COGNITIVE FOUNDATIONS OF KNOWLEDGE-BASED SYSTEMS

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Abstract: In the development of knowledge-based systems, information technology has reached a stage in its progress 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 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 framework enables developments in information technology to be seen as natural processes in the life world, and knowledge-based computing systems to be seen as providing logical extensions to existing media. The foundational role of work in brain physiology, psychology, linguistics and logic for the sixth generation program is made apparent.

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 and knowledge-based system developments are also occurring so rapidly that the relevant literature is exploding. The specifiers and designers of future computing systems have to contend with this world of change and make reasonable projections about technologies and user expectations over the next decade. This paper 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% 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% 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% 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 his book, *The Information Age*, and by many other information scientists and social commentators. Bell (1973) has given a thoughtful economic analysis in his book, *The Coming of Post-Industrial Society*, and Wojciechowski (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 civilization 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 economy, the explosive growth of computer technology from the 1940's 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 best 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. The Japanese initiative in 1981 of scheduling a development program for fifth generation computing system (Moto-oka 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 their 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 fifth generation computing systems providing *knowledge bases* that are readily accessed by people with no specialist computer skills and are integrated into all aspects of the operation of society.

The impact of early fifth generation computing systems 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 petro-chemical, 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 fifth generation computing systems are aware of the important role of logic in knowledge-based systems and are becoming increasingly aware of the philosophical 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 fifth generation computing systems. This universality presents major problems in the socio-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 their 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 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 Artificial Intelligence of The Council on Aerospace and Electronics Technology in Tokyo (STA 1985, Gaines 1986). The Council was asked by the Ministry of Science and Technology in January 1983 to report on artificial intelligence 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 sixth generation computing system 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 expansion 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. The application areas do not differ from those of the fifth generation computing systems program but the path specified to them is far more foundational.

The transition to knowledge-based computing systems motivating the fifth and sixth generation computing system development programs requires for its support a far deeper model of the nature of knowledge and its processes than is available from any one discipline today. We have to cross disciplinary boundaries and draw on philosophy, neurology, psychology, linguistics, sociology and anthropology, to provide a comprehensive account of knowledge processes. This must be formulated in such a way that mathematically sound theoretical foundations can be developed, and then made operational through computer algorithms that take full advantage of modern developments in software engineering: object paradigm; logic programming; and so on. This is the objective of the program of work outlined in this paper. The remaining sections provide a cognitive science framework for knowledge-based systems which encompasses the social and psychological processes of people as well as the related processes in knowledge-based systems.

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 (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 behavior, 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 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 (Gaines 1977, Michalski & Chilausky 1980). It has been shown that there is a very important link between these micro-inductive processes of the individual and the macro-inductive processes of the life-world which provides strong foundations for the concepts behind sixth generation developments (Shaw & Gaines 1986). This links the logic of induction with the social construct of *expertise*, and is based on Stich and Nisbett's (1984) amendment of Goodman's (1973) theory of induction in which they propose that: "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." They term the interplay between rules and data, whereby a rule if amended if it yields an unacceptable inference and an inference is rejected if it violates an unamendable rule, a *reflective equilibrium.*

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;
3) It emphasizes the social nature of expertise and suggests that we should be considering groups of experts rather than individual experts in developing expert systems;
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 sixth generation computing systems 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 (1955) proposed a cognitive model of the individual as an anticipatory system making distinctions about the world, and recursively building up distinctions about distinctions which are predictive models of the world. He called these distinctions *personal constructs*, and his model has been termed that of the individual as a *personal scientist* (Shaw 1980). A recent extension has been to apply the anticipatory system model to society, and view social organisations as *communal scientists* (Shaw & Gaines 1986). 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 and the extended model applies to all the knowledge processes of society.

The key concept behind Figure 1 is that the primary goal of living organisations is survival and this manifests itself in a drive to anticipate the future by modeling and anticipating the world (Rosen 1985). 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 communal scientist 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 communal scientist in Figure 1 shows Klir's (1976) 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.

Gaines (1977) 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 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 (Gaines & Shaw 1981a). 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.

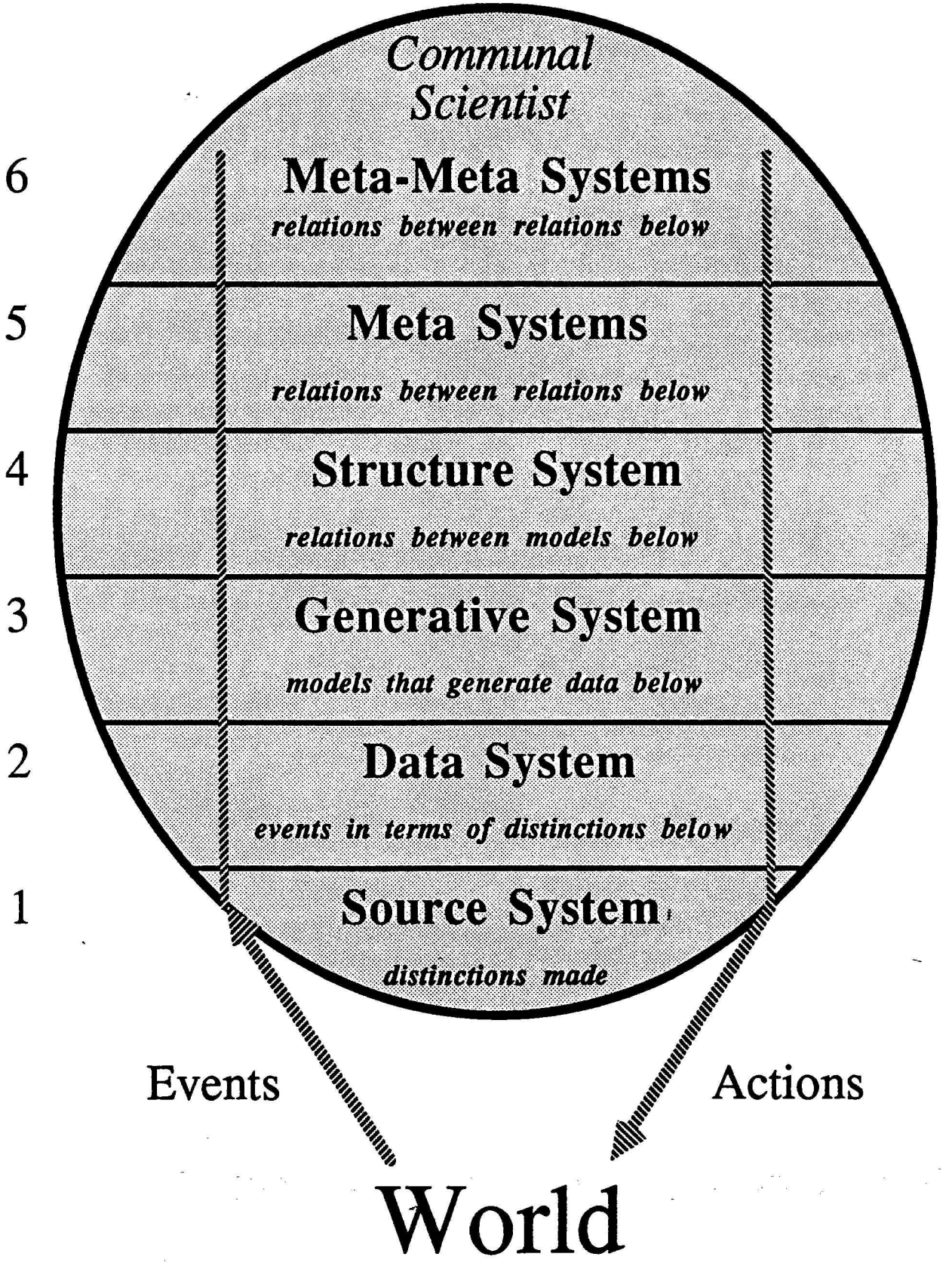

Fig.1 Modeling hierarchy of a communal scientist interacting with the world

There is physiological and behavioral evidence of the existence within the brain of the two channels of internal communication shown in Figure 1 (Tucker & Williamson 1984). 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.

Psycho-Social Processes Within a Communal Scientist

The individual within society is a cross-section of the modeling hierarchy of Figure 1 (Shaw & Gaines 1981a, Shaw 1985). Figure 2 shows three personal scientistss 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. Following Pask's (1975, 1980) *conversation theory*, an individual is defined in cognitive terms as a psychological process, or psychologically characterized individual *(P-Individual)*. Pask (1975) notes that the brain carrying out this process may be seen as a psychological processor which he terms a mechanically characterized individual *(M-Individual)*. He notes that an M-Individual is characterized as:

> "a human being (or his brain) as a biologically self-replicating system"

whereas:

> "a P-Individual...has many of the properties ascribed by anthropologists to a role, in society or industry, for example. A P-Individual is also a procedure and, as such, is run or executed in some M-Individual, qua processor."

He also notes that whilst an M-Individual may support many P-Individuals, that is, a person may play many roles, it is also possible that a P-Individual may be distributed over many M-Individuals, that is, a social unit may require the interplay of several persons.

These concepts allow more complex psychological and social structures to be shown in terms of the communal scientist and modeling hierarchy 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 communal scientist, CS1, and the personal scientists, 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 processes. In Figure 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

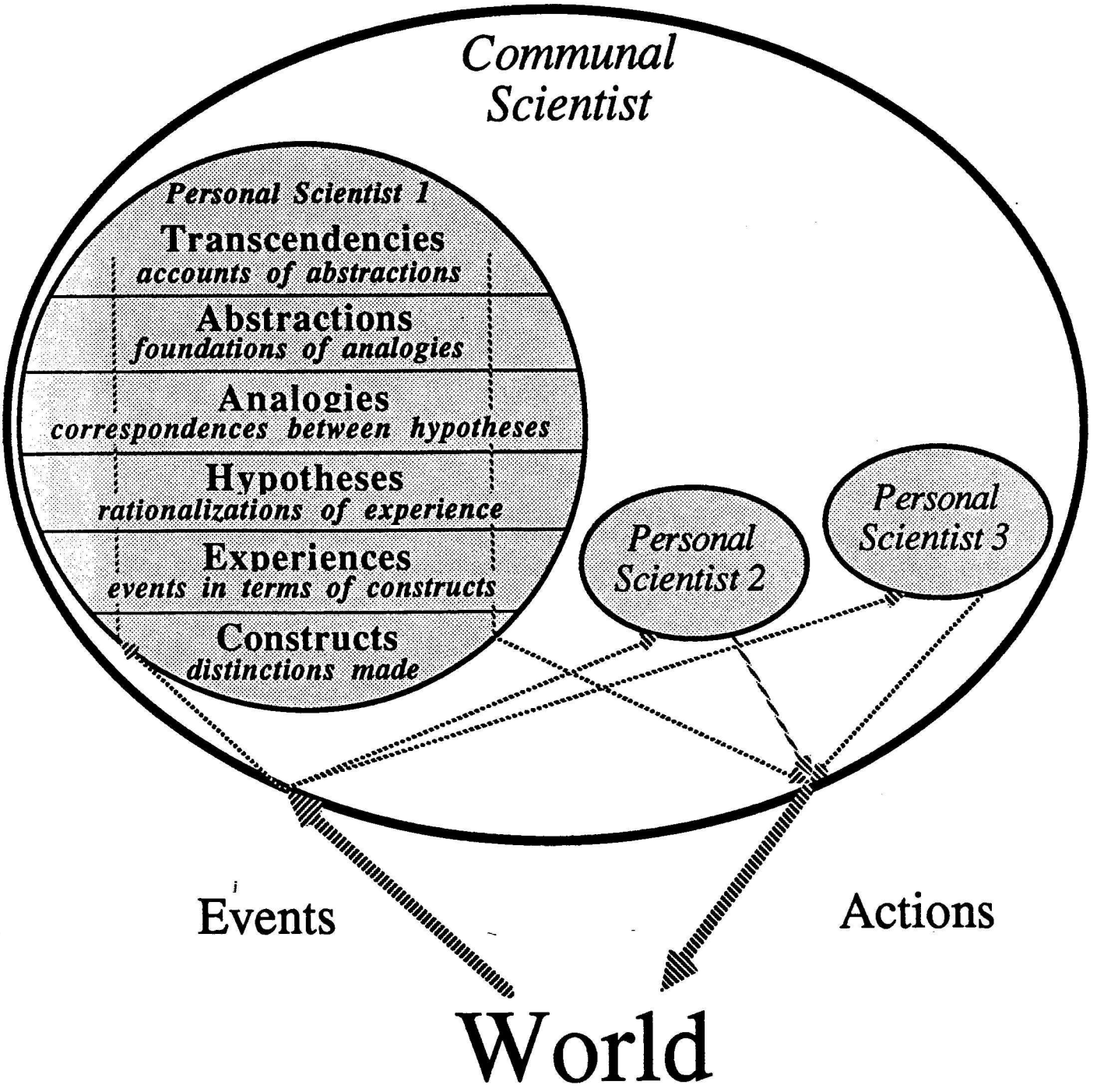

Fig.2 Differentiated personal scientists in a communal scientist interacting with the world

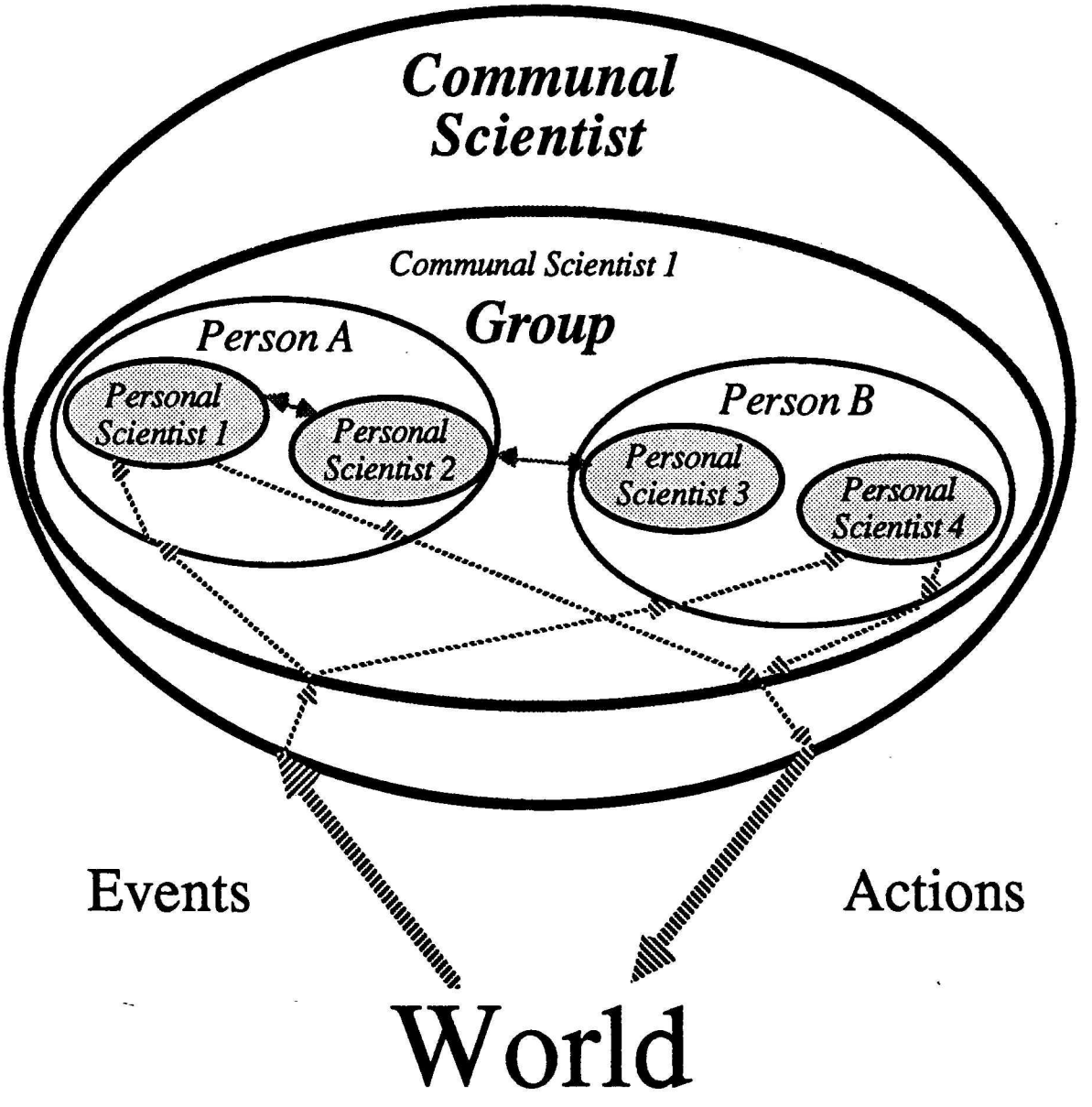

Fig.3 People, roles and groups in a communal scientist

another's actions as events in the world. PS2 and PS3 have external communication corresponding to the use of language. Pask's *conversation theory* provides an in-depth analysis of the processes whereby knowledge is transferred between individuals and has proved significant in the development of expert systems (Coombs & Alty 1984). Language in itself is an extremely difficult phenomenon to analyze and model. The communal scientist model shows it in a new perspective, as the coordinating mechanism for a hierarchical modeling system operating on distributed processors. There is an evolutionary rationale for the selective encouragement of linguistic processes in enabling the human species to perform as a social anticipatory system while operating as physically separate entities with a high degree of autonomy. It is also reasonable to expect language to be multi-level, multi-purpose and diverse in its features since it coordinates activities at multiple levels for different purpose between a variety of entities.

The concepts of Figure 3 are exemplified in more concrete terms in Figure 4 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 personal scientists. 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 an actor as a hobby. Sue is the production Vice President and another golfer. Each of these P-Individuals is distinguished and characterized by the construct system driving its processes, the distinctions it makes.

Sometimes John is acting with his wife, son 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 (Reiss 1981). John, Larry and Sue form 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 (Deal & Kennedy 1982). Anne in her role as mathematician is attempting to become part of a communal scientist which has a much longer history of existence and again sets standards and uses language which is quite different from those of the other groups shown (Wilder 1981).

The Logic of Construct Systems

Brown (1969) proposes a calculus of distinctions as a new basis for a logic more closely matching human knowledge processing, and it is reasonable to assume that

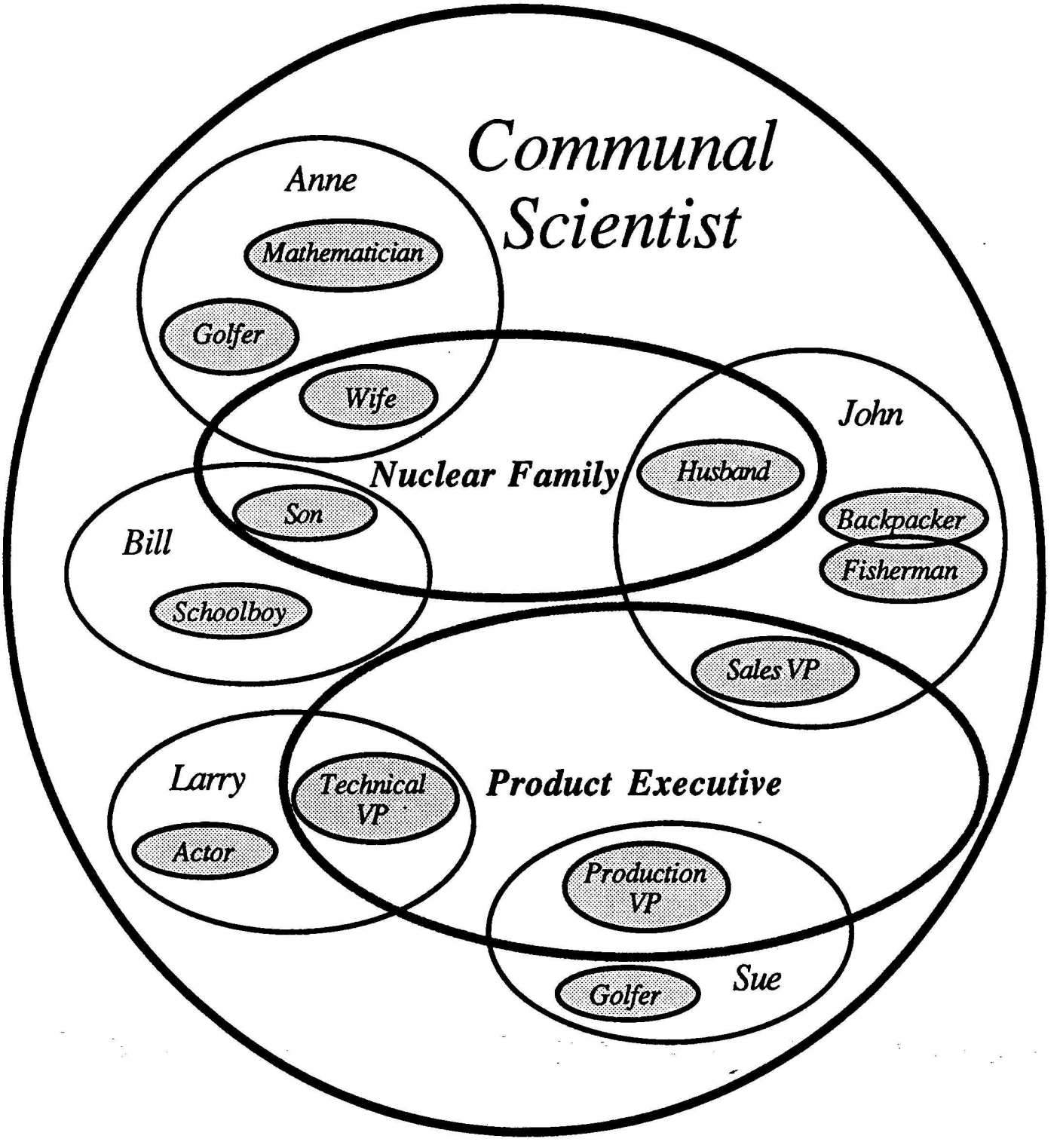

Fig.4 Examples of roles and groups in a communal scientist

"illogical" human reasoning (Wason & Johnson-Laird 1972) will not readily fit the framework of logics designed for mathematics and deliberately avoiding psychological connotations (Mohanty 1982). Kelly's personal construct psychology and Brown's calculus of distinctions both point to a knowledge representation system based on unrestricted predication as a primitive. The significance of such an axiom is that it forces us to develop system theories that do not run into the problems of this axiom in conventional mathematics. In set theory such predication allows self-reference and leads to the inconsistency that Russell discovered in Frege's (1884) *Foundations of Arithmetic*. A solution to this problem within the framework of standard predicate calculus requires the axiom of comprehension to be severely restricted by a complex set of rules defining a hierarchy of types (Copi 1971). However, this limits the naturality and applicability of logic and some logicians have attempted to develop systems that allow unrestricted predication and change the underlying logic (Fitch 1952, Martin 1970). One view is that the inconsistency may be better ascribed to the law of contradiction in standard logic: that the same predicate cannot be both true and false about the same proposition. Maydole (1975) proved that most contenders for an alternative logic led to inconsistencies in set theory, and White (1979) showed that Lukasiewicz infinitely valued logic gives a consistent set theory.

This was a particularly important result in bringing theory and practice together because it was just this logic that: Zadeh (1965) takes as a basis for fuzzy sets theory; Mamdani and Assilian (1981) used in one of the breakthrough expert systems for process control; and many later system developers have used as a basis for reasoning with uncertainty in expert systems (Gupta, Kandel, Badler & Kiszka 1985). The links from a calculus of distinctions to Lukasiewicz logic have been established: Goguen (1981) gives a model of concept formation based on a category-theoretic formulation of fuzzy reasoning; Varela (1975) used the calculus of distinctions to analyse self-referential systems using a construction based on Russell's paradox which gave a 3-valued logic; Gaines (1976) used a recursive form of this construction to generate the infinite valued Lukasiewicz logic; and Gaines (1983) shows that the Lukasiewicz axioms encompass modal, probability and fuzzy logics. The significance of this construction is that the axioms are taken first as defining a non-truth-functional *standard uncertainty logic*, fuzzy logic is then derived by adding the constraint that the logic be truth functional, and probability logic is derived by the alternative constraint that the law of contradiction applies.

The need for a system adequate to represent knowledge to encompass both imprecision and non-truth-functionality is obvious in retrospect. Most of the distinctions we make in everyday life do not have hard boundaries. The notion of a red rose is totally unambiguous and acceptable in human communication and reasoning. However, the set of red roses is not a standard set. It has boundary cases which are

neither precisely red nor not-red. Yet we can not exclude these borderline cases from being considered as red roses. The laws of contradiction and the excluded middle do not apply. This is not to say that they never apply. There are many crisp contexts in which these laws are derivable in a set theory based on Lukasiewicz logic, for example that an entity either is a number or it is not is derivable for the set of numbers defined according to the standard successor relation (White 1979).

Non-truth-functionality arises because it is not possible to ascribe truth-values to the conjunction and disjunction of uncertain events without further information about their relationship. In probability theory this is well-known: if it is 50% certain you will phone today and 50% certain that I will be out of the office, what is the certainty that you will phone when I am out of the office? The answer can range from 0% if we have pre-arranged, to 50% if the two events are not causally connected, to 100% if I do not want to talk to you. It is possible to compute the constraints upon the result but not a single-valued result. Quinlan (1983) has shown that the constraint systems of such non-truth-functional logics may be used as a basis for improved inference in expert systems with uncertain rules and data. Fuzzy logic can be seen as resulting from the requirement to avoid the calculation of such constraints by imposing truth-functionality. The common assumption of independence of events in probabilistic situations is an alternative way of forcing truth-functionality. Both these approaches are expedients whose utility depends on the problem domain.

Much work remains to be done on the reasoning processes deriving from the modeling hierarchy and the logics that may be seen as underlying them. Whatever model results will be characterized by taking unrestricted predication as a basic requirement and hence going beyond current standard predicate calculus.

The Dynamics of Construct Formation[i]

It is fairly straightforward to analyse the operations of P-Individuals once they exist. Psychology and sociology have a solid systemic foundation in terms of the theory of personal constructs and the calculus of distinctions. However this leaves open the generic question of how such unities form and change—Kelly took *constructive alternativism*, that we can always find new perspectives, as the most crucial feature of his psychology (Mancuso & Adams-Webber 1982). In psychological terms, emotional processes play an important role in the formation of the processes which are P-Individuals, although as Norman (1980) notes its role has been neglected in cognitive psychology. Melges (1982) notes that:

> "the normal function of emotions is to attune the person to overall discrepancies between the present and the future so that he adjusts his plans of action to his future images."

In systemic terms it is the surprise signal that travels up the modeling hierarchy to indicate discrepancies between the model and the data. In inductive inference terms this indication may be used either to amend the model or to reject the data. The distinctions which correspond to rules of inference that are regarded as unamendable are termed by Kelly (1955) *core* constructs:

> "Core constructs are those which govern a person's maintenance processes—that is, those by which he maintains his identity and existence."

Systemically, the existence of core constructs corresponds to our not being able to re-evaluate all past experience in the light of a new model. We encapsulate that experience in a model based on distinctions to which we give inertia through reluctance to change. A system that amends its core constructs becomes detached from its own history and loses what has been learned from past experience. The optimization between readiness and reluctance to change is a function of the stability of the system's environment and part of its adaptive process.

Kelly models negative emotions as resulting from experiences that threaten to require changes in core constructs, and McCoy (1981) has given a detailed taxonomy of emotions based on the type of core construct that may have to be changed. The deviation from the model indicated by the surprise signal may be seen as having adverse or beneficial consequences, being distracting, requiring attention, investigation, action, and so on. Thus human emotions may be seen as derived from surprise with the type of emotion varying according to circumstances: negative from distinctions we wish to retain and positive from those we prefer to change. From a systemic point of view human feeling tones are signals directing the inductive inference process.

Gray (1979) gives further insight into the system dynamics involved by linking the emotions with the processes of system formation. He introduces his notion of *system-forming precursors* as part of his *emotional-cognitive structure theory* for *understanding creative thought processes*. He notes that emotions are integrating devices for the formation of thoughts and coding devices for memory. He models system formation as occuring when *precursors* are brought together: *activators* initiate emergence of an organizing focus allowing entry to a group; and *blockers* inhibit emergence of an organizing focus preventing entry to a group. He defines *lock-out* as a situation in which blockers prevent entry to a group which may lead to the behavior of *break-in*, and *lock-in* as that in which withdrawal from a group is prevented which may lead to the behavior of *break-out*.

If we view a group as a surviving system that is dependent on its members for its own existence then the system dynamics proposed by Gray may be seen as part of the overall life cycle of the role of an individual within a group shown in Figure 5. At the first stage shown at the bottom of the diagram an individual who is not part of the

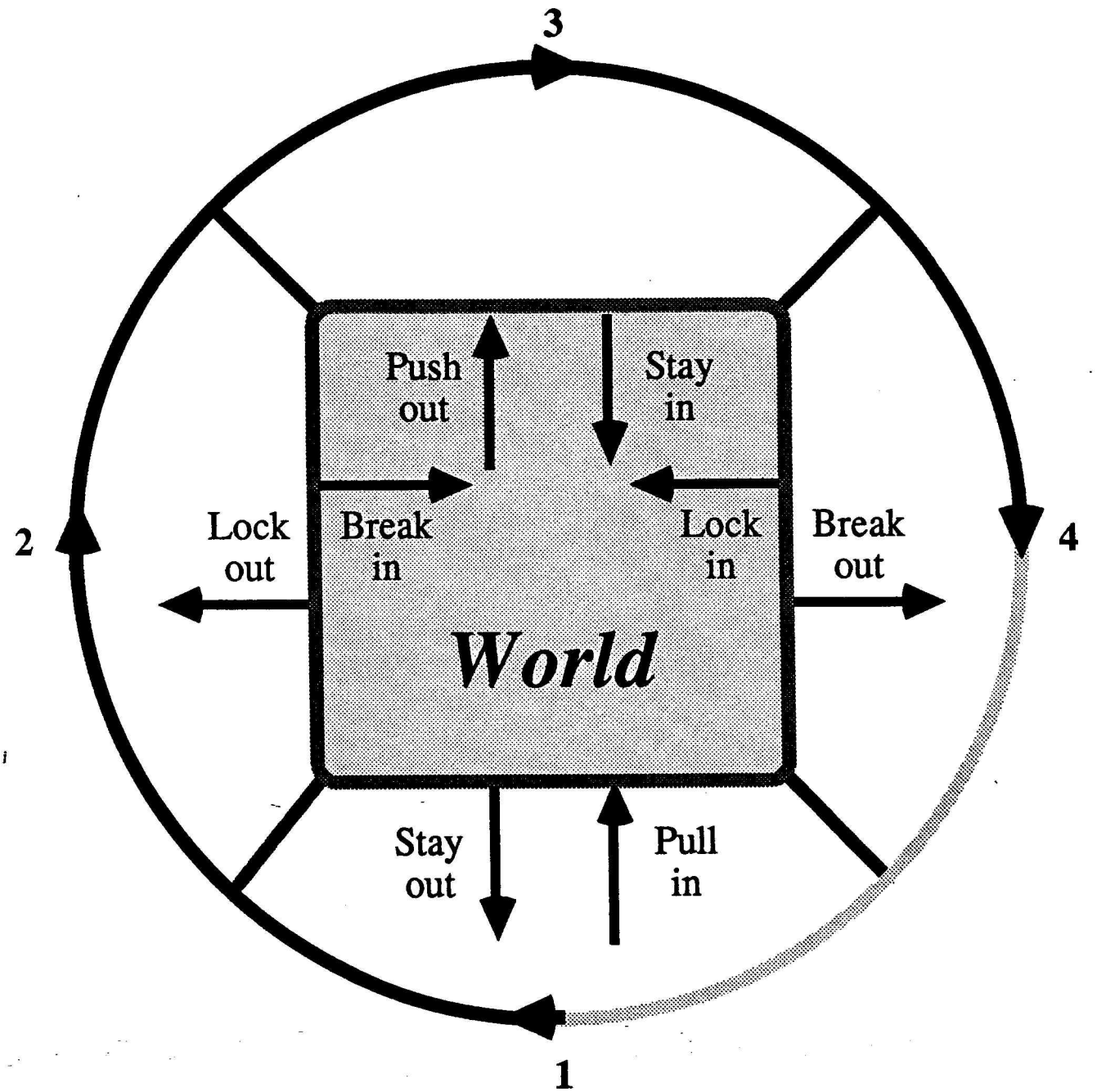

Fig.5 The life cycle of individual membership in a group

group is attracted to it but resists the attraction: the *pull-in—stay-out* dynamics. In systemic terms there is a possibility of bringing the *expertise* represented by the distinction system of the group into the *reflective equilibrium* of the individual. In personal construct terms: the attraction is summed up in Kelly's choice corollary, that alternatives are chosen through which greater possibilities for definition and extension of the model are anticipated; the reluctance stems from the need to discard core constructs in accepting the system characterizing the group. Maslow (1971) sees the pull-in as satisfying a *need to belong* and the systemic model gives the process underlying that need. Gray's *blockers* are the core constructs which we are reluctant to discard in accepting the system of the group and his *activators* are those where we welcome the discard.

At the second stage the individual has decided to attempt to join the group but now faces the barriers to membership, the requirement to acquire the core constructs of the group in order to become recognized as a valid member and not as a *stranger* in Simmel's (1950) terminology: the *lock-out—break-in* dynamics. At the third stage the individual has become part of the group but this is not a static process since the reflective equilibrium between his inference processes and those of the group must be maintained: the *push-out—stay-in* dynamics. At the fourth stage the individual has decided to reject the construct system of the group but has difficulty in ceasing to make distinctions which now correspond to his core constructs: the *lock-in—break-out* dynamics.

Worlds Defined by Construct Systems

The life-cycle model of individuals entering and leaving groups emphasizes that the groups have an identities that are distinct from those of the individuals forming them. This is defined by the construct systems of the groups which may become sufficiently separate from those of any individual that they become regarded as an abstract set of distinctions defining a *world*. Wolff's (1976) book about "experience and enquiry today" has much in it that is relevant to the formation of groups as communal scientists and the ways in which individuals enter into them, and bridges the gap between Gray's system-forming processes and abstract worlds. His basic model is one of *surrender* to a situation so that one may *catch* the essence of it—of becoming through surrender someone different in order to catch hold of something different—of relinquishing one's own core constructs in order to adopt those of a group. Using Wolff's terminology, we *surrender* ourselves to a particular role and *catch* its essential core constructs in order to become a physicist, a mathematician, a manager, a father, and so on.

The link between Wolff's model of surrender and catch and the notion of abstract worlds is most clearly presented in terms of his discussion of the nature of the *mathematician*:

> "From the standpoint of the world of everyday life, the mathematician, as we often put it, lives in the 'world of mathematics', dealing with 'nonreal' elements, notably numbers, whose relation to 'real' things, to 'reality', is not part of his concern. Analogously for the logician. What makes our subject-object approach to this attitude misleading is the fact that the subject, the student of mathematics or logic—his or her individuality, including motives and attitudes—is *irrelevant* for our understanding; the only thing that counts is the pursuit, with its results and questions." (Wolff 1976 pp.162-163)

He makes the key point that not only does the *real world,* the *object*, disappear to be replaced by the world of mathematics, but also that in entering into this world the person *doing mathematics,* the *subject,* also disappears to be replaced by a new entity, *the mathematician.*

Popper (1968) reifies the notion of such a world, which in the discussion so far has played only a descriptive role as the construct system binding together people into a social unity, and terms it a *world 3*. He explains the 3 worlds model in his autobiography (Popper in Schilpp 1974 p.143) by quoting Bolzano's notion of "truths in themselves" in contradistinction to "those thought processes by which a man may...grasp truths", proposing that:

> "thoughts in the sense of contents or statements in themselves and thoughts in the sense of thought processes belong to two entirely different 'worlds'."

and making the three-fold distinction:

> "If we call the world of 'things'—of physical objects—the *first world* and the world of subjective experience the *second world* we may call the world of statements in themselves the *third world* (...world 3)."

This notion of a world 3 is corresponds to Wolff's *object* that we catch and has its own ontological status:

> "I regard the third world as being essentially the product of the human mind. It is we who create third-world objects. That these objects have their own inherent or autonomous laws which create unintended and unforseeable consequences is only one instance (although a very interesting one) of a more general rule, the rule that all our actions have such consequences." (Popper in Schilpp 1974 p.148)

From a systemic point of view the world thus defined corresponds to the abstraction of the construct system of a group and its treatment as an entity in its own right, with its own coherence through superordinate constructs and hence its own *laws*. This viewpoint is illustrated in Figure 6 where the construct systems of those forming the groups in Figure 5 are abstracted out to define the worlds of mathematics, the family

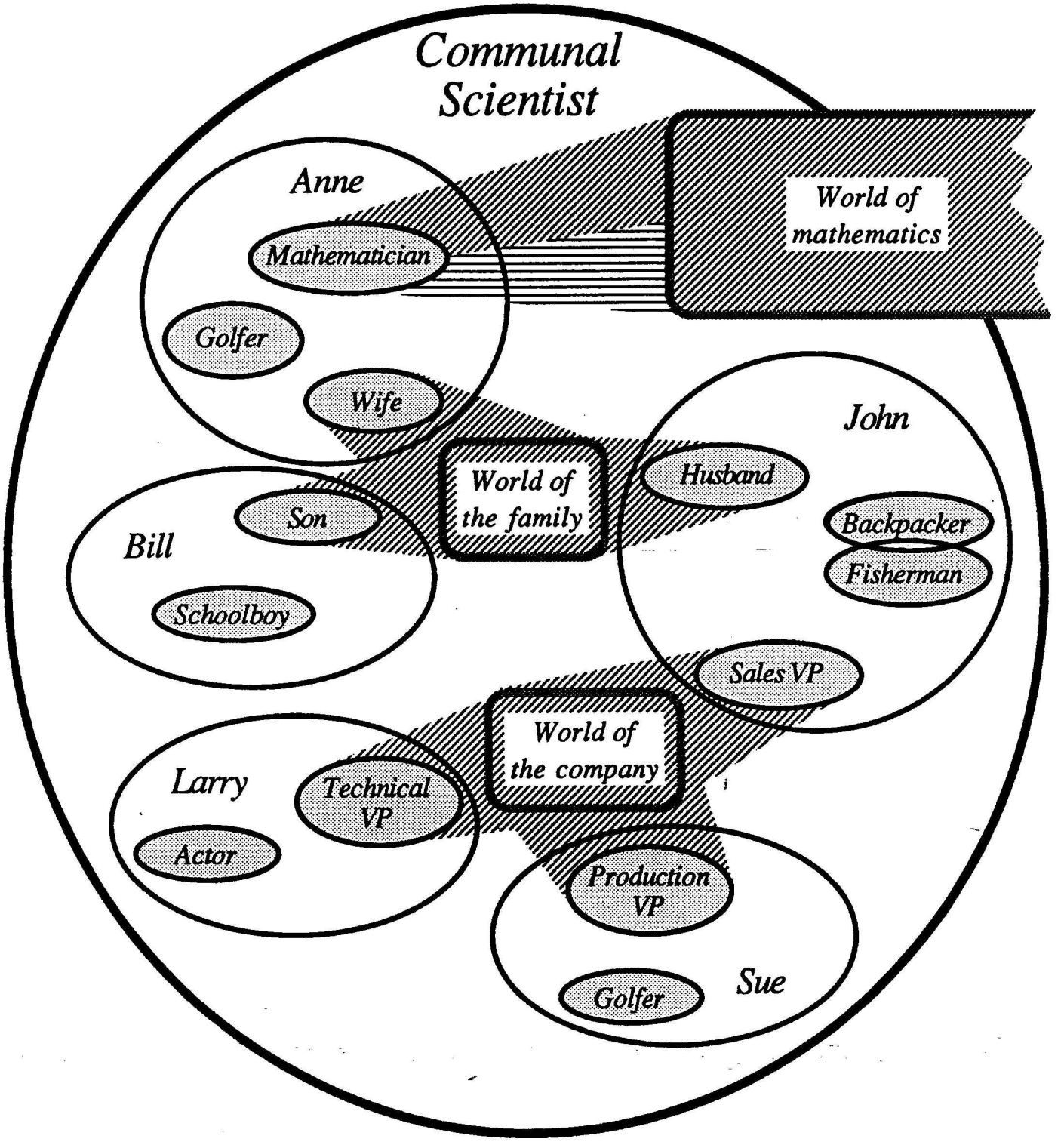

Fig.6 Worlds accessed by groups in a communal scientist

and the company. The worlds of the family and company are shown as part of the communal scientist since they are regarded as parochial to the communal scientist shown. The world of mathematics is shown as extending beyond the boundaries of the communal scientist under consideration reflecting its status as the product of many contributors over a period of time that extends beyond most of our other social organizations.

Anne's access to the world of mathematics is also shown as partial. She is attempting to carry over some constructs that are inappropriate and this presents her accessing the world of mathematics. Anne's situation is shown in more detail in Figure 7. Her surrender to the world of mathematics is inadequate and she cannot catch it because her attempt to break in is being locked out by the inappropriate constructs. She has surrendered to the world of the family but now wishes to break out of the situation to which she is locked in and is attempting to make familial constructs non-core and view the family unit through the constructs of an outsider.

The Significance of the Communal Scientist as a Cognitive Model

The communal scientist model links system-theoretic foundations of induction with the psycho-social dynamics of the human knowledge process including the essential role of emotion in cognition and the essential role of social processes in individual modeling and anticipation. If we are to develop knowledge-based systems and artificial intelligence we must have an adequate scientific theory of knowledge, human intelligence, and their mutual interaction. The raw material required to develop a theory is available but widely dispersed through many scientific disciplines. This section has shown the potential for bringing this material together in providing cognitive foundations for knowledge-based systems that have mathematical foundations supporting computer algorithms and also correspond to psychological, social and physiological reality. The next section examines some of the implications of the communal scientist model for the role of computer technology in knowledge processes.

EXPERTISE AND MEDIA WITHIN A COMMUNAL SCIENTIST

Media have been developed to support and enhance the knowledge processes of human society and are readily modeled within a communal scientist (Shaw & Gaines 1984). The direct experience of the world shown as the basis of the inductive modeling process in Figure 1 is very inefficient if carried out by every individual in a society. The distributed processors that make up the communal scientist need to share experience and the knowledge resulting from it. Direct communication through gesture, drawing and speech is a basic mechanism for such sharing but is itself inadequate on the scale of modern society.

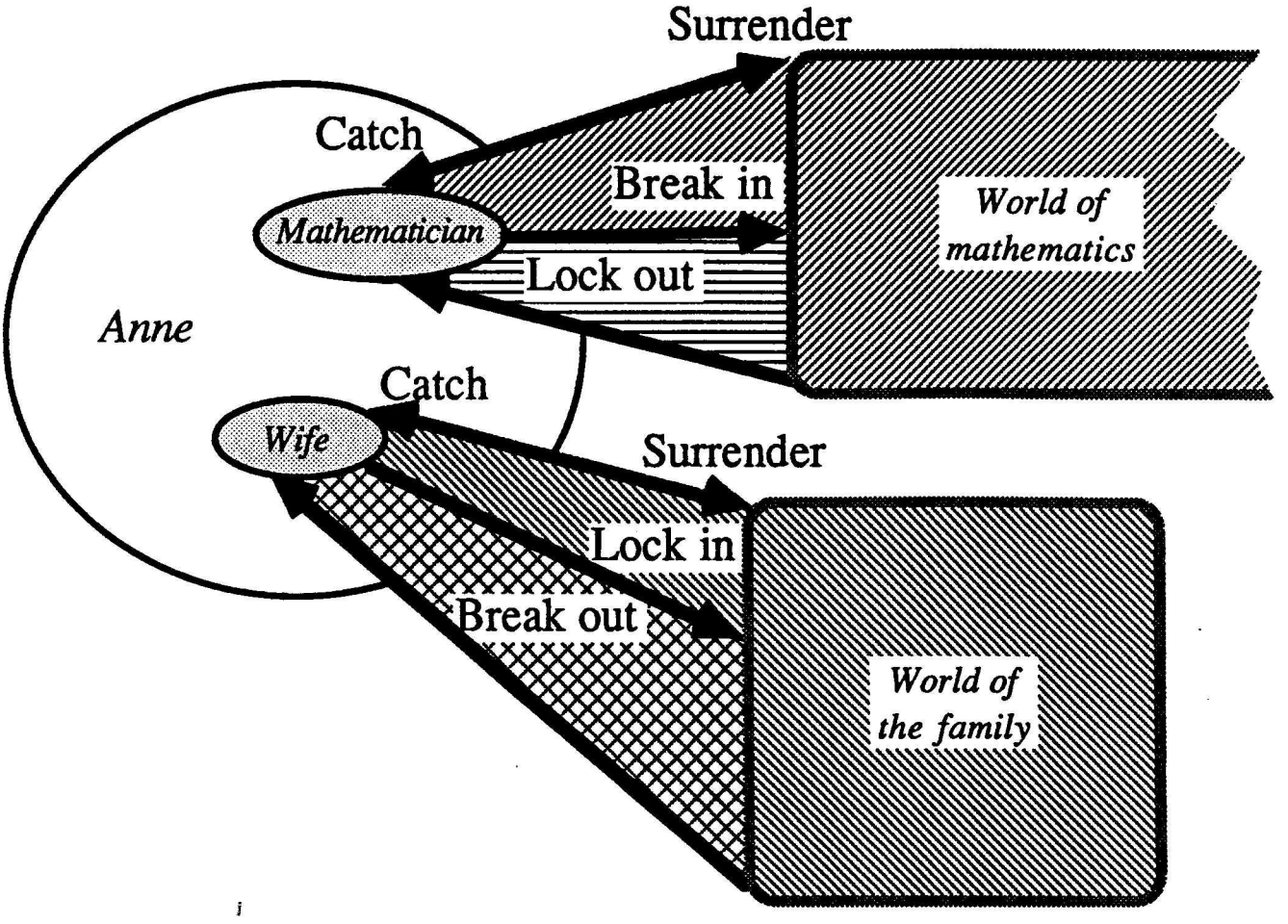

Fig.7 Examples of lock-out/break-in, lock-in/break-out and surrender/catch

Representational Media in the Communal Scientist

Figure 8 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 (Gaines & Shaw 1984a). 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.

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 (Gaines & Shaw 1985a). 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.

Symbolic Media and Expertise in the Communal Scientist

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 9 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 (Gaines & Shaw 1984a).

Some of the problems of knowledge engineering, of transferring knowledge from experts to expert systems, are also apparent in Figure 9. PS4 is the process with the required skill in Person B and has to communicate through PS3, an external language process, but sometimes this link may be unavailable (Bainbridge 1979). Similarly PS5 requires the skill in Person C and has to be able to communicate internally with a language process 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 Figure 9 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 10. The expert system has an internal structure of processes that mimic those of its source, Person B. A

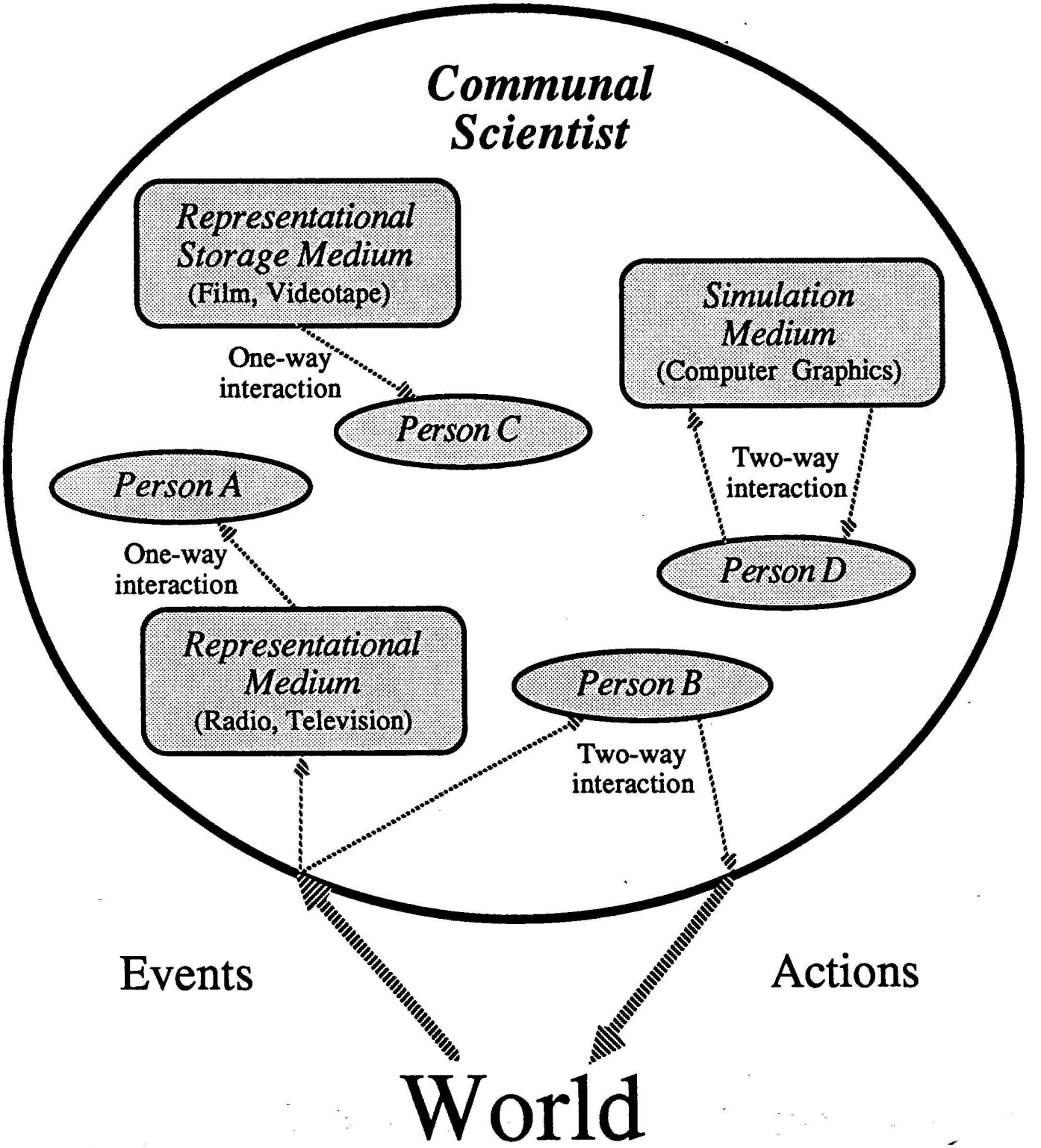

Fig.8 Representational media in a communal scientist

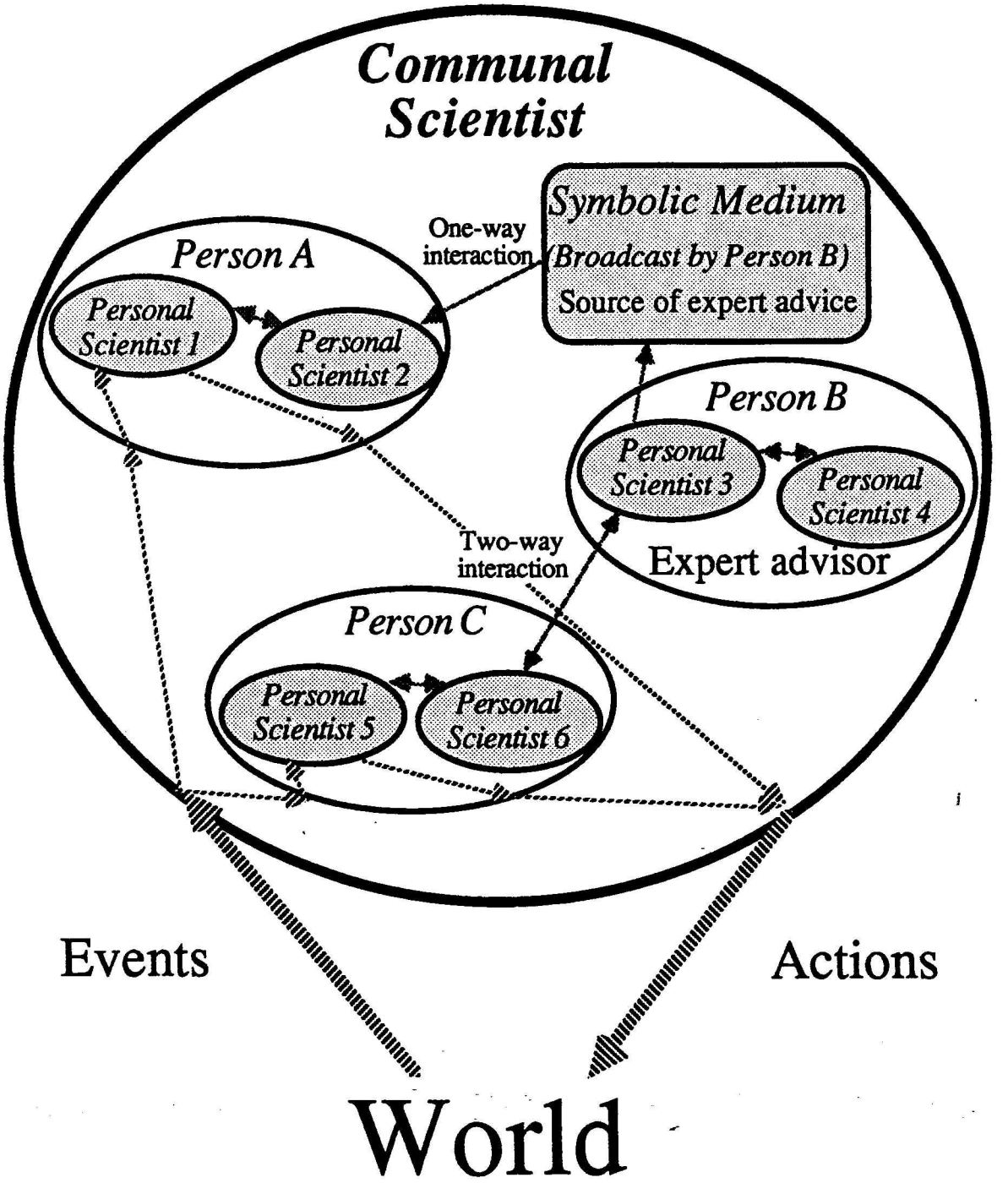

Fig.9 Symbolic media in a communal scientist

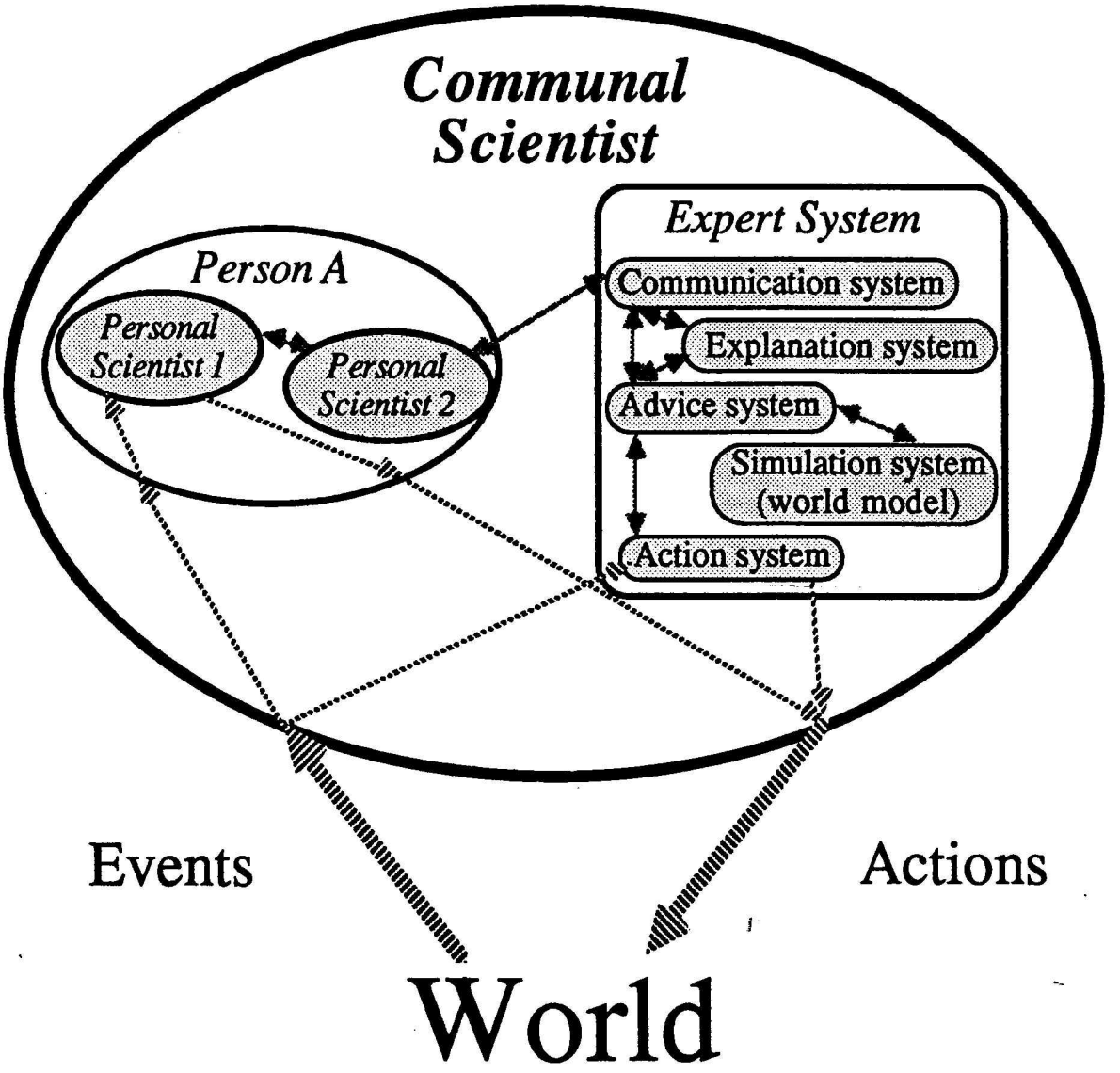

Fig.10 Structure of an expert system within a communal scientist

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; possibly, a simulation system if the advice is based on a deep model of the world; and, possibly, a control system if the expert system has direct access to the world.

Cultural Transmission of Knowledge

The communal scientist and personal scientist models apply to the expert system in Figure 10 as much as they apply to the person, and the structure of the expert system can be represented in the inductive system hierarchy of Figure 1. Figure 11 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 (1959) 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.

PLANET: A Conversational Support System

Knowledge transfer to expert systems 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 (Michalski & Chilausky 1980), and on interview techniques based on personal construct psychology at the formal level (Shaw & Gaines 1983b, Shaw 1984, Gaines & Shaw 1986, Boose 1985).

Figure 12 shows the *conversational support system*, PLANET, that has been developed using repertory grid elicitation to capture personal models of the world and make them available through an expert system (Gaines & Shaw 1981b, Shaw 1982, Shaw & Gaines 1981a,b, 1983a). Kelly (1955) developed the repertory grid as a means of accessing the personal construct systems of individuals. It has been operationalized through a suite of interactive computer programs that have been

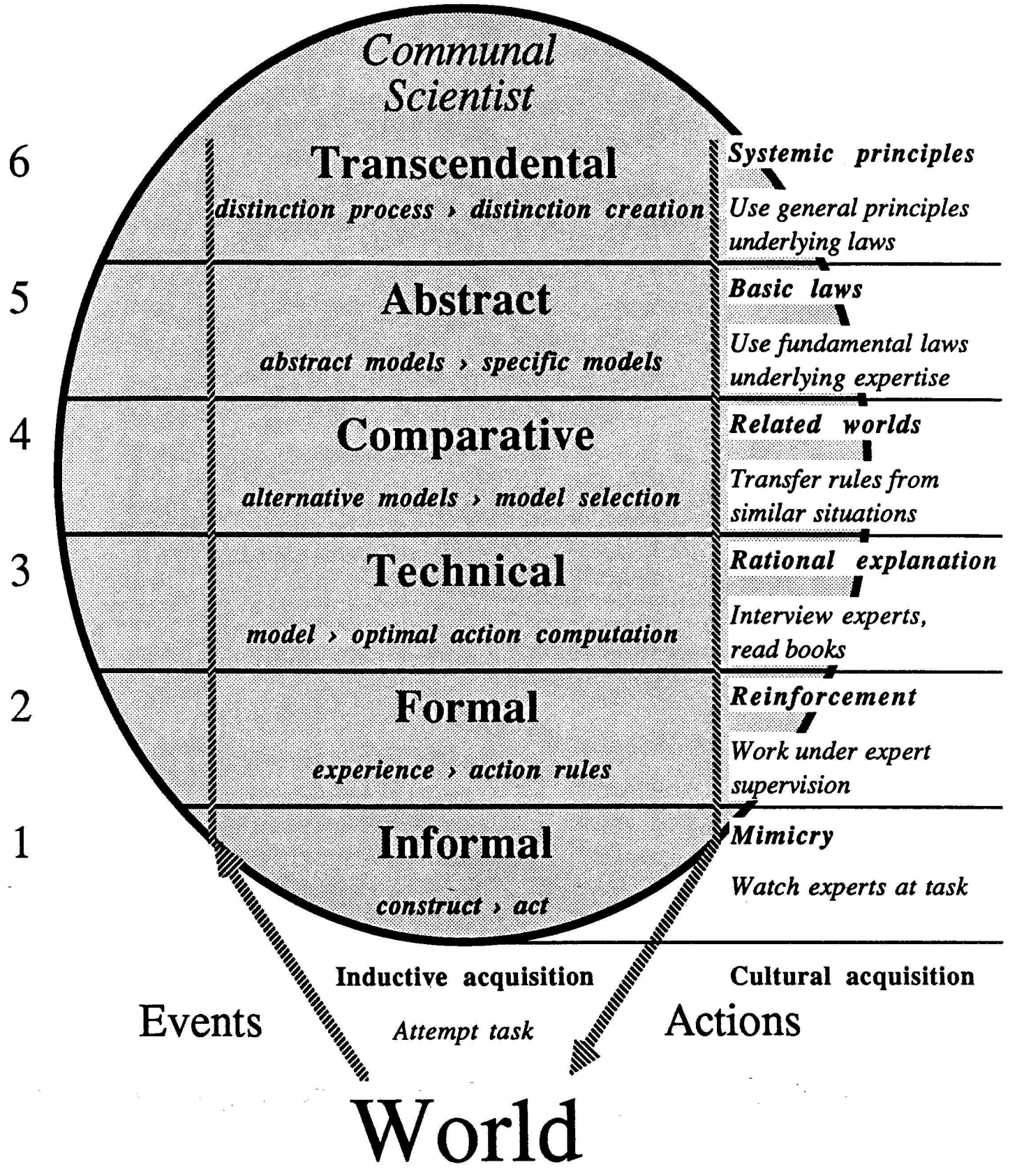

Fig.11 Sources in the cultural transmission hierarchy of a communal scientist with applications to knowledge engineering for expert systems

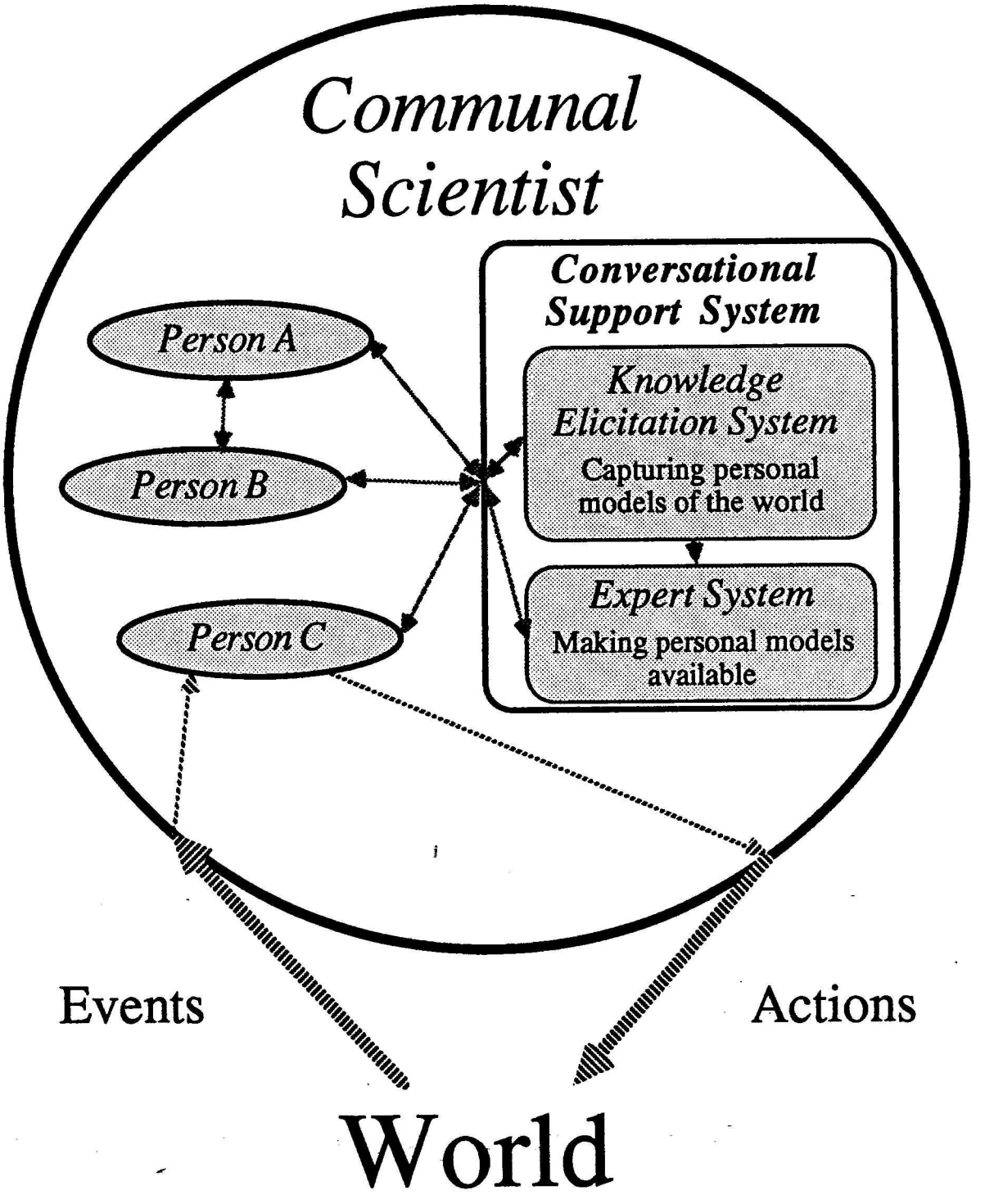

Fig.12 Conversational support system integrating a community

widely used in educational, clinical, management and industrial applications (Shaw 1980, 1981, Pope & Keen 1981, Shepherd & Watson 1982).

The Knowledge Construct and World 3

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 knowledge-based computing systems of the future will add such capabilities to the symbolic and representational storage media of current information technologies. Fifth and sixth generation computer technologies should be thought of as extending and integrating current media rather than replacing them.

Figure 13 shows how Wojciejowski's *knowledge construct* and Popper's *world 3* 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 develop *vehicles* to traverse world 3 (Gaines 1978), and trigger off an information revolution.

Towards the Prosthetic Brain

The social perspective of Fig. 13 is complemented by the personal perspective of Fig. 14 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 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 fifth and sixth generation priorities and developments that are leading to intelligent information systems.

CONCLUSIONS

The development of intelligent information systems 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 targeted on

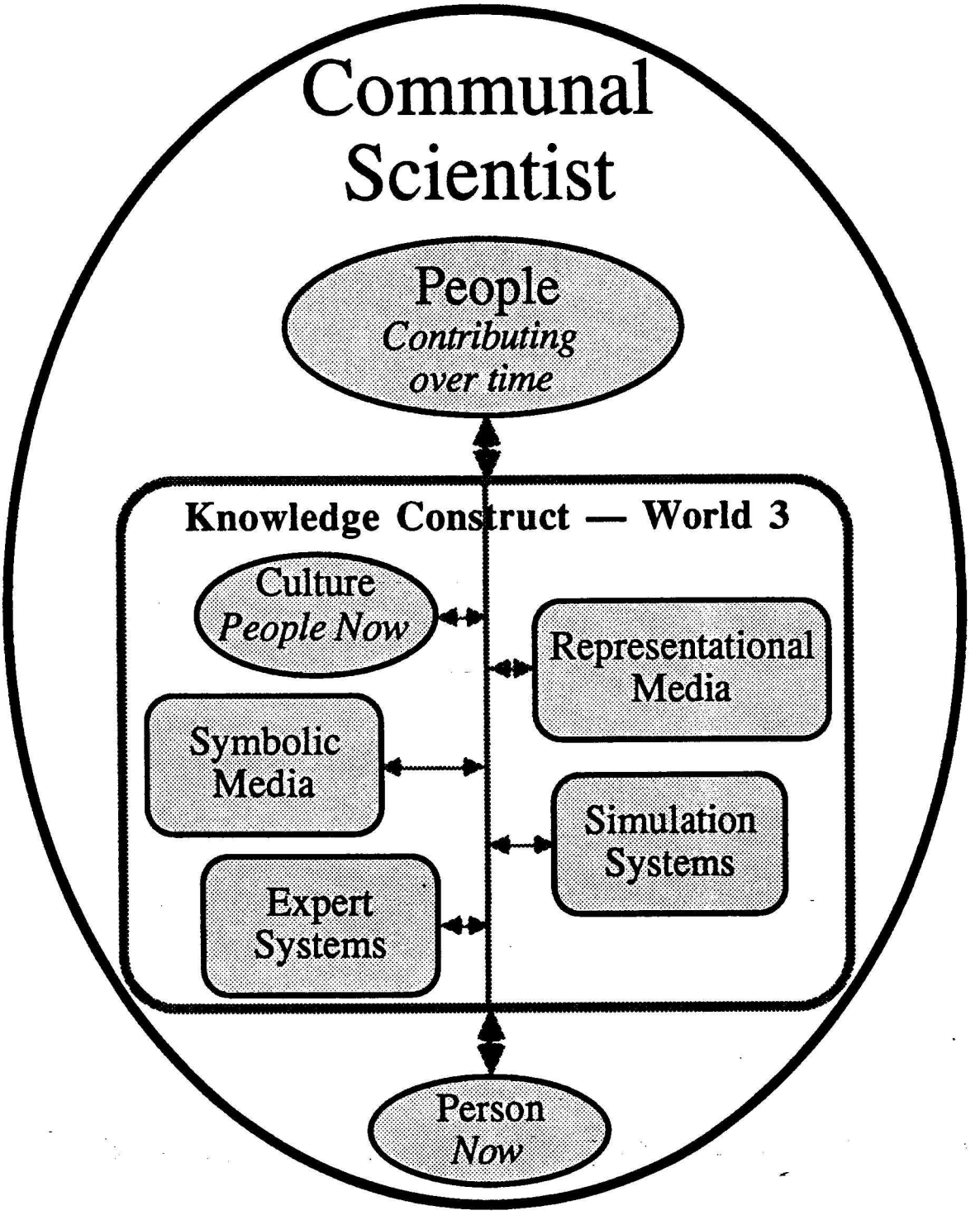

Fig.13 The knowledge construct—world 3

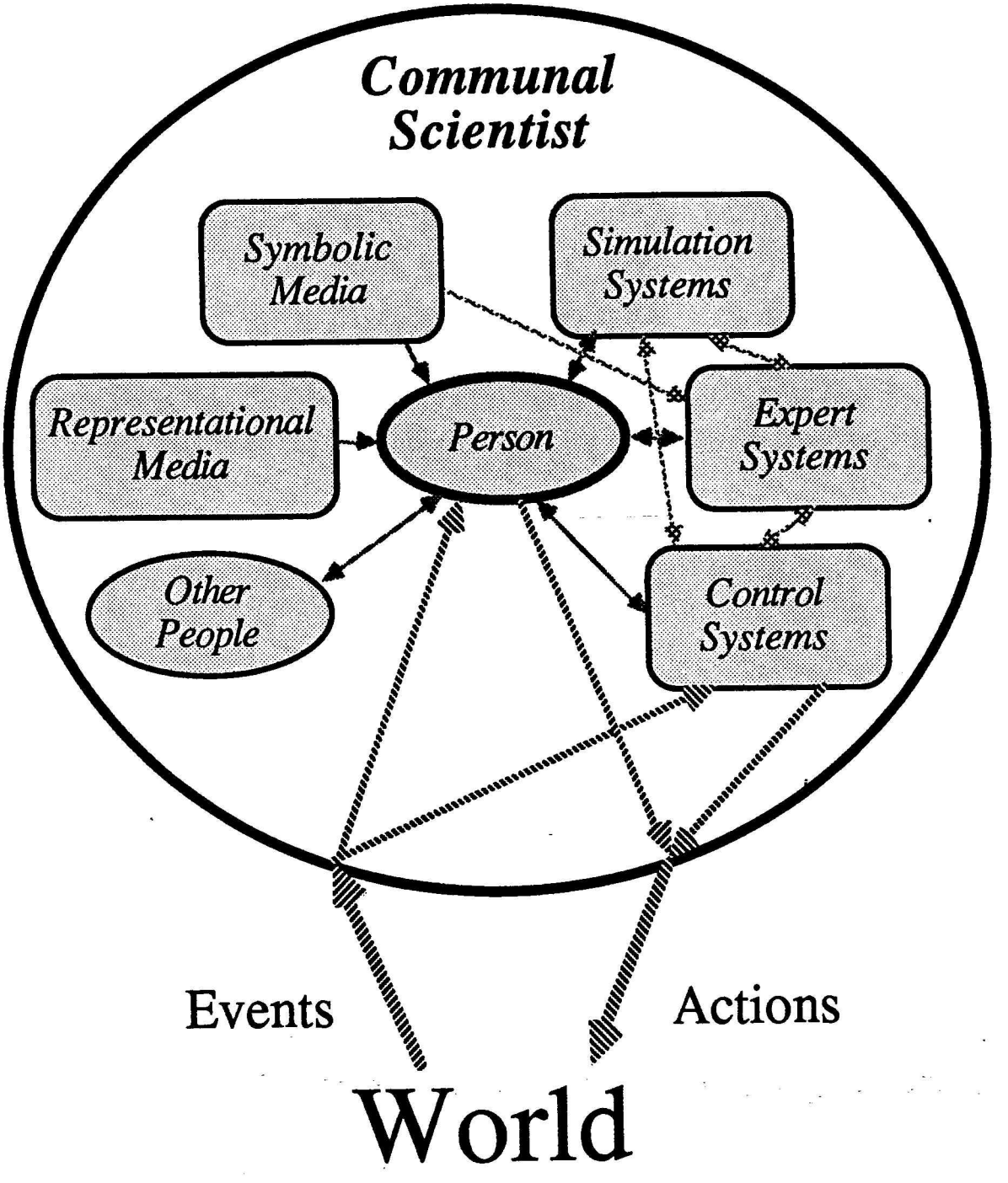

Fig.14 Knowledge support system for a personal scientist—the prosthetic brain

system integration and the sixth generation computing system development program is targeted on knowledge science.

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 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. The logic underlying the inductive and deductive reasoning processes of the system is one based on an axiom of unrestricted predication and able to cope with uncertainty and contradiction. 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.

Clearly psychology, logic, brain physiology and linguistics are key to the further understanding of knowledge processes necessary to the development of future computing systems. The fifth generation computing systems development program should give us knowledge processing hardware with the capabilities to operate on equal terms with the human brain. The sixth generation computing systems development program should give us the cross-disciplinary collaboration between physiology, psychology, philosophy and linguistics necessary to model the basic human knowledge processes. On the basis of this paper we speculate that seventh generation developments will find it necessary to go beyond these individualistic disciplines and develop further cross-disciplinary interaction with anthropology and sociology in order to model the full scope of the knowledge construct underlying human development.

ACKNOWLEDGEMENTS

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