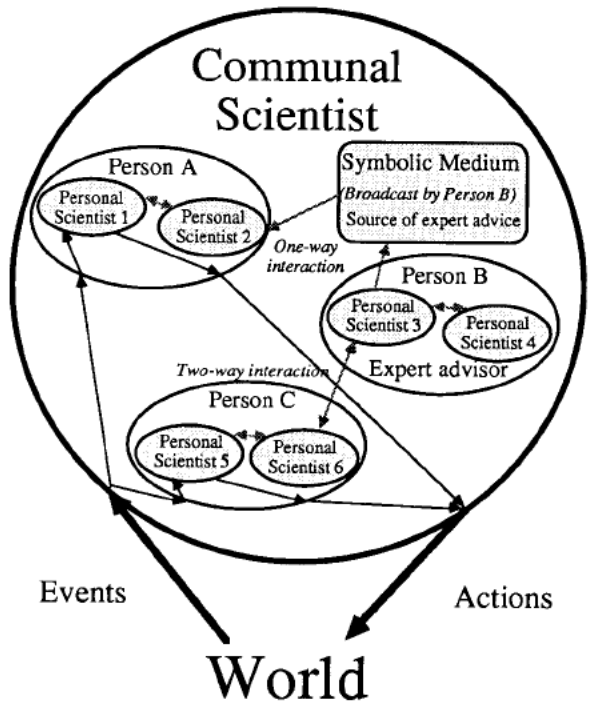

Fig.7 Symbolic media in communal scientist

The broadcast is a symbolic medium transcending space and, by adding storage, as shown in Figure 8 it is also possible to transcend time -- a book may be used as a source of expert advice long after its author is dead. Media such as books

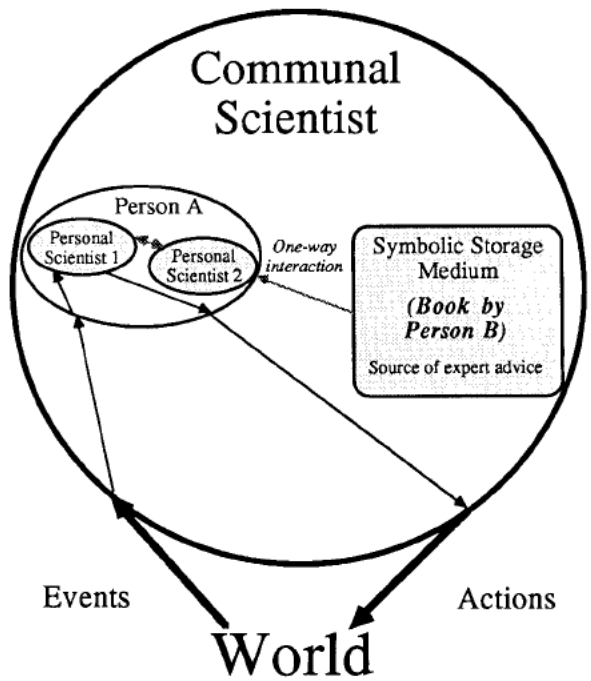

Fig. 8 Symbolic storage media in communal scientist

play an important role in the dynamics of communal knowledge creation in enabling construct systems to be propagated without the original acquirer being accessible (Gaines & Shaw 1984b). Wojciechowski (1983) has termed such externalized knowledge the **knowledge construct** and has noted its major significance in the dynamics of our present civilization.

Past media have been limited sources of expert advice because they are static embodiments of knowledge allowing only one-way communication. They cannot take part in a discussion and develop explanations of advice beyond those frozen in the medium. They cannot be extended with new constructs gained from continuing experience and they cannot easily be extended based on the experience of others. Computer-based ESs may be seen as attempting to provide a medium for the externalization of knowledge that is two-way and extendable as shown in Figure 9.

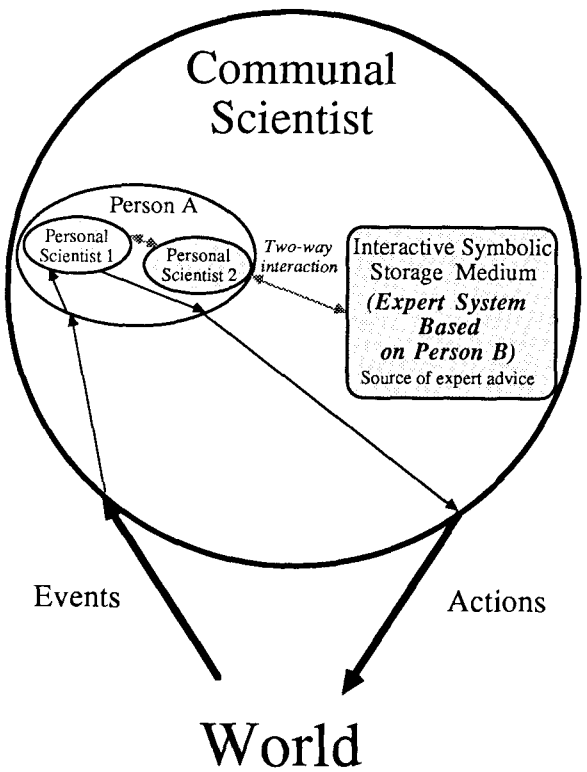

Fig. 9 Expert systems as interactive symbolic storage media

Combining Expert Systems and Simulation

Figure 10 shows how the concepts put forward in this paper combine to structure advanced expert systems combining simulation and control. Note that the overall ES is modeled as a set of communicating P-Individuals:-

* The **advice system** is that satisfying the common stereotype of an ES in that it uses a **knowledge base** and **inference system** to provide expert advice.
* As noted in the context of human interaction, the associated **communication system** is of critical importance in giving access to the

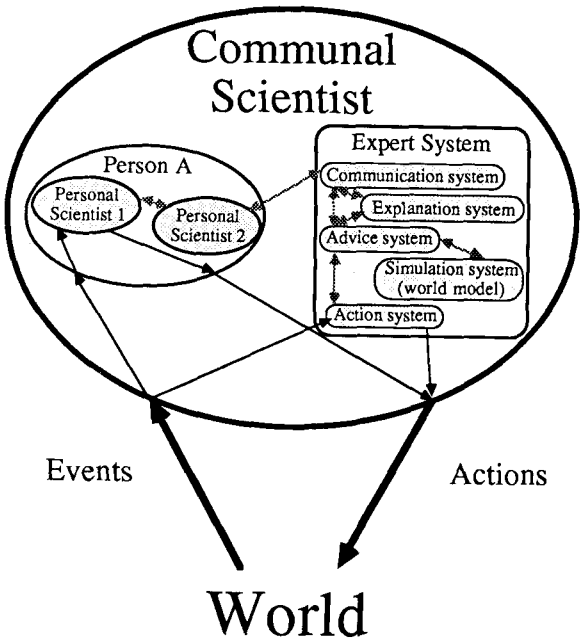

Fig.10 Structure of expert system in communal scientist

advice. Its role is somewhat neglected in the secondary ES literature but the primary literature on successful ES developments emphasizes the effort required to establish effective communications (e.g. TEIRESIAS, Davis & Lenat 1982).

* The **explanation system** is one of the most important developments in computing technology and its availability distinguishes some of the pseudo ESs now being marketed from true ESs. The concept of explanation in itself presents philosophical difficulties (Korner 1975) as advice may be explained at many different levels in many different terms. The basic mechanism in current ESs 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 ESs. They are based on mimicing 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 ESs is to integrate models of the world that may be used to simulate the effects of actions on the world (Gaines & Shaw 1985).
* The **action system** shown is also uncommon currently since the ESs are being used as advisors rather than active partipants. However, it is a logical extension of the technology and consistent with previous applications of computer-based systems in control and automation.

Note that all the sub-systems in Figure 10 have equivalent P-Individuals 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. PCP provides the foundations for a sociology of the communal scientist as an

anticipatory process. One may further conclude that PCP provides the foundations for a technology of knowledge-based systems. Some evidence for this comes from the success of knowledge engineering tools based on PCP for the automatic development of ESs (Shaw & Gaines 1983, 1984, Boose 1985, Gaines & Shaw 1984a).

CONCLUSIONS

Personal construct psychology is based on a conventionalist epistemological approach that has deep systemic foundations and is applicable to any anticipatory system. This includes social systems and technological systems as well as the individual person. 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.

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