Steps towards knowledge science

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There is growing convergence between psychology, systems theory and computer science towards what might be called knowledge science. Personal construct psychology is able to provide foundations for cognitive science that subsume previous information processing models and extend them to realms of human knowledge processes, including social interaction, creative thinking, emotion and personality. Systems theory is now at a stage where it can contribute a framework for these ideas that expresses them without unreasonable distortion. For psychology this opens up the possibility of an integrative theory encompassing all aspects of human life and contributing formal foundations to clinical, educational, social and applied psychology. For fifth and sixth generation computing systems this opens up the possibility of true human-computer symbiosis in which natural and artificial knowledge processes are fully integrated.

The Convergence of Psychology, Systems Theory and Computer Science

There is growing convergence between psychology, systems theory and computer science. The disciplines have interacted to become major influences on one another's development. The paradigm of *cognitive psychology* involves applying information processing concepts to human behavior (Newell & Simon 1972, Estes 1978). *General systems theory* (Von Bertalanffy 1968) and *cybernetics* (Wiener 1948) involve modeling the organism as an information processing entity. *Fifth generation computing* (Moto-oka 1982) offers natural person-computer interaction using techniques derived from artificial intelligence studies in computer science (Gaines 1984a). *Sixth generation computing* (STA 1985) is projected to integrate advances in neurology, psychology, linguistics and logic, into a new discipline, *knowledge science*, that will provide foundations for the knowledge-based systems of the future (Gaines 1986).

This convergence is now significant to the goals of each of these disciplines, all of which show immense promise but none of which has yet achieved its objectives. Cognitive psychology has concentrated on very limited aspects of human perception and cognition and has neglected key areas of psychological phenomena such as emotion and consciousness (Norman 1980). General systems theory and cybernetics have generated many interesting methodologies but no coherent overall theory with strong formal foundations and widespread application (Gaines & Shaw 1984). Fifth generation computing has been described by the Japanese as dependent on three major areas of development, hardware, software and human psychology, but the actual research program has activities only in the first two areas (Gaines 1984b); for the moment it is being assumed that classical logic adequately expresses human knowledge processes (Fuchi, Sato & Miller 1984), a dubious assumption. Sixth generation computing is still at a conceptual stage, and many doubt the possibility of the cross-disciplinary integration required.

We have argued in a number of papers that Kelly's *personal construct psychology* (PCP) provides the foundational material necessary and sufficient for the culmination of the convergence between the three disciplines (Gaines & Shaw 1981, 1984, Shaw & Gaines 1979, 1981):

- The information processing model of man may be subsumed and extended within PCP by generalizing the notion of information as suggested by Bar Hillel and Carnap (Bar Hillel 1964) to *semantic information*. PCP gives an operational explicatum for the notion of *search for meaning* as the basic human dynamic.
- General systems theory and cybernetics may be subsumed and extended within PCP by noting that they are products of the mind reflecting on nature, on itself, and on the results of its own reflection. PCP gives a theory of people theorizing, a fully recursive model of *man the modeler* and his models.
- The development of computational mind-tools may be subsumed and extended within PCP by using the theory of people as modelers to design computing that is consistent in its processes with that theory. PCP concepts are realizable through technology, both stand-alone as artificial intelligence, and interactively as a new medium extending man's capabilities through human-computer symbiosis.

The Systemic Nature of the Fundamental Postulate

Kelly's starting point, the fundamental postulate, is systemic in attributing the psychological processes of the person to his anticipation of the future:

> "A person's processes are psychologically channelized by the ways in which he anticipates events." (Kelly 1955, p.46)

It is significant to note that this postulate does not mention constructs—they arise through the construction corollary, and that Kelly spends considerable effort on detailing the role and importance of each word in this statement. This postulate has great generality and the specific wording used cannot capture this fully. In a sense every word in it is technical and should be construed free of all previous associations. This is clearly impossible but may be approximated by taking each word as evocative through associations of the general principle being stated. The fundamental postulate as stated is a parable indicating a general principle.

In systemic terms the postulate may be paralleled as:

> "An autonomous system is organizationally structured by the way in which it models information,"

- We use the term *autonomous* in the sense developed by Maturana (1975) and Varela (1979) as that distinction necessary and sufficient to chararacterize living organisms. Their characterization is organizational rather than physiological or teleological and specifies the structure of the system's organization rather than that of its cells or its goals. Pask (1981) and Zeleny (1977) have noted how the concepts apply to the psychological characterization of people and of social organizations, respectively.
- We use the term *models*, as Kelly does *anticipates* to encompass both prediction and action. in technological forecasting terms modeling may be either predictive or normative (Jantsch 1967). Whether we improve our models of the world by adjusting them to fit the world or the world to fit them is part of our modeling strategy, science does the first and technology the second, and the theory need make no fundamental distinction between them. Kelly (1955) emphasizes man the scientist forming a construct system to give meaning to experience, but he also gives examples of how this leads to action which changes the world and creates experience—PCP is also a theory of *man the technologist*.

- We use the term *information* as encompassing all sources and forms of message irrespective of their mode of transmittal. From a systemic point of view such messages arise as an artefact of our distinguishing one part of a system from another. To account for the correlations between processes boundaried by our distinction we have to hypothesize information passing between them. Natural boundaries are ones which minimize the message passing that we have to hypothesize, and delimit systems whose internal organization is substantially more complex than their external relationships. It is in this sense that autonomous systems are *informationally open* but *organizationally closed* (Varela 1979, Pask 1981).

The processes involving an autonomous system can be completely understood in terms of the structure necessary to organize information into a model. The logical or causal chain is from autonomy through organization to structure with modeling as an inferred telelogical principle. If we look for a deeper explanation then it lies in survival as the underlying dynamic. The organism devotes its capacity to self-organization to maintain its identity and then applies its surplus capacity to modeling its environment to the extent that the environment is relevant to its survival. *Anticipation projects survival into the future*.

The Modeling Hierarchy

Systemically, what Kelly terms a construct may be called a *distinction*, a concept upon which it is possible to build logical calculi of great generality (Brown 1969, Gaines & Shaw 1981,1985). Distinctions are not just static partitions of experience. They may be operations: actions in psychological terms; processes in computational terms. The role of distinctions at the base level of all models is evident in Klir's (1976) hierarchy of modeling shown in Figure 1. The loop from events through distinctions up through the modeling hierarchy and then down again to predictions and actions characterizes what Shaw (1980) has termed the *personal scientist* as an individual or the *communal scientist* as a group. Note that the upper levels of modeling are totally dependent on the system of distinctions, or personal constructs, used to express experience through the source system. Klir developed this hierarchy for work on symbolic modeling systems and Gaines (1977) has shown that it forms a basis for general knowledge acquisition algorithms.

This hierarchy does not introduce any additional primitives beyond that of making a distinction. The levels of the hierarchy are the results of distinctions that we make. Thus the *source system* is distinguished as those distinctions that the particular personal scientist makes; it is a distinction about distinctions defining the construct system of an individual. The *data system* is distinguished as those distinctions that have been made about a particular event; again a distinction about distinctions defining an event. The *generative system* is distinguished as a set of distinctions that also defines an event; these are model-generated rather than event-generated. It is the match between the model-generated and event-generated distinctions that determines the degree of approximation of the model to the world; this is a distinction about distinctions among distinctions that defines goodness of fit.

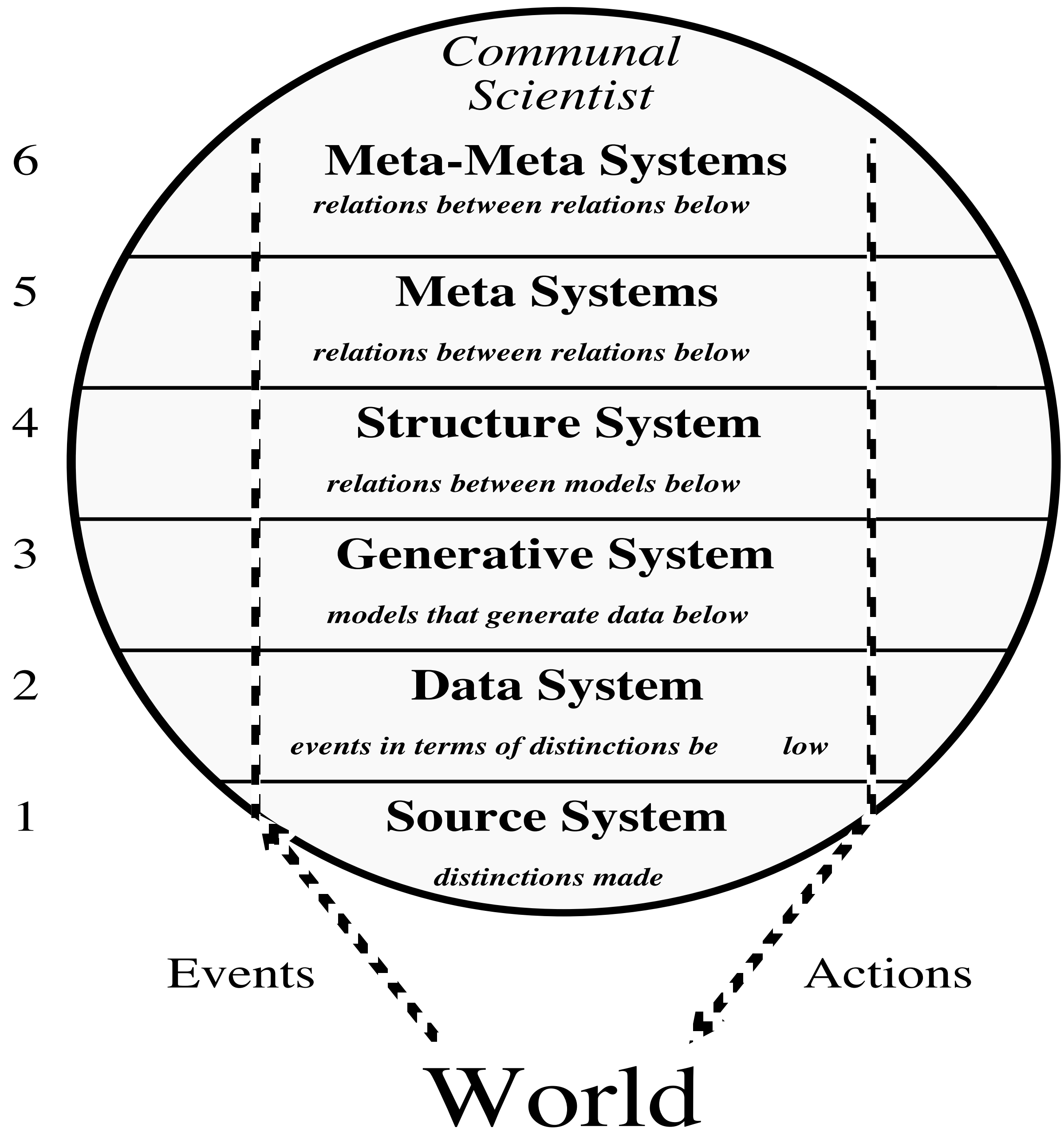

Figure 1 Distinctions in the modeling hierarchy

The systemic hierarchy based on a calculus of distinctions has an analog based on personal constructs (Gaines & Shaw 1981) shown in Figure 2. The lowest level is one of constructs, distinctions made in interacting with the world. The next level is one of experiences, events which happen to us, and we make happen, in terms of the distinctions already made. Levels above these are hypotheses which are rationalizations of experience, analogies between these rationalizations, abstractions of these analogies and transcendencies which are preconceptions underlying rationality. Interaction with the world is, therefore, mediated through the construct system to produce experience which is modeled through the higher levels and leads to predictions, decisions and actions again mediated through the construct system.

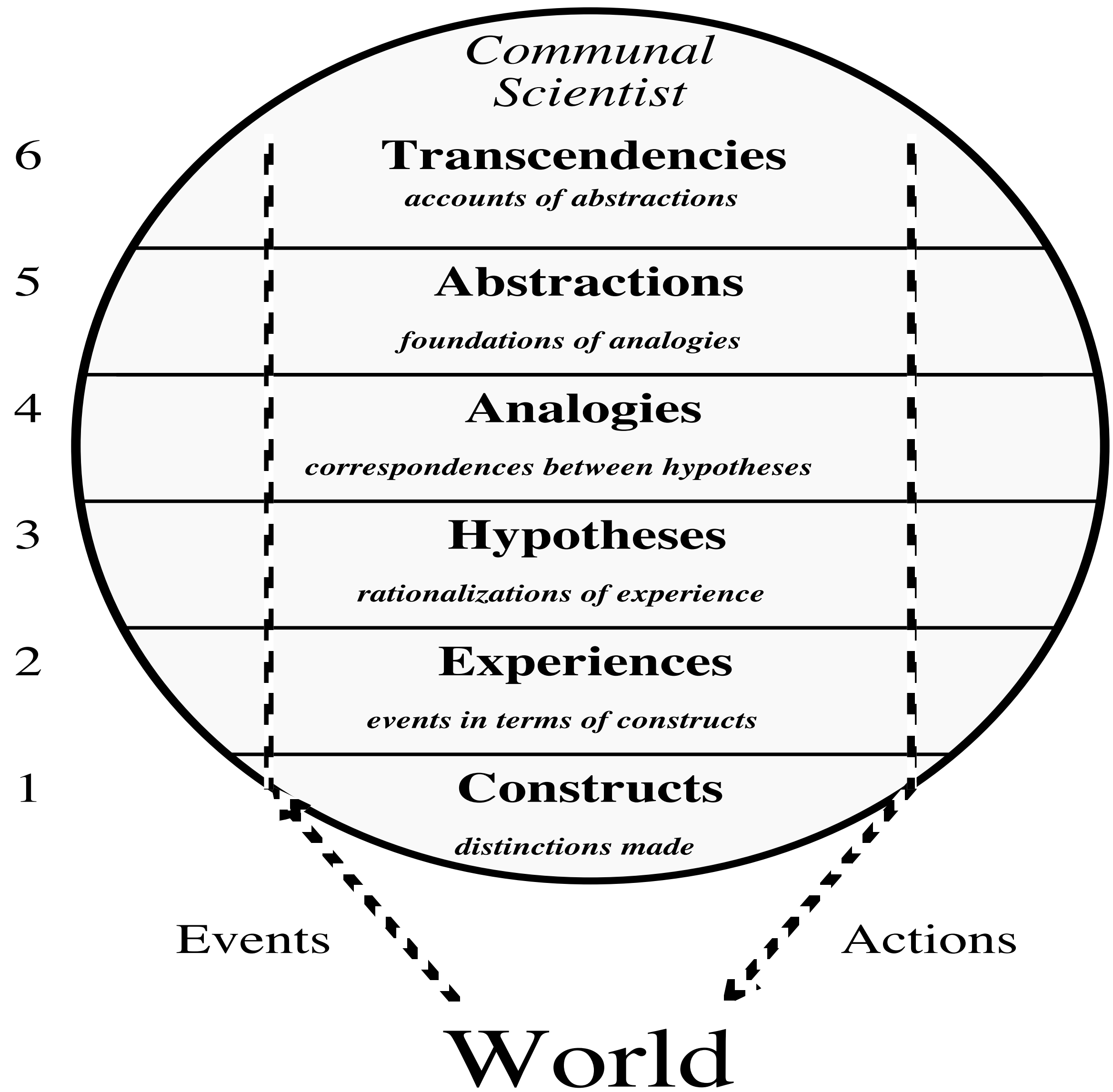

Figure 2 Construction hierarchy of communal scientist

Reflective Equilibrium—The Communal Scientist

The anticipatory processes of the modeling hierarchy extend naturally to those of society by viewing groups of people as larger cross-sections comprising multiple individuals (Shaw & Gaines 1981, 1986a, Shaw 1985). This concept may be given deeper significance by considering the inductive inference process underlying knowledge acquisition and modeled in the hierarchy. 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 as shown in Figure 3: "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 argument arose in the context of the explanation of the authority of experts in society, but it is also significant in suggesting that the basic system underlying knowledge acquisition has to be taken as a society rather than an individual.

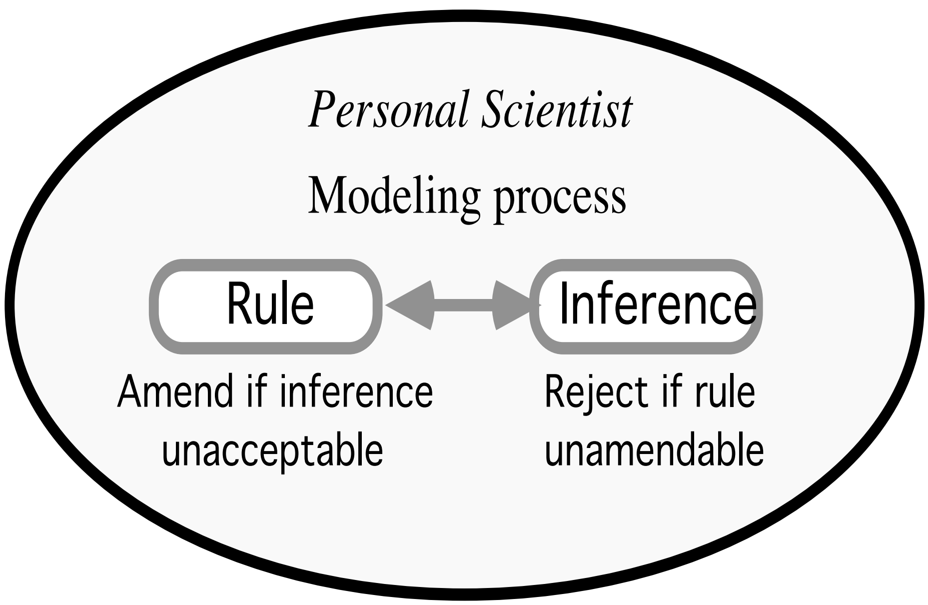

Figure 3 Reflective equilibrium in inductive reasoning

The extension of the modeling hierarchy to social processes is straightforward since Figure 1 presents a general modeling schema and applies as much to groups of people, companies and societies as it does to the roles of a person. The epistemological hierarchy of a person is a cross-section of the epistemological hierarchy of the society generating their life-world. Pask's (1975) concept of P-Individuals as the basic units of psycho-socio-processes allows roles, people, groups, organizations and societies to be treated in a uniform framework (Shaw & Gaines 1981, 1986a). An individual is defined in cognitive terms as a psychological process (Pask 1980) and more complex psychological and social structures may be defined similarly by taking into account the possibilities of timesharing, process switching and distributed processing with psychological processors. For example, one person may assume many psychological roles (process switching), whereas a group of people working together may act as a single goal-seeking entity and hence behave as one process (distributed processing).

Surprise, Preference and Language

A modeling schema results from distinctions about distinctions at each level in the hierarchy. In prediction the key distinction is to what degree a level accounts for the information flowing through it and hence we have termed this distinction one of *surprise* (Gaines 1977), borrowing the term from the economist Shackle (1955). Surprise goes in opposition to the degree of membership (Zadeh 1965, Gaines 1983) of a predicted event to an actual event and the expected surprise is a form of entropy. Surprise at the lowest level of the hierarchy corresponds to distinctions being inadequate to capture events; surprise at the next level to inadequate variety to experience events; at the next level to inadequate approximation to predict events; at the next level to inadequate simplicity to explain events; at the next level to inadequate comprehensiveness to account for events.

The formal theory of modeling is one in which models are selected at each level down the hierarchy to minimize the rate at which surprise is passing up the hierarchy. The criteria for model selection independent of the data are generally thought of as being ones of *simplicity/complexity*: of two models which fit the data equally well choose the simplest. However, notions of simplicity/complexity are not well-defined nor intrinsic to the class of models. The simplicity/complexity ordering is arbitrary and in its most general form is just one of *preference.* Hence the general modeling schema is one in which surprise flows up the hierarchy and preference flows down. In situations that are mathematically well-defined, such as determining the structure of a stochastic automaton from its behavior, such a model schema gives the correct results. Conversely, the success of the schema in stabilizing with regard to a given universe defines the characteristics of that universe. We can construct probability theory from the assumption that certain modeling schema stabilize (Gaines 1977).

The basic modeling system is one in which surprise flows up the hierarchy and preference flows down. Surprise is generated from experience so that it is easy to see its origins. However, where does preference come from? To some extent it may be preset, genetically encoded. However, this does not seem to account for the origins of novel models. *Language* is a way of by-passing the normal modeling procedures and interacting directly with the system at any level. In particular it can directly affect the preference system. Language is essential to much of human learning and our interaction with the knowledge construct (Wojciechowski 1983, Gaines & Shaw 1983) is just as important as our interaction with the world (Shaw & Gaines 1983a).

Surprise, Emotion and System Formation

Surprise is a primitive systemic notion. It is the feedback to a modeling system that what is being modeled does not accord with the model. 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."

Thus human *emotions* may be seen as derived from surprise with the type of emotion varying according to circumstances. The deviation from the model may be construed as having adverse or beneficial consequences, being distracting, requiring attention, investigation, action, and so on. This is consistent with Kelly's notion that negative emotions arise through the violation of core constructs (McCoy 1981). In the modeling hierarchy such core constructs are distinctions that we prefer not to change. Positive emotions arise from distinctions that 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. Emotions are integrating devices for the formation of thoughts and coding devices for memory. System formation occurs 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. *Lock-out* is a situation in which blockers prevent entry to a group which may lead to the behavior of break-in, and *lock-in* is 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 4.

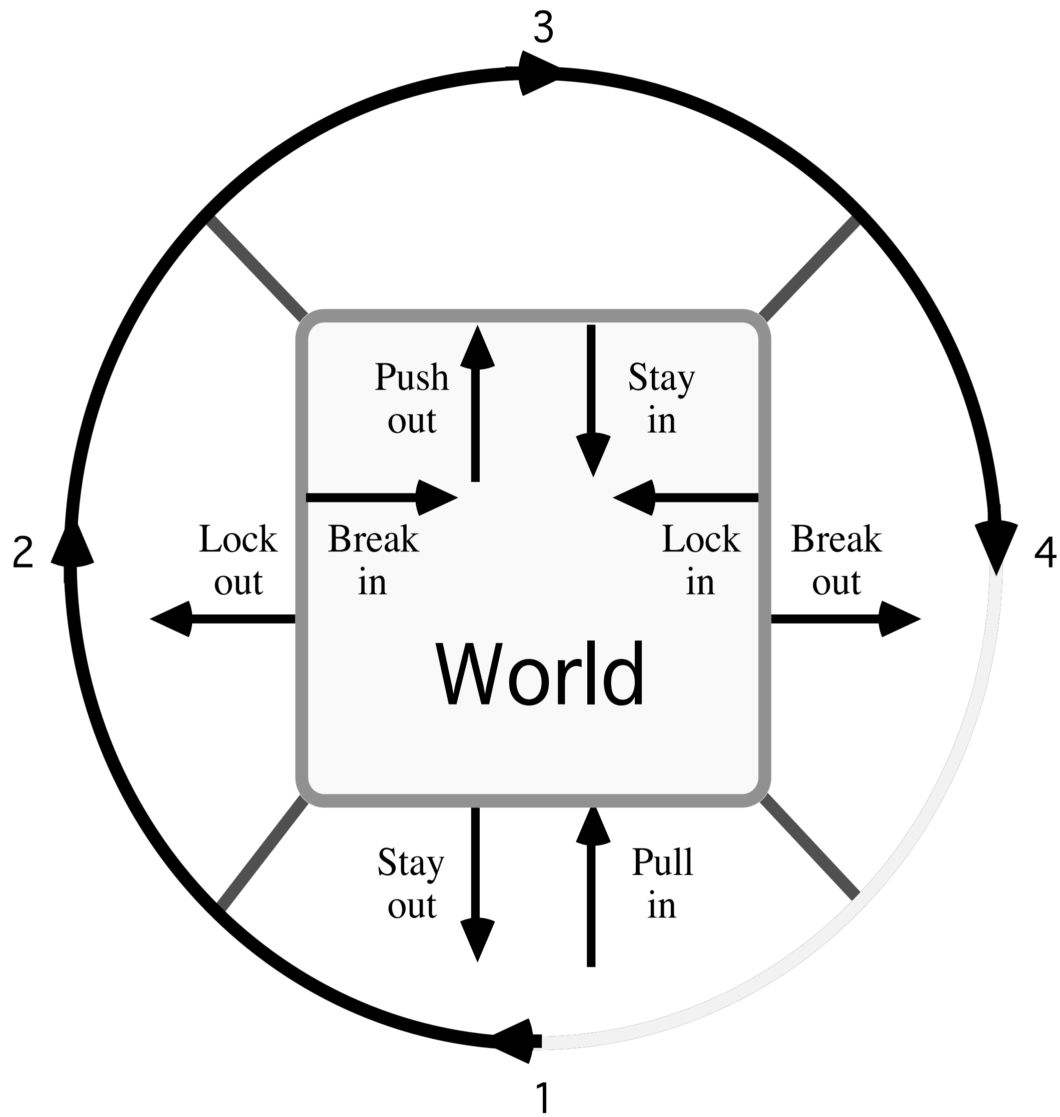

Figure 4 The life cycle of membership in a group

- At the first stage shown at the bottom of the diagram an individual who is not part of the 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. This constitutes 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. This constitutes 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. This constitutes the *lock-in—break-out dynamics*.

Constructive Alternativism in the Modeling Hierarchy

Kelly (1955) places the major emphasis of his work on the notion of *constructive alternativism* (Mancuso & Adams-Webber 1982), that we have a choice in our construct systems at every level in the hierarchy and that real-world problems may often be solved by exercising this choice. Note that this should not be interpreted as an idealist position that ascribes all phenomena to our interpretation of them. Since the construct hierarchy also leads to decision and action, changes in it may equally affect the real world. Kelly and Brown are both neutral to a philosophical stance such as idealism versus realism. It is the distinctions which a philosopher makes that determines his stance and these can be analysed in terms of the epistemological and knowledge hierarchies. PCP is reflexive and the only fundamental principle, apart from that of anticipation, is that of constructive alternativism.

The hierarchy is strongly idiosynchratic and formalization does not imply uniformity. Constructive alternativism emphasizes the dynamic and personal nature of the construct system. It is subject to change according to feedback from failure to anticipate events. It is individualistic in the constructs used, in the vocabulary used to name the constructs, in the relations between constructs in the hierarchy, and in those constructs most likely to change when necessary. Problems of communication arise because of the individualistic nature of construct systems. A person may be able to use his construction system whilst having no basis for communicating it to others. Two people may use exactly the same construct yet refer to it by different names. Two people may use the same names for a constructs and yet use it in different ways. Two people may use similar constructs at the lower level of the hierarchy and yet have them organized in different systems such that their reactions to the same event are quite different. Two people may have similar constructs at nearly all levels of the hierarchy and yet construe a novel event differently.

Another source of major individual differences is the emphasis on the construct system at different levels. The richness of the system will vary according to the focus of attention over a prolonged period. Core constructs are not necessarily superordinate in the hierarchy described here but can occur at any level. The notion of level emphasis gives an interesting taxonomy of individual types:

- Those whose primary concern is below level 1 will live for the sake of experience without having to have the means to describe it at level 1, remember it at level 2, explain it at level 3, value explanations at level 4, or value value-systems at level 5. Doers, people of action, existentialists emphasize this level.
- Those whose primary concern is at level 1 will seek a rich enough vocabulary to be able to express experience as they feel it. This may constrain what they are prepared to admit as experience. Poets, artists, linguistic precisionists emphasize this level.
- Those whose primary concern is at level 2 will seek to record as much experience as possible. This may constrain what vocabulary they allow and what they are prepared to admit as experience. Chroniclers, fact gatherers emphasize this level.
- Those whose primary concern is at level 3 will seek for a rich enough vocabulary of models to account for and subsume all their experience. This may constrain what they are prepared to admit as experience. Empirical scientists emphasize this level.
- Those whose primary concern is at level 4 will seek for analogical relations between models. This may change the perspectives of all lower levels. Paradigm changers and general systems theorists emphasize this level.
- Those whose primary concern is at level 5 will seek for abstract formulations of relations between models. This may change the vocabulary of all lower levels. Mathematicians and theoretical scientists emphasize this level.
- Those whose primary concern is at level 6 will seek values to determine paradigms but they are now so remote from experience that they will have to impose values rather than discover them. This may filter all lower levels. Religious leaders, mystics and world modelers emphasize this level.

Expressing a General Theory

What can we ask of a good general theory? First, the theory should not be expressed in such a parochial form as to be obsoleted by developments, or changes of fashion, in the modes of theoretical expression of our time. Mathematics is a tool for precise expression of theories in the sciences. However, mathematics is itself subject to rapid development so that new tools are continuing to become available. This is important because the mathematical expression of a theory imports presuppositions which are often tacit and go beyond those intended. Lewin (1935) fell into this trap with his psychological vector fields, Hull (1943) with his multiplicative habit and drive strengths, and Von Bertalanffy (1968) with his linear differential equations. Kelly (1955) avoided it by adumbrating PCP through the theoretical framework of a postulate and corollaries but avoiding any mathematical expression of them. He was wise to do so—the mathematics and logic available in the 1950s were inadequate to encapsulate PCP without substantial distortion. The situation has improved today with the development of category theory and modal logics and there is hope that the tools may be adequate. We have suggested elsewhere

(Gaines and Shaw 1984) that the criterion for an adequate general systems theory is that it should adequately represent the foundational notion of a construct, and argued that this is possible with a mathematical foundation prior to Fregean logic and set theory.

The second requirement for a good general theory is that it should be instantiable in a variety of forms, some subject to formal demonstrations of power and adequacy, and others subject to empirical demonstrations. This is the other side of the coin to our first requirement, that, although the theory should not be expressed in too parochial a form, it should have models that are so expressed and can be tested as required. One family of tests is the subsumption of existing classes of model for the relevant phenomena, for example information processing based on logic, automata, computability, complexity and probability theories. These may be termed tests of the theory instantiated in Popper's World 3 (Popper 1968). Another family of tests is the subsumption of existing classes of data appertaining to the relevant phenomena, for example human prediction and action as exhibited in the laboratory and everyday life. These may be termed tests of the theory instantiated in Popper's World 1. Another family of tests is the subsumption of existing forms of explanation that are comprehensible and acceptable to people, for example commonsense to the man in the street and expressible in the jargon of the expert in any discipline whether pure or applied. These may be termed tests of the theory instantiated in Popper's World 2. We believe PCP can satisfy all three forms of test and hope these notes sketch a basis for this.

Summary and Conclusions

This paper has concentrated on conceptual foundations and it is important to note that the framework for knowledge science presented here has proved highly applicable. For example, we have used it to model the socio-economic infrastructure of information technology, showing how generations of technology arise through individual and social processes (Gaines & Shaw 1986b). We have also developed programs that have been applied in a wide range of applications including knowledge engineering for expert systems (Shaw & Gaines 1983b, 1986b,c). Similar programs based on personal construct psychology have found extensive industrial application (Boose 1986). The theory of surprise described here has provided the essential mathematical foundations for the analysis of the data from such systems (Gaines & Shaw 1986a).

Returning to our opening theme, we noted a growing convergence between psychology, systems theory and computer science. We have concentrated in the notes above on the systemic foundations of personal construct psychology and the links between the formal model and human psychology. We believe that systems theory is now at a stage where it can contribute a framework for Kelly's ideas that expresses them reasonably well and does not distort them. Personal construct psychology is able to provide foundations for cognitive science that subsume previous information processing models and extend them to realms of human emotion and personality. For psychology this opens up the possibility of an integrative theory encompassing all aspects of human life and contributing formal foundations to clinical, educational, social and applied psychology. For future computing systems this opens up the possibility that aspects of inter-personal interaction may be programmed to add to person-computer interaction the overtones so significant in person-person interaction. It also opens up the possibility of true human-computer symbiosis in which natural and artificial knowledge processes are fully integrated.

It is the summation of all these possibilities, and others related to them, that we see as steps towards a new integrative meta-discipline which we have termed *knowledge science*.

Acknowledgements

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