KNOWLEDGE SCIENCE—TOWARDS THE PROSTHETIC BRAIN

Mildred L. G. Shaw

Department of Computer Science, University of Calgary
Calgary, Alberta, CANADA T2N 1N4

Information technology has reached a stage in its development where it necessary to cross disciplinary boundaries: within computer science to integrate technology into knowledge-based systems; and outside computer science to achieve an understanding of knowledge processing adequate to apply these systems. The fifth generation computing system development program is aimed at the system integration and the sixth generation computing system development program is aimed at knowledge science. This paper provides a cognitive science framework for knowledge-based systems which encompasses the social and psychological processes of people as well as similar processes in knowledge-based systems. The foundational role of work in brain physiology, psychology, linguistics and logic for the sixth generation program are made apparent.

INTRODUCTION

It is not so long since the Japanese initiative in 1981 of scheduling a development program for a fifth generation of computers [12,20] triggered off a wave of similar activities around the world [10,30]. Fifth generation computing systems (FGCS) were projected to integrate advances in very large scale integration, database management systems, artificial intelligence, and the human computer interface into a new range of computers that were closer to people in their communication and knowledge processing capabilities. It may be difficult to recapture the shock of this announcement: it was unforeseen, from an unexpected source, gave a status to AI research that was yet unrecognized in the West, and proposed an integration of technologies that were still seen as distinct [4,5].

In 1985 a new Japanese initiative proposing a development program for a sixth generation of computers [29] has yet to trigger off a Western response, yet the assumptions behind this program are considerably more radical than for FGCS. Sixth generation computing systems (SGCS) are projected to integrate advances in brain physiology, human psychology, linguistics and logic, into a new discipline, knowledge science, that can be seen as foundations for the knowledge-based systems of the future.

The FGCS proposal crossed disciplinary boundaries within computer science in its quest for a unified systems architecture. The SGCS proposal goes across disciplinary boundaries outside computer science in its quest for a unified knowledge science on which to base applications of such an architecture. What do these attempts at unification imply for the computing industry, computer applications, and computer science? This paper gives a cognitive science model of the role of computing in the development of human society that leads naturally to the SGCS concepts and answers these questions.

SOCIAL FOUNDATIONS OF COGNITIVE SCIENCE

Sociologists and social psychologists have long held that human behavior, and that of human society, can only be understood in the context of the total social milieu. The individual must be seen as embedded in the life-world constituted by the social processes of other individuals and made explicit through cultural pressures, social norms, language, literature and the total knowledge base accreted by society and stored in variety of media [24]. In recent years this concept has been extended to the knowledge acquisition process itself, and it has been noted that the processes of science can be best understood as social cognitive dynamics [23].

This examination of human cognitive behavior, the processes of science and the dyanmics of knowledge acquisition have led to increaingly formal and operational theories. The German sociologist, Luhmann [15], has used systems theory to formalize the operation of trust and power in organizations commencing with the survival drive and noting the peculiar problems presented to one individual by the cognitive processes of another. The Canadian philosopher, Wojciechowski [33], has documented the exponential rate of increase of human knowledge, noting that most human problems are now created by that knowledge as well as soluble by it, and proposed a set of laws underlying an ecology of knowledge. The late American economist, Machlup [16,17,18], has carried out statistical studies of the increasing role of knowledge-based industries in the US economy and highlighted their dominant role from the 1970s onwards.

These large-scale analyses have been paralleled by more specific studies of the individual carrying out the inductive inference processes of knowledge acquisition. Computational models of inductive inference were given rigorous foundations in the 1970s and shown to have practical applications in expert systems [3,19]. A very important link between these micro-inductive processes of the individual and the macro-inductive processes of the life-world was established recently which provides strong foundations for the concepts behind sixth generation developments. This links the logic of induction with the social construct of expertise.

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 [11] 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 [8] proposed that we accept the circularity but note that it involves a dynamic equilibrium between data and inference rules: "A rule is amended if it yields an inference we are unwilling to accept; an inference is rejected if it vioalates a rule we are unwilling to

CH2364-8/86/0000-1030$1.00 © 1986 IEEE

amend." Rawls [22] in his theory of justice terms this a reflective equilibrium. Recently Stich and Nisbett [31] 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 social formulation of inductive inference is a significant development for computer science currently because:

1) It suggests that the basic cognitive system that should be considered is a social organization, rather than an individual;
2) 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 (ESs);
3) It emphasizes the social nature of expertise and suggests that we should be considering groups of experts rather than individual experts in developing ESs;
4) It provides an operational model for the growth of knowledge in a society involving the differentiation into "disciplines"corresponding to the reflective equilibria of different areas of expertise—and hence supports knowledge science encompassing the complete process and necessarily crossing disciplinary boundaries;
5) It provides a model for the role of media in communicating and storing knowledge with a continuity from classical media to present computer-based systems;
6) The computational models of inductive inference already developed can be applied directly to the social model;
7) There are links between these models and neurological processes in the brain which begin to give meaning to the role of brain physiology studies in the proposed SGCS program.

The remainder of this paper sketches the key features of cognitive science based on a social reflective equilibrium, showing how these results arise and give substance to the sixth generation objectives.

THE COMMUNAL SCIENTIST

Figure 1 shows the basic system under consideration, a knowledge-acquiring social organisation which experiences the world and acts upon it. Kelly [13] proposed a cognitive model of the individual as an anticipatory system making distinctions about the world, which he called "personal constructs", and recursively building up distinctions about distinctions which were predictive models of the world. His model has been termed that of the individual as a personal scientist (PS) [25] and we have extended the terminology to social organisations as communal scientists (CSs). The term "scientist"should be read as meaning "knowledge acquirer", with no connotations of positivistic physical science—Kelly's model applies to all the psychological processes of the individual.

The key concept behind Fig.1 is that the primary goal of living organisations is survival and this manifests itself in a drive to anticipate the future by modeling the world. Action is accounted for as active anticipation which acts upon the world to change it to make it more predictable and project survival further into the future.

In system-theoretic terms the CS is a system using prediction and control to maximize the probability of its continued existence. General models of the structure necessary to such systems have been developed, and the interior of the CS in Fig.1 shows Klir's [14] epistemological hierarchy of modeling systems. The system makes distinctions which produce data about experience which it models in such a way as to regenerate the data. At the higher levels this sequence is applied recursively to the internal models to enable change between model classes and the transfer of models from one class of experience to another.

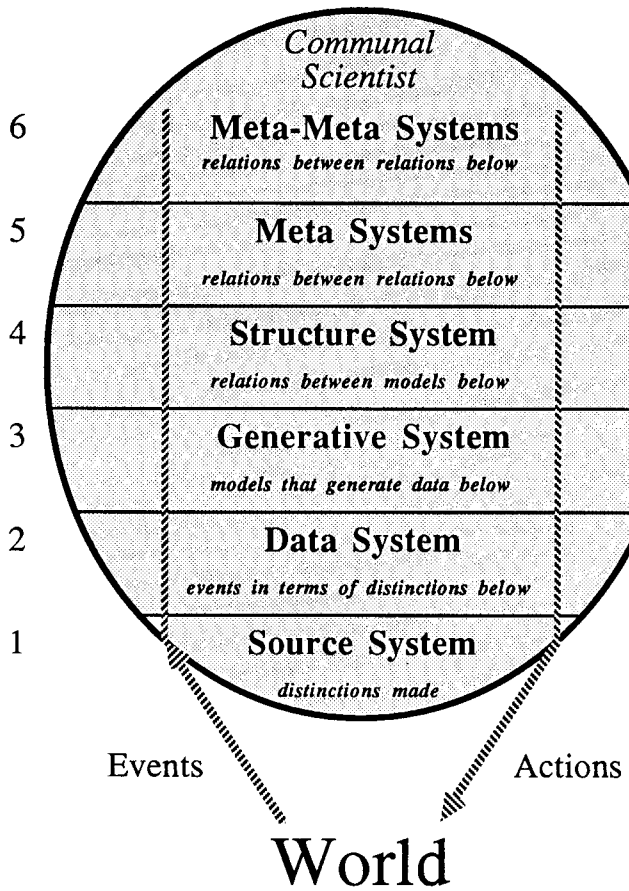

Fig.1 Systemic Structure of Communal Scientist as a Modeling System

Gaines [3] gave a general account of the algorithms for implementing such modeling systems and demonstrated their efficacy with problems of inferring probabilistic models from behavioral data. One side-effect of this account is to introduce two very general control signal: surprise flowing up the hierarchy as lower levels cannot account for data; and preference flowing down the hierarchy as higher levels attempt to influence the anticipated future. This modeling schema has been shown formally to solve the problem of inductive inference for worlds that conform to certain classes of widely used models, deterministic, linear, probabilistic, fuzzy, and so on.

There is physiological and behavioral evidence of the existence within the brain of the two channels of communication shown in Fig.1 [32]. The arousal system passes surprise upwards to the cortex from the limbic region when unexpected events occur. The activation system passes preferences down from the cortex to the motor regions.

PSYCHOLOGICAL PROCESSES WITHIN A COMMUNAL SCIENTIST

The individual within society is a cross-section of the modeling hierarchy of Fig. 1. Figure 2 shows three PSs differentiated within the CS, and also replaces the abstract vocabulary of Fig. 1 in a cognitive science context by giving psychological terms to the levels in the hierarchy [6]. An individual is defined in cognitive terms as a psychological process. The brain carrying out this process may be seen as a psychological processor [21].

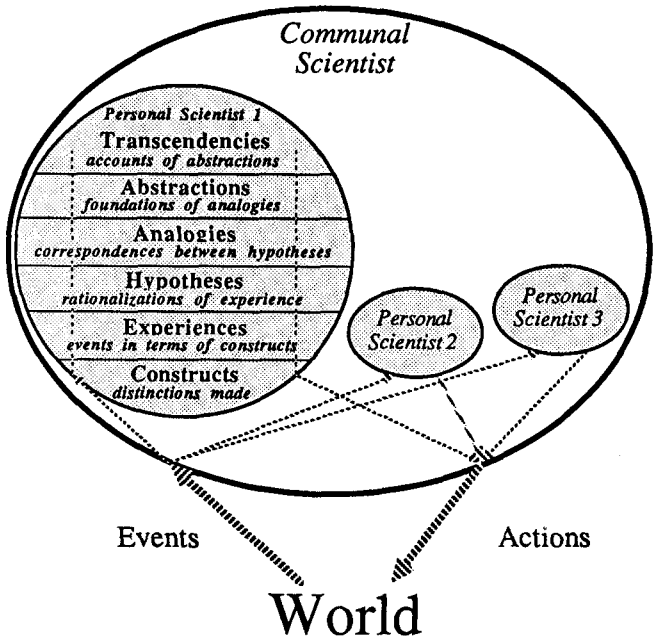

Fig.2 Psychological Structure of Personal Scientists Within a Communal Scientist

More complex psychological and social structures may also be shown in terms of such concepts 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 3 shows two people, each with two roles, forming a group. The original CS, CS1, and PS1 through PS4, are all psychological processes. Person A and Person B as physical entities are psychological processors.

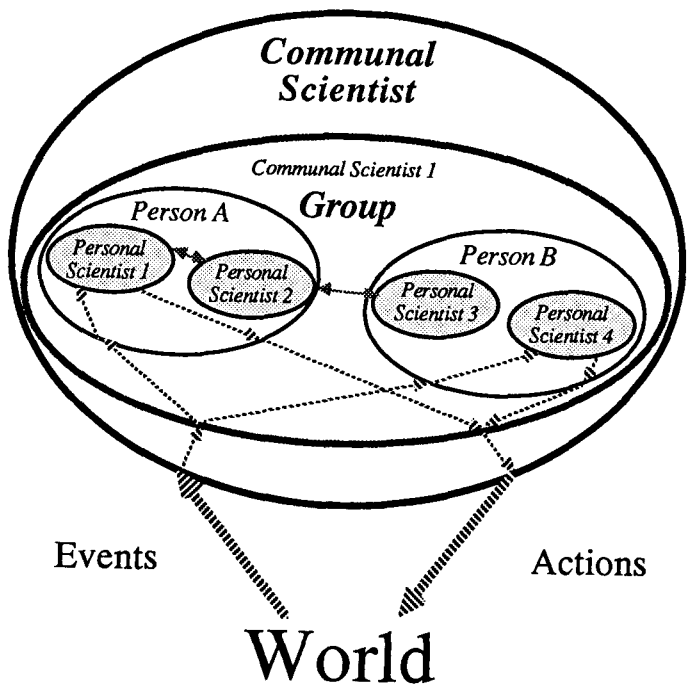

Fig.3 Roles and Groups Within a Communal Scientist

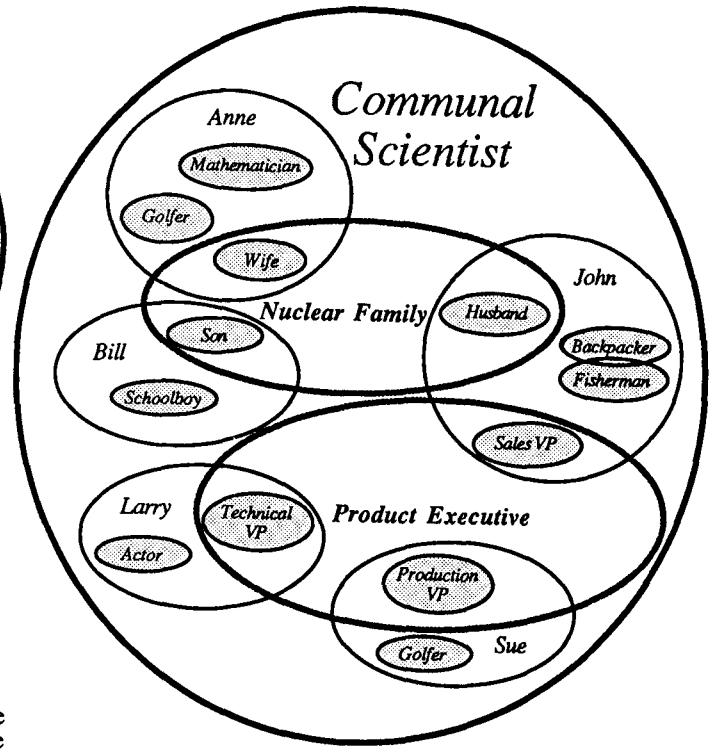

Fig.4 People in a Number of Roles and Groups Within a Communal Scientist

Symbolic communication is important in co-ordinating psychological processes. In Fig.3 PS1 and PS2 are shown as having internal communication. PS3 and PS4 are shown not to have such communication and can only coordinate by monitoring one another's actions as events in the world. PS2 and PS3 have external communication corresponding to the use of language.

These concepts are exemplified in more concrete terms in Fig. 4 showing people in a number of roles and groups [26]. John has roles as a husband, a sales Vice President of his company, a backpacker and a fisherman. John uses different constructs when he is in the role of husband from when he is in the role of fisherman, but some of the constructs he uses in the role of fisherman are also used in the role of backpacker and this is shown as overlapping PSs. Anne is John's wife, a mathematician and a golfer. Bill is their son and a schoolboy. Larry is the technical Vice President in John's company, and Sue is the production Vice President. Sometimes John is acting with his wife or colleagues to form group processes that have some constructs that are shared between participants and others that arise from only one of them. For example, John, Anne and Bill form a nuclear family. This is a distributed process which has legal rights, specific behaviour, concepts and language which go beyond those of its sub-processes. The product executive of the company is another distributed process which has authority, responsibility, and behaviour which is unique to the entity and not that of any one of its participants.

EXPERTISE AND MEDIA WITHIN A COMMUNAL SCIENTIST

The role of an expert is readily modeled within a CS. Person C in Fig.5 is carrying out a task with help from an expert advisor, Person B who has no other interaction with the task. The role of symbolic media is also shown in that Person A is carrying out the task with broadcast advice from Person B. However, the

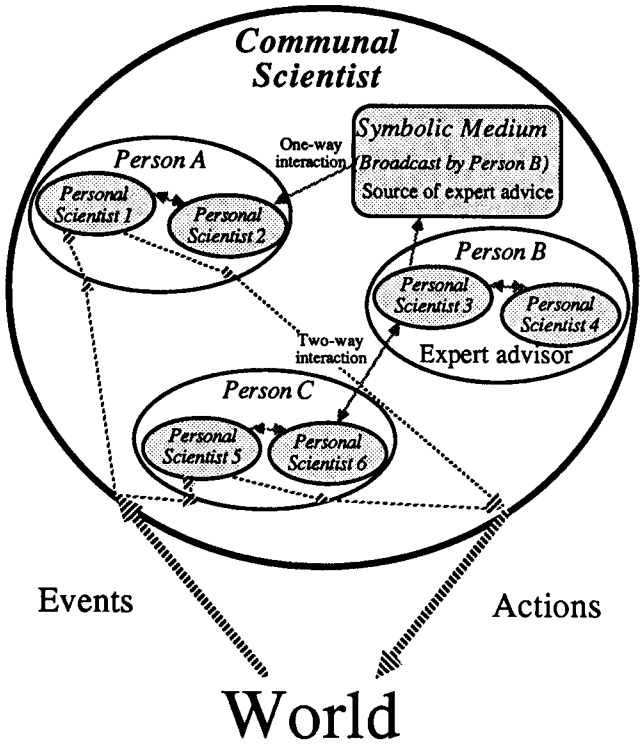

Fig.5 Expert Advisors and Symbolic Media Within a Communal Scientist

mediated communication is one-way whereas the direct communication is two way [28]. Some of the problems of knowledge engineering are also apparent in Fig.5. PS4 is the processor with the required skill in Person B and has to communicate through PS3, an external language processor, but sometimes this link may be unavailable [1]. Similarly PS5 requires the skill in Person C and has to be able to communicate internally with a language processor PS6 which itself has to be able to communicate externally with PS3; lack of effective communication on either link will prevent knowledge transfer.

A symbolic storage medium, such as a book or paper, may replace Person B in Fig.5 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 ES has an internal structure of processes that mimic those of its source, Person B. A communication system interacts linguistically with Person A, and draws upon: an advice system to suggest actions; an explanation system to give reasons for the suggestions; and, possibly, a simulation system if the advice is based on a deep model of the world.

The CS and PS models apply to the expert system in Fig. 6 as much as they apply to the person, and the structure of the ES can be represented in the inductive system hierarchy of Fig. 1. Figure 7 shows the feedback processes at different levels of this hierarchy to provide a model for knowledge acquisition in both people and ESs. The levels have been labeled in terms of Hall's [9] 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

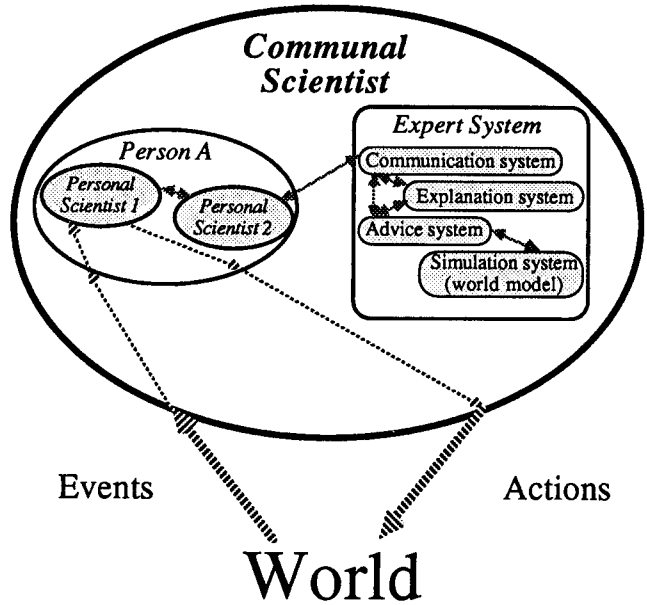

Fig.6 Structure of an Expert System as a Two-Way Symbolic Medium Within a Communal Scientist

acquired by the reinforcement of reward and punishment; the third level is technical where knowledge is acquired from its overt expression largely in symbolic media; the fourth is comparative where knowledge is acquired by analogies between cultures; the sixth is abstract where knowledge is acquired as basic laws; and the sixth is transcendental where knowledge is acquired by deriving the principles underlying it.

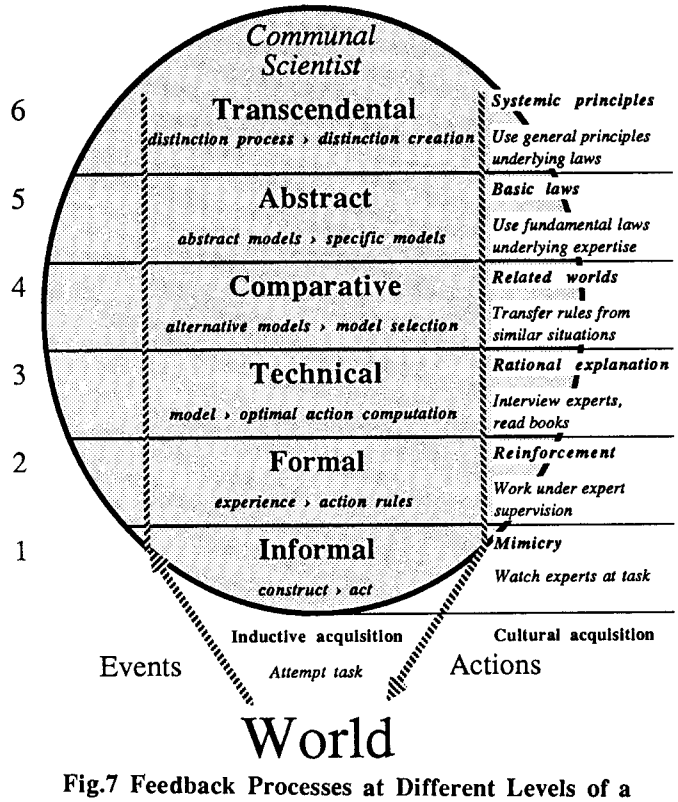

Fig.7 Feedback Processes at Different Levels of a Modeling System Representing Knowledge Acquisition in Both People and Expert Systems

Knowledge transfer to ESs now takes place at the technical level, although experiments are taking place on its transmission at all the other levels. In particular, successful systems have been based on mimicry at the informal level [19], and on interview techniques based on personal construct psychology at the formal level [2,7,27].

CONCLUSIONS

This paper has provided a cognitive science framework for knowledge-based systems which encompasses the social and psychological processes of people as well as similar processes in knowledge-based systems. The foundations are based on a systemic model of inductive knowledge acquisition and the overall model accounts for the role of culture, media, experts and expert systems in the human knowledge process. Physiological systems are known in the brain that appear to carry out the basic functions of arousal and activation required by the model. Language plays the role of co-ordinating the multiple processors which are individual brains within a knowledge-acquiring society.

The foundational role of work in brain physiology, psychology, linguistics and logic for the sixth generation program is apparent in the analysis of this paper. Figure 8 summarizes the way in which a person acquiring a knowledge is supported by other people, media and various forms of information technology. From the individual's point of view these may be regarded as extensions of the processes within his brain, and the total structure may be properly termed a *prosthetic brain*. From a social point of view the entire sub-system shown is part of the knowledge process of the society and may be understood in terms of *knowledge science*. These two perspectives are the key to understanding sixth generation priorities and developments.

ACKNOWLEDGEMENTS

Financial assistance for this work has been made available by the National Sciences and Engineering Research Council of Canada.

REFERENCES

Bainbridge, L. (1979). Verbal reports as evidence of the process operator's knowledge. **International Journal of Man-Machine Studies, 11**(4), 411-436 (July).

Boose, J.H. (1985). A knowledge acquisition program for expert systems based on personal construct psychology. **International Journal of Man-Machine Studies 20**(1), 21-43.

Gaines, B.R. (1977). System identification, approximation and complexity. **International Journal of General Systems, 3**, 145-174.

Gaines, B.R. (1984a). A framework for the fifth generation. **Proceedings of National Computer Conference, 53**, 453-459. Arlington, Virginia: AFIPS Press.

Gaines, B.R. (1984b). Perspectives on fifth generation computing. **Oxford Surveys in Information Technology, 1**, 1-53.

Gaines, B.R. & Shaw, M.L.G. (1981). A programme for the development of a systems methodology of knowledge and action. Reckmeyer, W.J., Ed. **General Systems Research and Design: Precursors and Futures**. pp. 255-264. Society for General Systems Research (January).

Gaines, B.R. & Shaw, M.L.G. (1986). Induction of inference rules for expert systems. **Fuzzy Sets and Systems 8**(3) 315-328.

Goodman, N. (1973). **Fact, Fiction and Forecast**. Indianapolis: Bobbs-Merrill.

Hall, E.T. (1959). **The Silent Language**. New York: Doubleday.

HMSO (1982). **A Programme for Advanced Information Technology: Report of Alvey Committee**. London: HMSO.

Hume, D. (1739). **A Treatise of Human Nature**. London: John Noon.

ICOT (1983). **Outline of Research and Development Plans for Fifth Generation Computer Systems**. Tokyo: ICOT (April).

Kelly, G.A. (1955). **The Psychology of Personal Constructs**. New York: Norton.

Klir, G.J. (1976). Identification of generative structures in empirical data. **International Journal of General Systems, 3**, 89-104.

Luhmann, N. (1979). **Trust and Power**. Chichester: John Wiley.

Machlup, F. (1980). **Knowledge and Knowledge Production**. Princeton University Press.

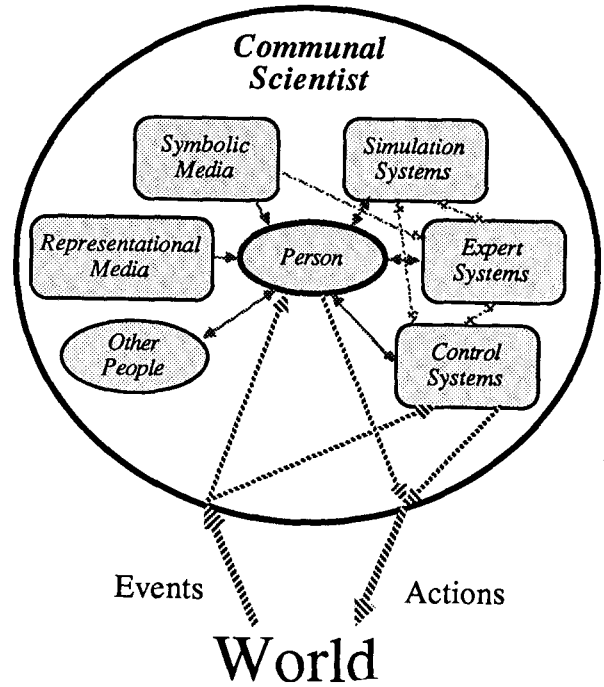

Fig.8 Support of Individual Knowledge Acquisition by People, Media and Information Technology—the "Prosthetic Brain"

Machlup, F. (1982). **The Branches of Learning**. Princeton University Press.

Machlup, F. (1984). **The Economics of Information and Human Capital**. Princeton University Press.

Michalski, R.S. & Chilausky, R.L. (1980). Knowledge acquisition by encoding expert rules versus computer induction from examples—A case study involving soyabean pathology. **International Journal of Man-Machine Studies, 12**, 63-87.

Moto-oka, T., Ed. (1982). **Fifth Generation Computer Systems**. Amsterdam: North-Holland.

Pask, G. (1980). Developments in conversation theory—I. **International Journal of Man-Machine Studies**, 13(4), 357-411.

Rawls, J. (1971). **A Theory of Justice**. Cambridge, Massachusetts: Harvard University Press.

Rubinstein, R.A., Laughlin, C.D. & McManus, J. (1984). **Science as a Cognitive Process**. Philadelphia: University of Pennsylvania Press.

Schutz, A. & Luckmann, T. (1973). **The Structures of the Life-World**. London: Heinemann.

Shaw, M.L.G. (1980). **On Becoming a Personal Scientist**. London: Academic Press.

Shaw, M.L.G. (1985). Communities of knowledge. Epting, F. & Landfield, A.W., Eds. **Anticipating Personal Construct Psychology**. pp. 25-35. Lincoln: University of Nebraska Press.

Shaw, M.L.G. & Gaines, B.R. (1983). A computer aid to knowledge engineering. **Proceedings of British Computer Society Conference on Expert Systems**, 263-271 (December). Cambridge.

Shaw, M.L.G. & Gaines, B.R. (1984). Fifth generation computers as the next stage of a new medium. **Proceedings of National Computer Conference, 53**, 445-451. Arlington, Virginia: AFIPS Press.

STA (1985). **Promotion of R&D on Electronics and Information Systems That May Complement or Substitute for Human Intelligence**. Tokyo: Science and Technology Agency.

Steier, R. (1983). Cooperation is the key: An interview with B. R.Inman. **Communications of the ACM, 26**(9), 642-645.

Stich, S.P. & Nisbett, R.E. (1984). Expertise, justification and the psychology of inductive reasoning. Haskell, T.L., Ed. **The Authority of Experts**. pp. 226-241. Bloomington: Indiana University Press.

Tucker, D.M. & Williamson, P.A. (1984). Asymmetric neural control systems in human self-regulation. **Psychological Review, 91**(2), 185-215 (April).

Wojciechowski, J. (1983). The impact of knowledge on man: the ecology of knowledge. **Hommage a Francois Meyer**. pp. 161-175. Marseille: Laffitte.