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# 9

# A cognitive model for intelligent information systems

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## 1. INTRODUCTION

We are in era of rapid change in information systems technology. The information processing systems of yesterday are becoming the knowledge processing systems of today. Software and hardware developments are proceeding at such a pace that it has become impossible to keep up-to-date with the basic technology. In addition, human–computer interface (HCI) and knowledge-based system (KBS) developments are also occurring so rapidly that the relevant literature is exploding. The specifiers and designers of intelligent information systems, the libraries of the future, have to contend with this world of change and make reasonable projections about technologies and user expectations over the next decade. This chapter provides one framework for such projections, a cognitive science model of the user community and the role of information technology within it.

### Fifth generation knowledge-based systems

Knowledge has always been significant to our civilization. However, in the past fifty years this significance has grown to a level where it is coming to dominate other socio-economic factors (Marschak 1968). Machlup (1962) drew attention to the major and growing role of information services in the US economy and estimated that in 1958 knowledge production accounted for 29 percent of the US GNP. Porat (1977) made a detailed analysis of the 1967 US national-income-and-accounts and estimated that the information sector accounted for 46 percent of GNP. Drucker (1968) took this up as a major issue in his book, *The Age of Discontinuity*, and estimated that by 1975 the knowledge sector would account for 50 percent of US GNP.

More dramatic presentations of the socio-economic consequences have been made by Toffler (1980) in his book, *The third Wave*, by Dizard (1982) in this book, *The Information Age*, and by many other information scientists and social commentators. Bell (1973) has given a thoughtful economic analysis on his book, *The Coming of Post-Industrial Society*, and Wojcie-

chowski (1983) has analysed the increasing significance of the knowledge construct to human society and emphasized the importance of understanding and managing the knowledge ecology. These global models of a changing human civilisation emphasize the increasing dependence of the human race on the effective dissemination, use and extension of the store of knowledge. Our over-crowded planet with its diminishing resources can support the still-increasing human population only because we have the knowledge to make efficient use of the resources available.

From the perspective of a shift to a knowledge ecomomy, the explosive growth of computer technology from the 1940s may be seen not as a cause of the information society but rather as providing a necessary infrastructure through which to support it. Computer technology has advanced at a rate that is extremely high and has been sustained over such a period that it can be seen as a series of revolutions rather than as technology evolution. Between 1959 and 1980 the number of active devices on a circuit chip increased from one to one million; by 1990 it will reach one thousand million (Robinson 1984). Over the same period information storage costs have declined to the level where it is now possible to store the *Encyclopaedia Britannica* on an optical disk costing a few dollars in a drive that is coupled to a personal computer and costs a few hundred dollars (Gaines & Shaw 1984b). Every eight years computer technology has advanced in performance parameters by the order of one hundred times (Gaines & Shaw 1985b). Five such periods of advance may be distinguished historically, and we are now in the sixth, termed the **fifth generation**. For comparison the aircraft industry has seen only one such comparable advance in its 75-year history.

The technological culmination of the socio-economic pressure to generate technologies adequate to support a knowledge-based civilization may be upon us now in fifth generation computing systems (FGCS). The Japanese initiative in 1981 of scheduling a development program for FGCS (Motooka 1982, ICOT 1983) triggered off a wave of similar activities around the world (HMSO 1982, Steier 1983). The work at ICOT in Tokyo is 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 are closer to people in thier communication and knowledge processing capabilities (Fuchi 1984, Gaines 1984a,b). The major change expected in this generation will be a shift from information technology to knowledge technology with FGCS providing knowledge bases that are readily accessed by people with no specialist computer skill and are integrated into all aspects of the operation of society.

The impact of early FGCS is already apparent in the rapid growth in the past five years of an expert systems industry concerned with encoding the high-level knowledge and decision-making skills of key professionals and making them widely available through computer systems (Gevarter 1983). Initially these systems were expensive and primarily of interest to the petrochemical mineral exploration and pharmaceutical industries where expert knowledge in explorative research is essential to risk-reduction in high-cost

ventures. Declining computer costs have made expert systems significant for more routine knowledge and skill dissemination, for example in industries where the retirement of skilled employees is a major problem (Hayes–Roth 1984).

**Sixth generation knowledge science**

Understanding the nature of knowledge is a topic for several branches of philosophy (Gaines & Shaw 1983). In the context of applications it is part of the philosophy of science, of technology, of the professions and of practical reasoning. The practical tools are those of logic, of which only the logic underlying mathematics is very well developed. Computer scientists, particularly those working on FGCS are aware of the important role of logic in knowledge -based systems and are becoming increasingly aware of the philosphical problems involved. Philosophers also are becoming increasingly interested in the role of computing as an operational domain for the expression and exploration of philosophical problems.

Understanding the role of knowledge in an application is a topic for the scientific discipline and profession associated with that application. Every discipline and every profession will become increasingly involved with the knowledge-based technology of FGCS. This universality presents major problems in the social-economic management of knowledge technology. There is no natural forum for information collection and dissemination. There is no single discipline that can serve as a focus for most, let alone all, activities. Computer science is only now becoming well-established and is primarily concerned with the development of the technological infrastructure, the scaffolding. Each of the professional disciplines has its own contribution to make to the encoding of the knowledge that underlies it for dissemination through computing systems. Each of the scientific disciplines has the possibility of a new impetus to its own development through the use of knowledge technology. The social sciences and the humanities have dual roles to play in that they can make major use of knowledge technology in thier own development and are also important to the understanding of its impact on our society and civilization.

This need for cross-disciplinary interchange has been recognized in the sixth generation computing system (SGCS) development proposal put forward in the report, 'Promotion of R&D on Electronics and Information Systems that may Complement or Substitute for Human Intelligence', from the Subcommittee on Artifical Intelligence of The Council on Aerospace and Electronics Technology in Tokyo (STA 1985). The Council was asked by the Ministry of Science and Technology in January 1983 to report on AI in these terms. It formed a sub-committee that met twelve times in preparing this report, used the term *knowledge science* for its subject matter, and reported in March 1985. The English translation comprises some 18,000 words. It is reported that MITI has agreed to fund at least part of the SGCS proposal with $32 million over 10 years commencing mid-1986 as an extension of ICOT's activities (Chapman 1985).

Four objectives are specified for promoting knowledge science:

innovations in frontier high technologies; economic and cultural advancements; contributions to the explosion of human potential; and establishing a foundation for creative science. The proposed research program moves outside the boundaries of computing technology and requires inter-disciplinary interaction between computing science and physiology, psychology, linguistics and logic. The report analyses the state of the art in these four relevant sciences and proposes the development of eight technologies based on them for application in four major areas (Fig. 1). The application areas do not differ from those of the FGCS program but the path specified to them is far more foundational.

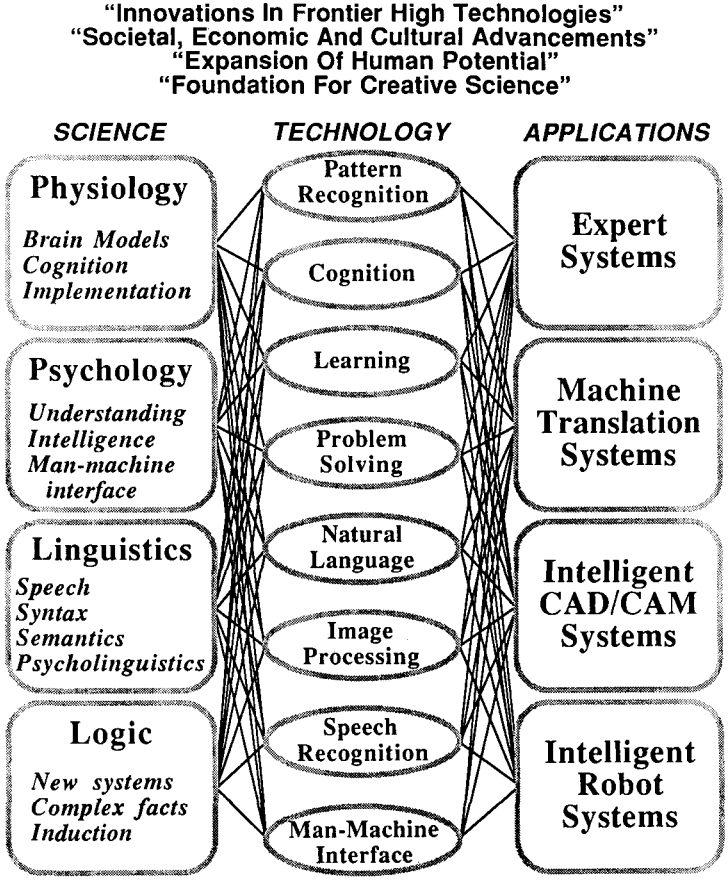


Fig. 1 — The Japanese Sixth Generation Computer System development proposal — knowledge science, technology and applications.

This path through the brain and human sciences to future generation computing was previewed in an interview with Fuchi, the Director of ICOT, when in reply to the question: 'Are you saying that the design of the fifth-

generation may be modeled by learning more about the human thinking process?', he answered:

> Yes, we should have more research on human thinking processes, but we already have some basic structures. For more than 2000 years man has tried to find the basic operation of thinking and has established logic. The result is not necessarily sufficient; it's just the one that mankind found. At present we have only one solution — a system like predicate calculus. It is rather similar to the way man thinks. But we need more research. What, really, is going on in our brain? It's a rather difficult problem. (Fuchi *et al.* 1984)

The FGCS program has been targeted on the development of very high-speed deductive reasoning machines using predicate calculus as a knowledge-representation language. However, standard logic bears only a remote resemblance to human reasoning processes (Wason & Johnson-Laird 1972). Modern formal logic was developed as a foundation for mathematics just because mathematical rigor is so foreign to everyday human activity (Mohanty 1982). Causal models may be incapable of encompassing the process of biological systems, and currently we have no formalism in which to express the anticipatory dynamics of living systems (Rosen 1985). What is going on in our brain is certainly a difficult problem, but the development of intelligent information systems demands that we resolve it. The SGCS proposal sets out to do this and makes no detours to avoid using words such as 'intuition, analogy and creativity' in its description of human reasoning capabilities.

Information technology has reached a stage in its development where it is necessary to cross disciplinary boundaries: within information science to integrate technology into knowledge-based systems; and outside information 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. The remainder of this chapter 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.

## 2. SOCIAL FOUNDATIONS OF COGNITIVE SCIENCE

Sociologists and social psychologists have long held that human behaviour, 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 consituted 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 (Schutz and Luckman 1973). In recent years this concept has been extended to the

knowledge acquisition itself, and it has been noted that the processes of science can be best understood as social cognitive dynamics (Rubinstein, Laughlin & McManus 1984).

This examination of human cognitive behaviour, the processes of science and the dynamics of knowledge acquisition have led to increasingly formal and operational theories. The sociologist, Luhmann (1979), 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 philosopher, Popper (1968), has noted that knowledge itself forms a world with an ontological status equivalent to that of the physical world, which he terms World 3. Another philosopher, Wojciechowski (1983), 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 American economist, Machlup (1980, 1982, 1984), has carried our statistical studies of the increasing role of knowledge-based industries in the US economy and highlighted their dominant role from the 1970s onwards.

Whereas the deductive logical inference that underlies the operation of conventional computers is well-understood and well-founded, the inductive inference that underlies human learning is not. Deduction guarantees to take us from valid data to valid inferences, but the inferences are thereby part of the data — no new knowledge is generated. Induction takes us from valid data to models of that data that go beyond it — by predicting data we have not yet observed, and by giving explanations of the data in terms of concepts that are unobservable. Induction generates new knowledge but, as Hume (1739) pointed out over 200 years ago, the process is not deductively valid, and it is a circular argument to claim that it is inductively valid.

Philosophers have continued to debate Hume's arguments and search for justification of the inductive process. Goodman (1973) proposed that we accept the circularity but note that it involves a dynamic equilibrium between data and inference rules: 'A rule is amended if it yields an inference we are unwilling to accept; an inference is rejected if it violates a rule we are unwilling to amend.' Rawls (1971) in his theory of justice terms this a reflective equilibrium. Recently Stich and Nisbett (1984) noted flaws in Goodman's argument and repaired them by proposing that the equilibrium is social not individual: 'a rule of inference is justified if it captures the reflective practice not of the person using it but of the appropriate experts in our society.'

This social formulation of inductive inference is a significant development for intelligent information systems 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 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 chapter 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.

## 3. THE COMMUNAL SCIENTIST

Fig. 2 shows the basic system under consideration, a knowledge-acquiring social organisation which experiences the world and acts upon it. Kelly (1955) 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 are predictive models of the world. His model has been termed that of the individual as a *personal scientist* (PS), (Shaw 1980) and we have extended the terminology to social organizations as *communal scientists* (CSs). The term 'scientist' should be read as meaning 'knowledge acquirer', with no connotations of postive physical science — Kelly's model applies to all the psychological processes of the individual.

The key concept behind Fig. 2 is that the primary goal of living organizations is survival, and this manifests itself in a drive to anticipate the future by modelling 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 maximise 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. 2 shows Klir's (1976) epistomological 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

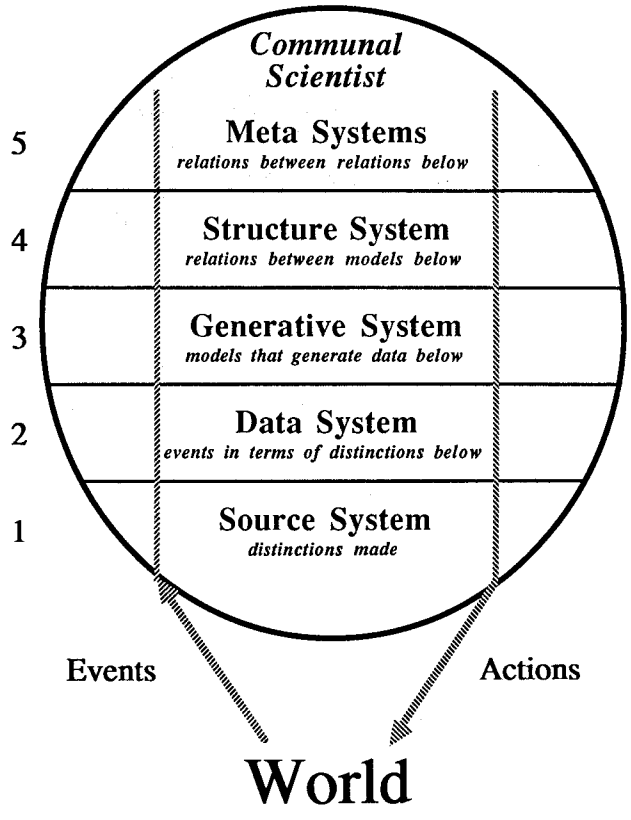


Fig. 2 — Systematic structure of communal scientist as a modeling system, experiencing the world and acting upon it.

applied recursively to the internal models to enable change between model classes and the transfer of models from one class of experience to another.

Gaines (1977) gave a general account of the algorithms for implementing such modelling 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 signals: *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 modelling 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, probablistic, 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. 2 (Tucker & Williamson 1984). The *arousal* system passes surprise upwards to the cortex from the limbic region when unexpected event occur. The *activation* system passes preferences down from the cortex to the motor regions.

## 4. PSYCHOLOGICAL PROCESSES WITHIN A COMMUNAL SCIENTIST

The individual within society is a cross-section of the modelling hierarchy of Fig. 2. Fig. 3 shows two PSs differentiated within the CS, and also replaces the abstract vocabulary of Fig. 2 in a cognitive science context by giving psychological terms to the levels in the hierarchy (Gaines & Shaw 1981a).

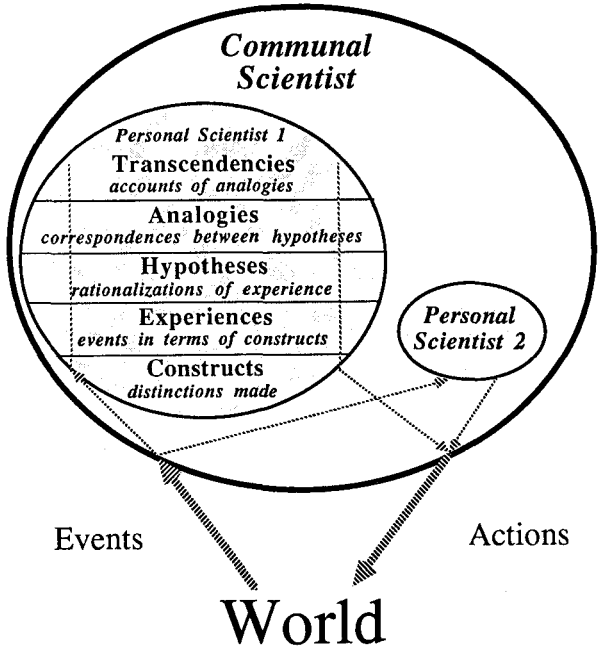


Fig. 3 — Psychological structure of personal scientists within a communal scientist.

An individual is defined in cognitive terms as a psychological process. The brain carrying out this process may be seen as a psychological processor (Pask 1980).

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). Fig. 4 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.

Symbolic communication is important in co-ordinating psychological processess. In Fig. 4, 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. 5 showing people in a number of roles and groups (Shaw 1985). 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. 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 and Anne (and their children) form a nuclear family. This is 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.

## 5. EXPERTISE AND MEDIA WITHIN A COMMUNAL SCIENTIST

The roles of media are readily modeled within a CS (Shaw & Gaines 1984). Fig. 6 shows Person A interacting with the world through a representational medium such as radio or television. The interaction contrasts with that of Person A interacting directly with the world in that it is only one-way rather than two-way (Gaines & Shaw 1984a). Person A can preceive 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 transcends time allowing past events to be experienced but are still one-way. The simulation media based on computer graphics being used by Person D allows two-way access to a simulated world, and as they become more realistic can increasingly replace direct experience (Gaines & Shaw 1985a). Note how Persons C and D have no necessary interaction with the real world. Computer graphic media in intelligent information systems can give access to experience in worlds of simulated reality that may, or may not, model real world events.

The role of an expert may also be modeled within a CS. Person C in Fig. 7 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, as with representational media, the mediated communication is one-way whereas the direct communication is two-way (Gaines & Shaw 1984a). Some of the problems of knowledge engineering, of transferring knowledge from experts to expert systems, are also apparent in Fig. 7.

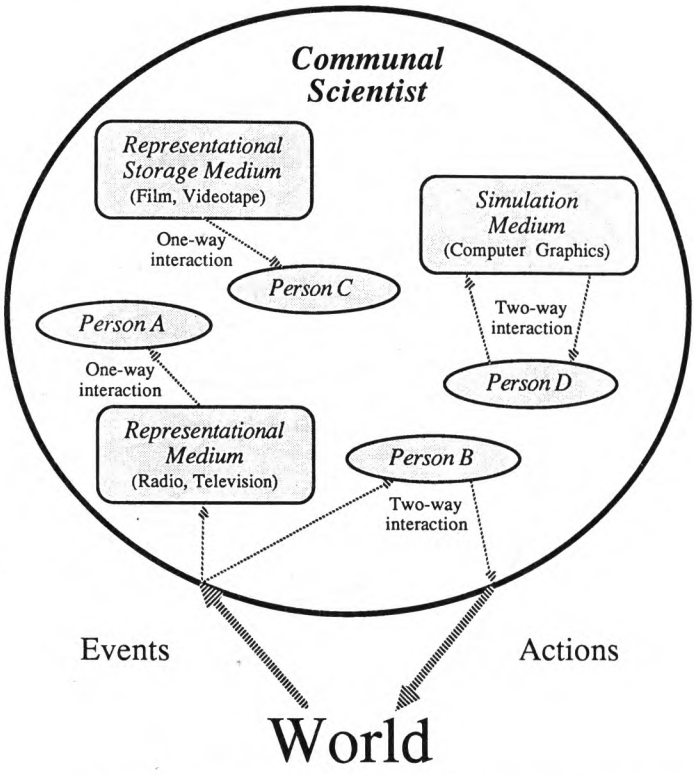


Fig. 6 — Various forms of representational media within a communal scientist.

1982). PLANET, expert systems, communications networks and advanced simulation may be seen as precursors to intelligent information systems that support the knowledge processes of large-scale communities through interactive computer knowledge bases. The library of the future will add such capabilities to the symbolic and representational storage media of current library systems. Fifth and sixth generation computer technologies should be thought of as extending and integrating current media rather than replacing them. Fig. 11 shows how Popper's World 3 and Wojciejowski's knowledge construct are becoming manifest through the integration of past and present knowledge using computer and communications media. The conversational and experiential access that we have with other people and the existing world is being extended to conversational and experiential access to people and events of the past, and to knowledge and experience that correspond to possible worlds rather than reality. As the steam engine provided power that gave control over the physical world and triggered off the industrial revolution so is computing providing power to control the knowledge construct, enabling us to construct vehicles to traverse World 3 (Gaines 1978), and trigger off an information revolution.

The social perspective of Fig. 11 is complemented by the personal

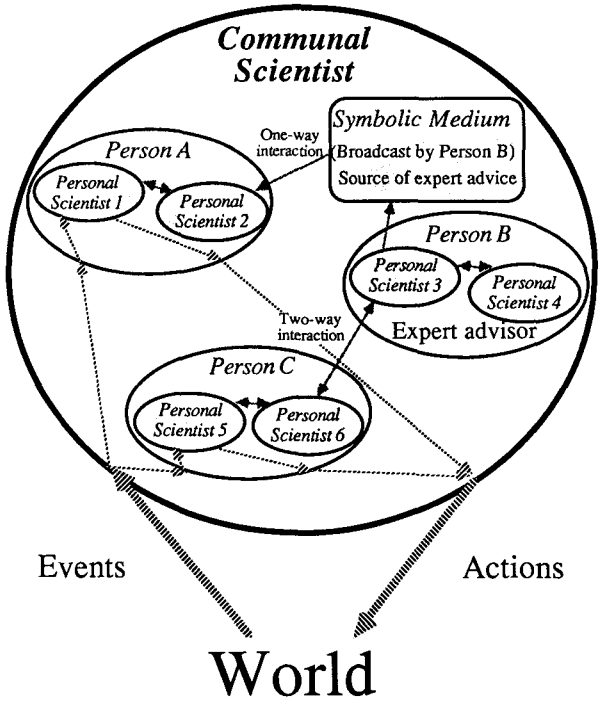


Fig. 7 — The representation of expert advisors and symbolic media within a communal scientist.

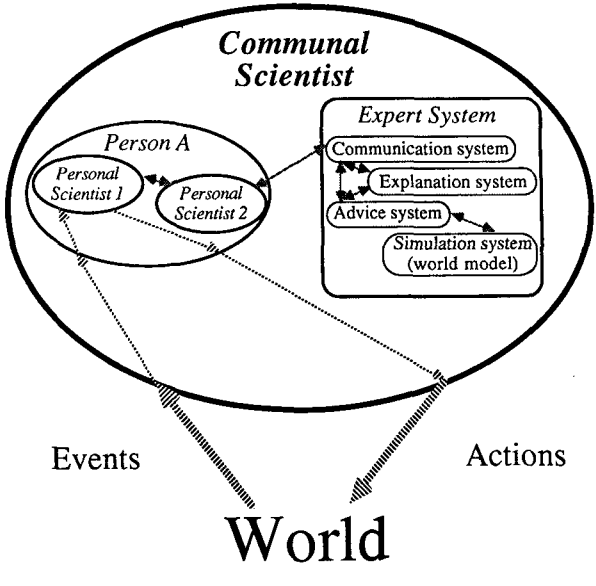


Fig. 8 — Structure of an expert system as a two-way symbolic medium within a communal scientist.

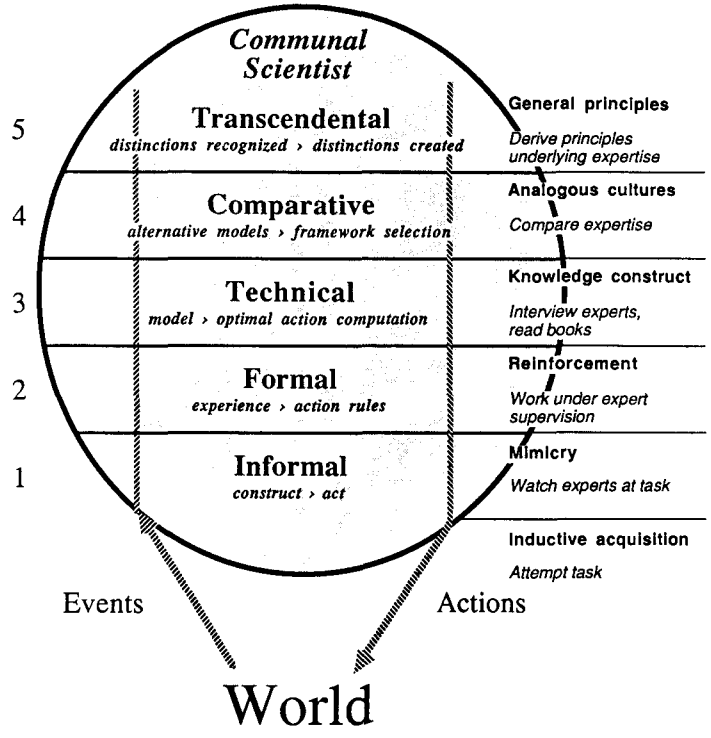


Fig. 9 — Feedback processes at different levels of a modeling system representation knowledge acquisition in both people and expert systems.

perspective of Fig. 12 in which a person acquiring knowledge is seen as 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 subsystem 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 fifth and sixth generation priorities and developments that are leading to intelligent information systems.

## 7. CONCLUSIONS

The development of intelligent information systems has reached a stage in its development where it is 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 targeted on the system integration and the sixth generation computing system development program is targeted on knowledge science.

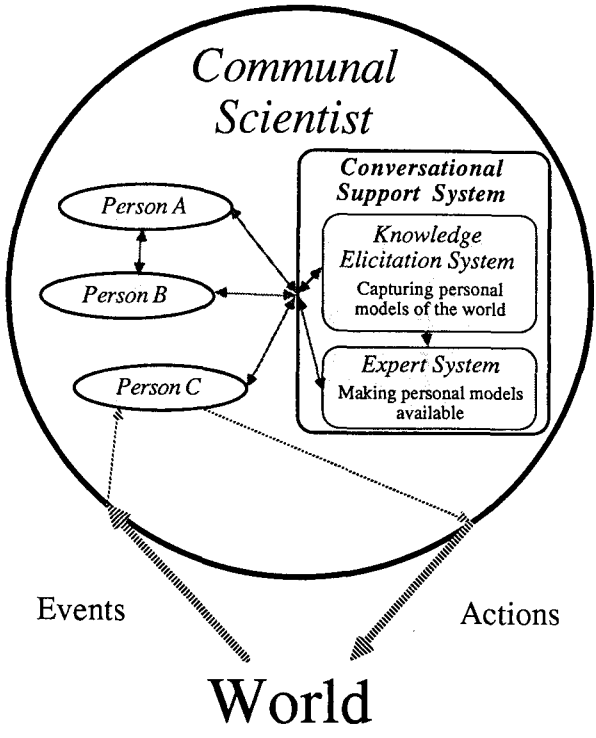


Fig. 10 — Conversational support system eliciting individual knowledge and making it available to a community.

This chapter has provided a cognitive science framework for intelligent information systems which encompasses the social and psychological processes of people as well as similar processes in computer-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 coordinating the multiple processors which are individual brains within a knowledge-acquiring society.

## ACKNOWLEDGEMENTS

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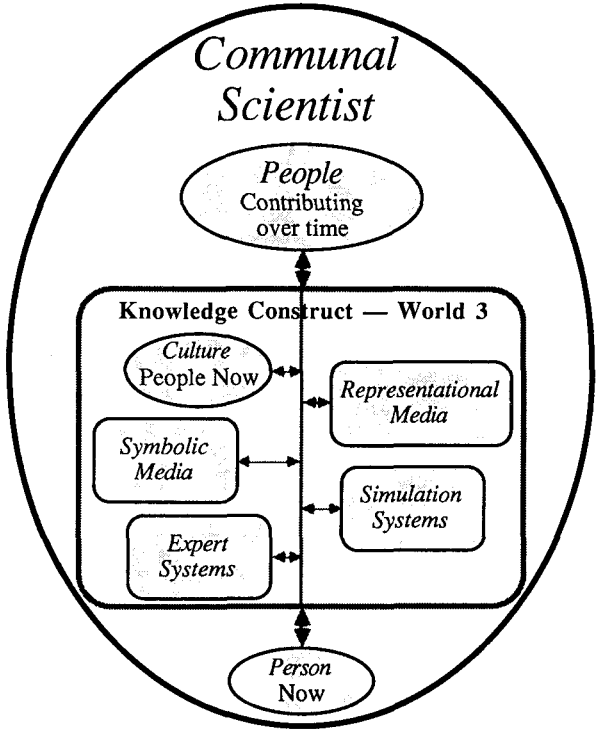


Fig. 11 — Intelligent information systems supporting the knowledge construct — computing as a vehicle to traverse World 3.

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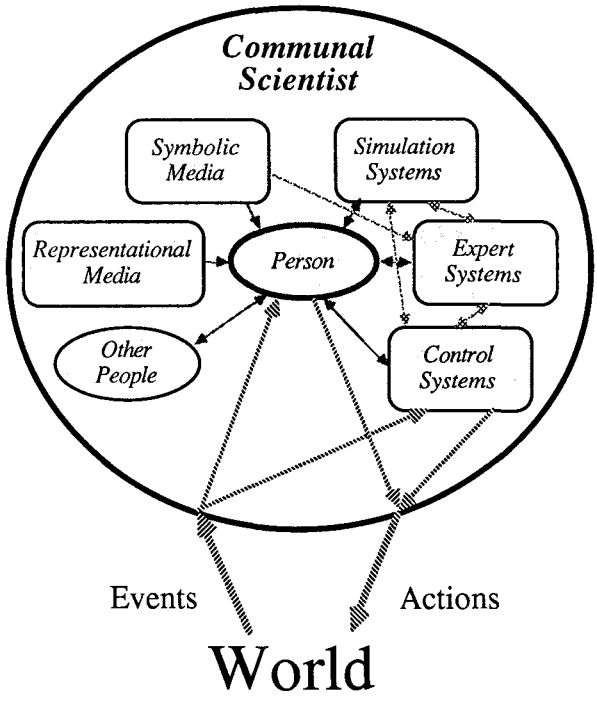


Fig. 12 — The knowledge support system of an individual — the prosthetic brain.

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