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Abstract: Personal construct psychology is a theory of individual and group psychological and social processes that has been used extensively in knowledge acquisition research to model the cognitive processes of human experts. The psychology has the advantage of taking a constructivist position appropriate to the modeling of specialist human knowledge but basing this on a positivist scientific position that characterizes human conceptual structures in axiomatic terms that translate directly to computational form. The repertory grid knowledge elicitation methodology is directly derived from personal construct psychology. In its original form, this methodology was based on the notion of dichotomous constructs and did not encompass the ordinal relations between them captured in semantic net elicitation. However, it was extended in successive tools developed for applied knowledge acquisition and tested in a wide variety of applications. This paper gives an overview of personal construct psychology and its expression as an intensional logic describing the cognitive processes of anticipatory agents, and uses this to survey knowledge acquisition tools deriving from personal construct psychology and to suggest how future tool architectures may be designed in an integrated fashion within this framework.

1 INTRODUCTION

The repertory grid has become a widely used and accepted technique for knowledge elicitation, and has been implemented as a major component of many computer-based knowledge acquisition systems. The grid itself dates back to Kelly's (1955) application of the *personal construct psychology* that he had developed on the basis of his clinical and teaching experience. A comprehensive computer-based elicitation and analysis system for repertory grids was developed by Shaw (1979) with applications mainly in educational, clinical and management studies. Gaines and Shaw (1980) suggested that repertory grids would provide a useful development technique for expert systems, and later published a validation study of the elicitation of the BIAIT methodology from accountants and accounting students using computer-based repertory grid elicitation (Shaw & Gaines, 1983). Boose (1984) in an independent parallel study reported success in a wide range of industrial expert system developments using computer elicitation of repertory grids, and since then many knowledge acquisition systems have incorporated repertory grids as a major elicitation technique (Boose & Bradshaw, 1987; Diederich, Ruhmann & May, 1987; Gaines & Shaw, 1987; Garg-Janardan & Salvendy, 1987; Shaw & Gaines, 1987; Ford, Stahl, Adams-Webber, Novak & Jones, 1990).

The 'repertory grid' methodology has evolved in the light of application experience and now has major differences from that described by Kelly. Shaw (1980) took advantage of the processing power and interactivity of computers to introduce on-line analysis and feedback to the person from whom the grid was being elicited. In expert systems terms, this can be seen as highlighting correlations that might be spurious and lead to incorrect rules in later analysis. Shaw and Gaines (1979) introduced new forms of analysis of the repertory grid based on fuzzy sets theory which became the basis of rule extraction (Gaines & Shaw, 1986). Boose and Bradshaw (1987) made changes to the grid structure introducing hierarchical data structures to cope with more complex domains. Bradshaw, Boose, Covington and Russo (1988) showed how many problems that did not seem appropriate to repertory grids could be formulated in terms of them.

The repertory grid was an instrument designed by Kelly to bypass cognitive defences and give access to a person's underlying construction system by asking them to compare and contrast relevant examples (significant people in their life in the original application). This has also been its significance in expertise modeling, that it is often easier and more accurate for the expert to provide critical cases rather than a domain ontology. The power of a few critical cases described in terms of relevant attributes to build a domain ontology is remarkable but statistically well-founded (Gaines, 1989), and is the basis of the success of repertory-grid techniques.

The original repertory grid methodology is based primarily on only one aspect of Kelly's personal construct psychology, his *dichotomy corollary* that, "A person's construction system is composed of a finite number of dichotomous constructs." The standard grid is a flat structure of elements described in terms of dichotomous attributes or constructs that does not represent the hierarchical structure of Kelly's organization corollary that, "Each person characteristically evolves, for his convenience of anticipating events, a construction system embracing ordinal relationships between constructs." Hinkle (1965) developed a technique of *laddering*, based on "why" and "how" questions, for investigating ordinal relations between constructs, and Boose (1986a) incorporated a laddering tool in ETS. However, ordinal relations between constructs were not the primary focus in initial applications of repertory grid tools.

This changed as the second generation toolbench, AQUINAS (Boose & Bradshaw, 1987), was developed in the light of experience with ETS, and hierarchical structures of tasks, experts, elements and constructs were introduced into the data structures and interfaces. It also changed as conceptual induction techniques were used to derive hierarchical concept structures from the rules extracted from repertory grids (Gaines, 1990). Recently, the intensional logic underlying the psychological primitives of personal construct psychology has been developed in detail (Gaines & Shaw, 1990), and this has been used to develop knowledge acquisition tools based on a visual language that corresponds to a formal semantics for semantic nets (Gaines, 1991c).

These later developments suggest that personal construct psychology can also provide foundations for tools in which ordinal relations are a primary focus, such as those that use some form of semantic network to build an overall domain and task ontologies directly. These include a wide range of significant knowledge acquisition tools such as MOLE (Eshelman, Ehret., McDermott & Tan, 1987), KNACK (Klinker, Bentolila, Genetet, Grimes, & McDermott, 1987), SALT (Marcus, 1987), ONTOS (Monarch & Nirenburg, 1987), Cognosys (Woodward, 1990), KEATS (Motta, Eisenstadt, Pitman & West, 1988), and CODE (Skuce, Shenkang & Beauville, 1989), CAMEO (Jones, 1989). The tools vary in their interfaces, sources, emphasis on declarative or procedural knowledge, and domain dependence, but all result in domain models based on a network of directed relations between concepts. These tools are different in approach from those based on repertory grids, but as the trend towards the integration of tools and techniques continues it is becoming important to understand the relationship between them. Similar considerations apply to other tools now being incorporated in integrated knowledge acquisition systems such as those for empirical induction and conceptual clustering.

This paper develops cognitive foundations for current knowledge acquisition tools and techniques in terms of Kelly's personal construct psychology. It uses a systemic analysis of the psychology in terms of a calculus of distinctions (Gaines & Shaw, 1981, 1984) to provide a framework for knowledge acquisition that is both psychologically and logically well-founded, and which has direct, operational interpretation in terms of knowledge acquisition tools and techniques. It surveys significant tools that have been developed directly from personal construct psychology, and shows how other tools developed more pragmatically can also be rationally reconstructed within a personal construct psychology framework.

The first part of the paper is devoted to the psychological and logical foundations underlying the implementation of tools based on personal construct psychology, rather than the tools themselves. There is a major literature on the repertory grid (Fransella & Bannister, 1977) and related tools (Mancuso & Shaw, 1988) and another major literature on personal construct psychology (Mancuso & Adams-Webber, 1982), but there is very little material bridging the two and supporting both implementors and users to understand the relation between tools and theory. This paper attempts to bridge the gap.

2 PERSONAL CONSTRUCT PSYCHOLOGY

George Kelly was a clinical psychologist who lived between 1905 and 1967, published a two volume work defining personal construct psychology in 1955, and went on to publish a large number of papers further developing the theory many of which have been issued in collected form (Maher, 1969). Figure 1 attempts to encapsulate the historic forces at work in psychology, logic, cognitive science and artificial intelligence before and after Kelly's work. Personal construct psychology can be seen to be an heir to European logical positivism and American pragmatism, taking an alternative path to behaviorism that is similar in many respects to what later became termed *cognitive science*. In this Kelly was preceded by Vygotsky in the USSR whose book *Thought and Language* appeared in 1934 but was suppressed until 1962 (Wertsch, 1985; Vygotsky, 1989). Luria, who had been a student of Vygotsky invited Kelly to Moscow in 1961 where he delivered a particularly clear statement of the formal principles of personal construct psychology in the light of reactions to his earlier book (Kelly, 1969). Kelly was working on a second book when he died of which, unfortunately, only the preface has been published (Kelly, 1970), and he also began to become involved with the computer simulation of personality (Kelly, 1963). However, his work never became part of the mainstream cognitive science literature although it has attracted widespread attention and application in management, education and clinical psychology (Shaw, 1981).

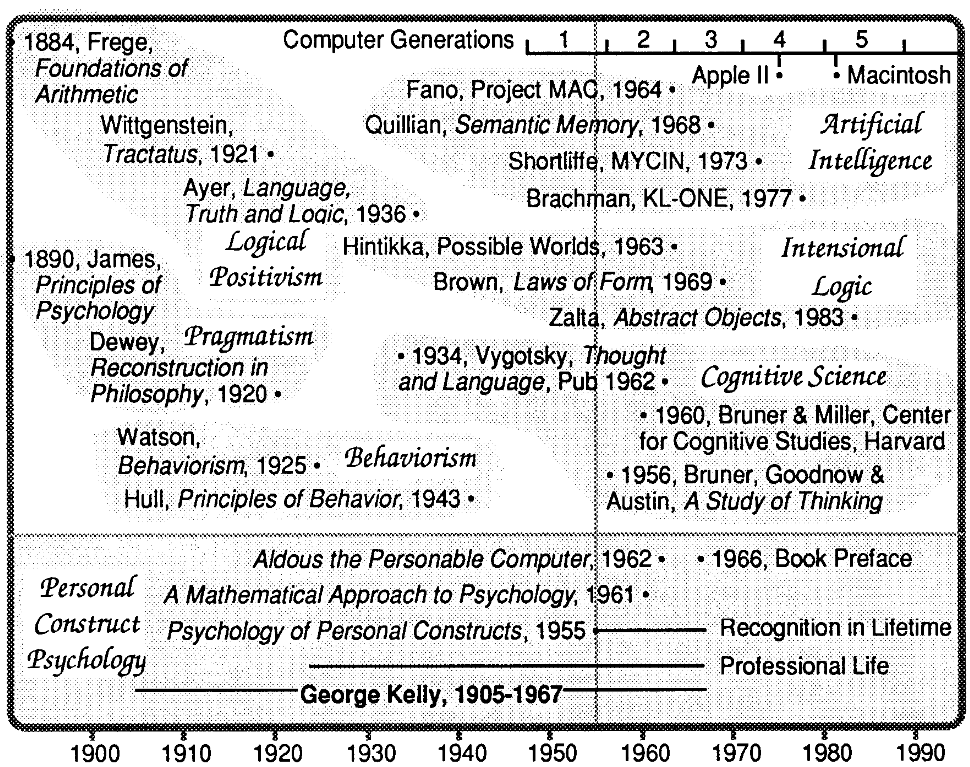

Figure 1 The intellectual setting of personal construct psychology

Kelly was a keen geometer with experience in navigation and an interest in multi-dimensional geometry. When he came to formalize his theory he took as his model Euclid's *Elements* and axiomatized personal construct psychology as a *fundamental postulate* together with eleven *corollaries*, terming the primitives involves *elements* and *constructs*. Kelly took far more than a vocabulary from Euclid. The *Elements* were the normative model for the science that arose out of the Greek enlightenment, and fulfilled a similar role in the second enlightenment for Descartes, Kant and others (Russell, 1946). The careful definition of terms, with attention to exact and overt presuppositions, and then the development of a rigorous deductive sequence with precise specification of hypothesis and constructions, provided an intellectual model that we follow today. Indeed in the post-modern literature the modern age has been characterized as based on the *ethics of geometry* (Lachterman, 1989).

The standard translation of the *Elements* used for geometry classes in schools contains a deep philosophical discussion of the nature of Euclid's reasoning (Euclid, trans. Heath, 1908). In particular, it discusses the status of Euclid's corollaries, or *porisms*, as "things which are sought, but need some finding and are neither pure bringing into existence nor simple theoretic argument." This is the sense in which Kelly used the term, and what he was attempting to find were operational definitions of psychological terms such as motivation and learning that treated them as phenomena of man's psychological existence rather than as causal variables. This was his departure from behaviorism, to base psychology on a formal existentialism that saw all behavior observed in people as based on their anticipatory processes in being in the world.

Kelly presented his theory as a *geometry of psychological space* (Kelly, 1969), and his conceptual framework is very clear if seen in these terms. It may seem strange to base cognitive science on geometry rather than logic until one remembers that the reasoning structure of the *Elements* was the basis for both Greek and modern logic, and that geometry and logic in a category-theoretic framework are equivalent (Mac Lane, 1971). What Kelly achieved through the use of geometry was an intensional logic, one in which predicates are defined in terms of their properties rather than extensionally in terms of those entities that fall under them. In his time there were no adequate formal foundations for intensional logic—it was not until 1963 that Hintikka (1963) published the model sets formulation that gave intensional logic its *possible worlds* formal foundations. Logics of knowledge and belief are essentially intensional (Hintikka, 1962) and hence formal foundations for cognitive science in logical terms only became possible in the late 1960s. The intensional nature of semantic networks in artificial intelligence was recognized in the late 1970s (Woods, 1975; Brachman, 1977; Shapiro, 1979), and their philosophical and logical structure as cognitive models has been detailed by Zalta (1988).

Thus, those developing and using tools based on personal construct psychology will find rich foundations in the original writings of Kelly and in publications deriving from it. However, much of the vocabulary and conceptual framework will be unfamiliar and it is important to read Kelly with the formal geometrical model in mind. It is an underlying theme in all his work even when he does not make it very explicit. It is also important to realize that much of the derived work is detached from this theme, partly because of its unfamiliarity for psychologists not having taken formal courses in geometry, but partly also because Kelly's existential constructivist position was seen by some as antipathetic to his formal development—they could not reconcile the two and omitted the latter in their own work. However, in a computational context, Kelly's approach is attractive in leading very directly to representations and algorithms, and its rephrasing in terms of modern intensional logic appears both strikingly original and wholly appropriate to a cognitive psychology of human psychological processes that readily transfers to their support and emulation by computers.

In this paper we will not attempt to give a historical account of Kelly's own development of personal construct psychology but rather move rapidly from his geometrical framework to a logical formulation that encompasses semantic networks and repertory grids and can be seen as the principles behind the development and use of some major knowledge acquisition tools.

3 PSYCHOLOGICAL GEOMETRY

Kelly's "fundamental postulate" for personal construct psychology was that:

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

This was stated as a postulate to emphasize that it was presented as a convenient viewpoint from which to understand human behavior, not imputed to an underlying physiological or psychological reality. The basis of Kelly's approach to psychotherapy was that this was also a convenient viewpoint from which someone could understand, and modify, their own behavior. He saw all men as "personal scientists" in anticipating the world, and attempted to develop techniques where this anticipatory modeling activity was reflexively applied to the self. His first corollary, the construction corollary, states:

> "A person anticipates events by construing their replications." (p.50)

This emphasis on the role in behavior of a view to the future is what distinguishes Kelly's approach to psychology. He saw man as driven by the need to cope with coming events in the world and all other aspects of behavior as deriving from this:

> "A person's processes, psychologically speaking, slip into the grooves which are cut out by the mechanisms he adopts for realizing his objectives." (p.49)

These grooves provide templets for construing events which he termed "personal constructs":

> "Man looks at his world through transparent templets which he creates and then attempts to fit over the realities of which the world is composed." (pp.8-9)

> "Constructs are used for predictions of things to come, and the world keeps on rolling on and revealing these predictions to be either correct or misleading. This fact provides the basis for the revision of constructs and, eventually, of whole construct systems." (p.14)

Kelly introduces the notion of a *psychological space* as a term for a region in which we may place and classify elements of our experience. It is important to note that he did not suppose this space to pre-exist as a world of such elements, but rather to come into being through a process of construction by which we create a space in which to place elements as we come to construe them. He sees us as creating dimensions in personal psychological space as a way of providing a coordinate system for our experience, and emphasizes that the topology of the space comes into existence as it is divided:

> "Our psychological geometry is a geometry of dichotomies rather than the geometry of areas envisioned by the classical logic of concepts, or the geometry of lines envisioned by classical mathematical geometries. Each of our dichotomies has both a differentiating and an integrating function. That is to say it is the generalized form of the differentiating and integrating act by which man intervenes in his world. By such an act he interposes a difference between incidents — incidents that would otherwise be imperceptible to him because they are infinitely homogeneous. But also, by such an intervening act, he ascribes integrity to incidents that are otherwise imperceptible because they are infinitesimally fragmented. In this kind of geometrically structured world there are no distances. Each axis of reference represents not a line or continuum, as in analytic geometry, but one, and only one, distinction. However, there are angles. These are represented by contingencies or overlapping frequencies of incidents. Moreover, these angles of relationship between personal constructs change with the context of incidents to which the constructs are applied. Thus our psychological space is a space without distance, and, as in the case of non-Euclidian geometries, the relationships between directions change with the context." (Kelly, 1969)

It is this emphasis on the space itself being created by a process of making distinctions rather than being defined by the elements distinguished that gives personal construct psychology its intensional nature:

> "the construct is a basis of making a distinction...not a class of objects, or an abstraction of a class, but a dichotomous reference axis" (Kelly, 1970)

Figure 2 shows the main features of Kelly's notion of psychological space. A construct is a dichotomous reference axis. It defines a family of planes orthogonal to it that divide the space:

> "To catch a glimpse of psychological space we may imagine a system of planes, each with two sides or aspects, slicing through a galaxy of events" (Kelly, 1970)

However, only part of the space that is divided is used in placing elements:

> "A construct is convenient for the anticipation of a finite range of events only. A personal construct system can hardly be said to have universal utility. Not everything that happens in the world can be projected upon all the dichotomies that make up a person's outlook. . . The geometry of the mind is never a complete system." (Kelly, 1970)

This division defines the dichotomous poles of the construct:

> "Each construct involves two poles, one at each end of its dichotomy. The elements associated at each pole are like each other with respect to the construct and are unlike the elements at the other pole" (Kelly, 1955)

Even though Kelly's geometry is not metrically defined, he has no problems in using the defined constructs to generate a metric as shown in Figure 3:

> "imagine a system of planes, each with two sides or aspects, slicing through a galaxy of events...If the set is moved into all possible positions it generates a paracartesian hyperspace with its relatively concrete scalar axes" (Kelly, 1970)

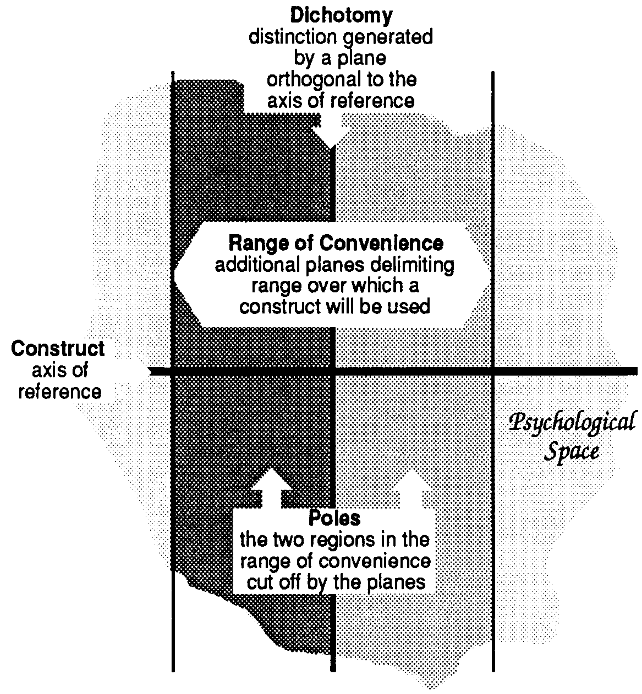

Figure 2 The geometry of psychological space

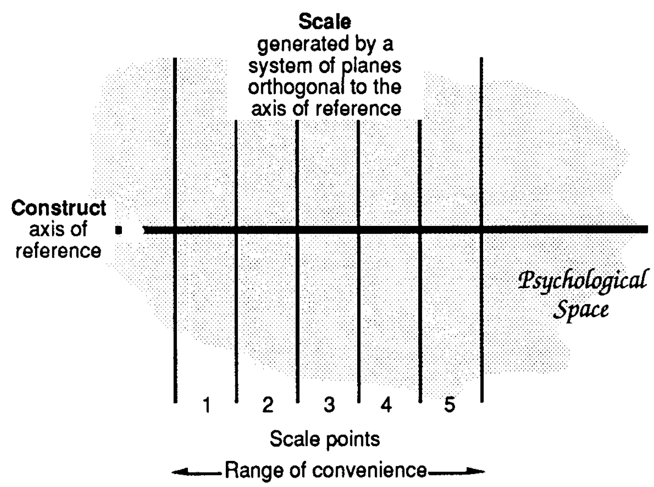

Figure 3 Scales in psychological space

Kelly does not intend that the system described be seen to be at the verbal level:

> "I have probably given the impression that a construct is highly articulate and cognitive...but personal construct theory is no more a cognitive theory than it is an affective or conative one. There are grounds for distinction that operate in one's life that seem to elude verbal expression" (Kelly, 1955)

He sees no conflict between his psychology and a neurological perspective:

> "A person develops a physiological construct system...but that does not prevent us examining the person's private system from a psychological point of view" (Kelly, 1955)

He sees his psychological geometry as providing a framework for a variety of viewpoints:

> "For the present we do not need to ask how man performs this intervening act — whether with his brain, his stomach, or his glands. Nor do we need to concern ourselves just yet with the essence of the act — whether it is cognitive, conative, or affective. Finally we need not agree on what kind of substance fills the psychological space we have structured — whether the space is stuffed with physiological things, social things, or mental things. All these matters are, at most, no more than subsequent issues, and indeed, as I personally suspect, may prove to be no issues at all, after we have put our mathematics to work." (Kelly, 1969)

Kelly introduces anticipation within the geometry by attaching actions to regions of psychological space:

> "A young girl anticipates marriage...The predicted husband does not exist for her in the flesh, but simply as the intersect of a limited number of conceptual dimensions. One day a young man plumps himself down on this waiting intersect...she marries him" (Kelly, 1955, p.121)

It is possible to develop a complete theory of cognition, action, learning and intention with the geometry. However, it is more useful to first develop an intensional logic isomorphic to the geometry and then present Kelly's psychology in both the geometry and the logic.

4 CONSTRUCTS AND CONCEPTS

One obvious question about Kelly's use of the term construct was how it differs from the more conventional term "concept." He discusses this in the following terms:

> "We use the term *construct* in a manner which is somewhat parallel to the common usage of 'concept.' However, if one attempts to translate our *construct* into the more familiar term, 'concept,' he may find some confusion. We have included, as indeed some recent users of the term 'concept' have done, the more concretistic concepts which nineteenth-century psychologists would have insisted on calling 'percepts.' The notion of 'percept' has always carried the idea of its being a personal act—in that sense, our *construct* is in the tradition of 'percepts.' But we also see our *construct* as involving abstraction—in that sense our *construct* bears a resemblance to the traditional usage of 'concept.' ... Now when we assume that the construct is basically dichotomous, that it includes percepts, and that it is a better term for our purposes than the term 'concept,' we are not quarreling with those who would use it otherwise. Within some systems of logic the notion of contrast as something distinct from irrelevancy is not part of the assumptive structure. We, on the other hand are simply assuming that this is the way people do, in fact, think." (Kelly, 1955, p.70)

The dichotomous aspect of constructs is the most significant aspect of the difference between Kelly's constructs and current usage of the term, 'concept.' His *dichotomy corollary* states this:

> "A person's construction system is composed of a finite number of dichotomous constructs." (p.59)

and it is a consequence of the two-sided nature of a distinction represented in the geometry. The range of convenience captures the notion of relevancy and the distinction within it then generates a natural opposition. That people tend to conceptualize the world in terms of restricted sorts that are then dichotomized is a phenomenon identified in antiquity (Lloyd, 1966) and common across many cultures (Maybury-Lewis & Almagor, 1989). In a technical context, Kelly's construction is related to that of Zermelo-Fraenkel set theory in which the logical paradoxes of unrestricted comprehension are avoided by the restriction that conceptual definitions apply only to existing sub-sets, giving rise to a well-defined relative negation (Hatcher, 1982).

Since the term "concept" is used in psychology and in knowledge representation in somewhat different ways, it is useful to define it clearly in these contexts for the purposes of this paper. A psychological concept is defined to be that mental entity *imputed* to a distinction making agent as enabling it to make a particular distinction. Note that concepts are separated both from the distinctions they support and the entities they distinguish, and are not reified but seen as imputed to the agent. They are themselves distinctions made by an observer—possibly, a reflective observer. This is equivalent to Zadeh's (1964) introduction of the notion of the *state* of a system as an imputed parametrization accounting for a system's behavior. Concepts are state variables we impute to a knowledgeable agent. This definition also corresponds to Anglin's:

> "a concept is all of the knowledge possessed by an individual about a category of objects or events"—
> "Concepts mediate categorization but concepts are not the resultant categories." (Anglin, 1977)

A computational knowledge representation concept is defined to be that data structure used by a distinction making algorithm to enable it to make a particular distinction. No discussion of imputation is necessary because we are not dealing with identification of a black box from its behavior, but rather with the internal structure of an accessible open box. These differing interpretations correspond to the two sides of the Husserl-Frege debate (Mohanty, 1982): distinctions as mental phenomena underlying the interpretations the human mind places on experience, and distinctions as formal structures in their own right independent of their origins.

None of these additional connotations are necessary to the formal development of personal construct psychology. For the psychology, the geometry and the logic, distinctions are the only primitives. One might ask "what is distinguished?", but the answer will be "distinctions." This corresponds to deriving the two phenomena in Kelly's *construction corollary* from a single primitive, that we distinguish events in the undifferentiated stream of circumstance, and then we further distinguish among the distinguished events by construing.

5 FROM GEOMETRY TO LOGIC

It is very easy and highly instructive to move from Kelly's geometry to a corresponding intensional logic. We may take Kelly's notion of a distinction as primitive and see how distinctions may relate to each other in psychological space. If an element is placed within the region carved out by a distinction then we may say that the distinction is *asserted* to apply to the element. This corresponds to Zalta's (1983) distinction in his intensional logic of abstract objects that "abstract objects *encode* properties whereas existent objects cannot encode properties but do *exhibit* them." If one distinction carves out a region that contains that carved out by another then the first distinction may be said to *subsume* the second. If one distinction carves out a region that does not overlap that carved out by another then the first distinction may be said to be *disjoint* to the second. These relations are in themselves sufficient to define an intensional logic of distinctions in that more complex relations may be composed from them.

The subsumption and disjoint relations may be defined in an algebraic formalism by representing distinctions by bold lower case letters such that a distinction applied to another distinction is concatenated to the right of it. Then the definition above translates as one distinction will be said to *subsume* another if it can always be applied whenever the other can. It can be represented formally as:

"**b** subsumes **a**" $\quad \mathbf{a} \rightarrow \mathbf{b} \Leftrightarrow \vdash \mathbf{xa} \Rightarrow \vdash \mathbf{xb}$ (1)

That is, **b** subsumes **a**, if and only if whenever one asserts **xa** one also asserts **xb**. The definition is to be read intensionally in terms of a *commitment* to the way in which distinctions will be made, such that if **a** is made then there is a commitment to **b** being made also. This is why the form $\forall$**x** is avoided—the notion of all the distinctions to which **a** and **b** may be applied is not well-defined. However, if this extension is well-defined then the intensional formulation of (1) implies the extensional formulation in terms of $\forall$**x**. Marcus' (1962) non-standard, *substitutional* reading of the universal quantifier would be appropriate to the definition above, but the notation is avoided because the extensional reading is prevalent and significant in its own right.

Subsumption corresponds to increasing generality since the subsuming distinction can be applied to at least as many things as that subsumed. In (1) concept **a** is said to be *subordinate* to concept **b**, and **b** *superordinate* to **a**. Subsumption is an asymmetric, transitive relation, a partial pre-order, over distinctions, that supports the ordinal relations of Kelly's *organization corollary.*:

> "Each person characteristically evolves, for his convenience of anticipating events, a construction system embracing ordinal relationships between constructs." (p.56)

This notion of subsumption is adequate to capture Kelly's use of the term that one construct subsumes another, and also the use of the same term in knowledge representation, that one concept subsumes another. Subsumption between computational concepts corresponds to the "is-a" relation in knowledge representation schema. The interpretation of subsumption in terms of commitment above corresponds to the definitional form of the "is-a" relation. The computed form of "is-a" requires some further structures which are developed in the next Section when primitive and non-primitive concepts are differentiated.

The disjoint relation is definable in similar terms, that one distinction is disjoint with another in that one can never be applied whenever the other can. It can be represented formally as:

"**a** disjoint **b**" $\quad\quad \mathbf{a} — \mathbf{b} \Leftrightarrow\ \vdash \mathbf{xa} \Rightarrow \neg \vdash \mathbf{xb}$ (2)

That is, **a** is disjoint with **b**, if and only if whenever one asserts **xa** one does not assert **xb**. The definition is again to be read intensionally in terms of a commitment to the way in which distinctions will be made, such that if **a** is made then there is a commitment to **b** not being made. Disjoint is a symmetric, intransitive relation over distinctions, and supports Kelly's *dichotomy corollary* and the definition of disjoint concepts in knowledge representation.

It is interesting to note that definition (2) is an asymmetric definition of what is clearly a symmetric relation. Logically, this is is possible because the reverse implication can be derived from (2), that is, if one asserts **xb** one cannot assert **xa** because that would imply $\neg\vdash$ **xb**. This derivation of symmetry from asymmetry may be logically simple, but it is not semantically trivial. In terms of knowledge representation it corresponds to the essential sequence of definitions: if we define **a** first we cannot define it to be disjoint with **b** because **b** is not yet defined. Psychologically, this asymmetry appears to be related to the empirical asymmetries Adams-Webber (1979) has observed in the use of the, apparently symmetric, poles of a construct.

The $\rightarrow$ and — relations are complementary in establishing four possible binary relations between distinctions, that **a**$\rightarrow$**b**, **b**$\rightarrow$**a**, **a**—**b**, or none of these. The two subsumption relations can hold together giving an equivalence relation on distinctions. The disjoint relation is incompatible with the subsumption relations, and is *inherited* through subsumption, that is:

$$\mathbf{a} — \mathbf{b} \text{ and } \mathbf{c} \rightarrow \mathbf{a} \Rightarrow \mathbf{c} — \mathbf{b} \quad (3)$$

The logic defined so far is one of pure entailment, of strict or necessary implication, which forms the basis of a large family of intensional logics (Lemmon, Meredith, Meredith, Prior & Thomas, 1969). Before extending it further it is worth defining a visual language for the logic that parallels Kelly's psychological geometry in a more compact notation.

6 A VISUAL LANGUAGE FOR THE LOGIC

The arrow and line notion adopted in definitions (1) and (2) translates nicely to a graphical notation defining a *visual language* for the logic (Gaines, 1991c) as shown at the bottom of Figure 4. Kelly's 'construct' in psychological space is conveniently represented by a pair of disjoint concepts corresponding to the construct poles, both subsumed by a third corresponding to the range of convenience. This diagram is already a simple semantic network in the style of KL-ONE (Brachman & Schmolze, 1985) or KRS (Gaines, 1991b), but it has well-defined logical semantics as defined above, and also strong psychological foundations in personal construct psychology.

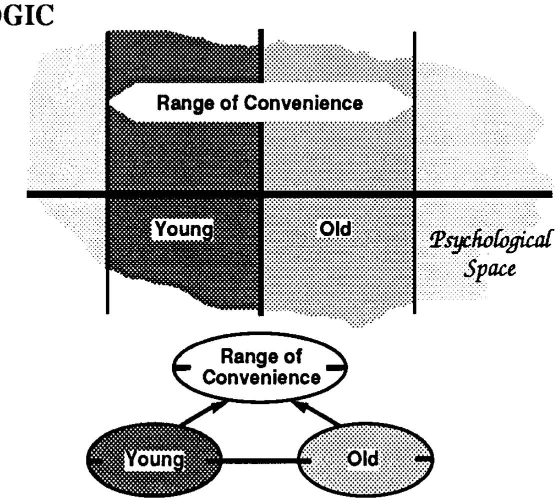

Figure 4 A visual language for the logic

There is an analogy between the visual language and the representation of chemical structures as atoms and bonds. Distinctions are the atomic primitives in personal construct psychology, and further constructions may be seen as complex 'molecules' formed by distinctions joined through subsumption and disjoint 'bonds.' For example, Figure 5 shows how the geometry and the logical visual language may both be used to represent different foci of convenience and contexts:

> "A construct's range of convenience comprises all those things to which the user would find its application useful. A construct's focus of convenience comprises those particular things to which the user would find its application maximally useful. The context...is somewhat more restricted than the range of convenience...somewhat more extensive than the focus of convenience" (Kelly, 1955)

The distinctions, that cut out regions for 'person' and 'wine' each involve an additional dimension and are not adequately in a two-dimensional diagram. This is a problem for the geometry that is overcome in the visual language for the logic.

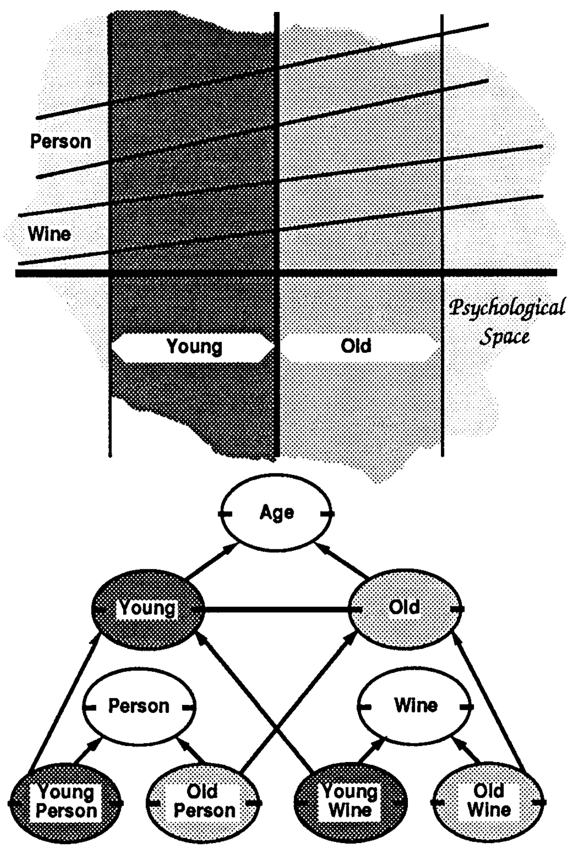

Figure 5 Logic of subsumed foci of convenience

Multiple constructs in psychological space correspond to multiple axes of reference, and the plans representing their distinctions and ranges of convenience intersect to define regions of the space corresponding to conjunction, composition and multiple inheritance in the logic as shown in Figure 6.

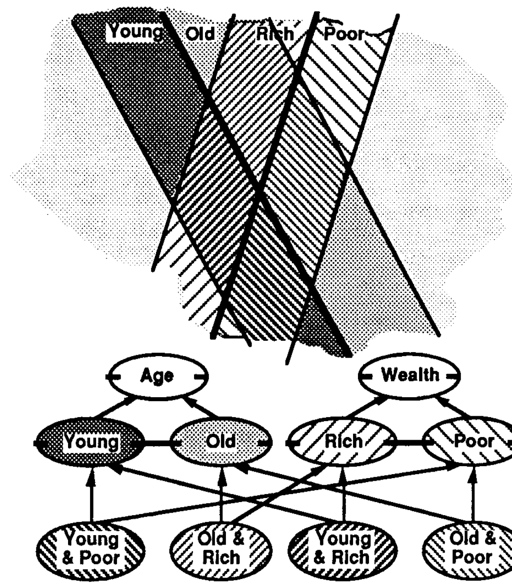

Figure 6 Logic of overlapping distinctions and their intersections

There is an important distinction to be made between the concepts defined by basic distinctions and those defined by intersections. The former are said to be *primitive concepts* and the latter non-primitive, or computed, concepts. In the visual language primitive concepts are distinguished by having a small internal horizontal line at their left and right edges. Primitive concepts are incompletely defined in that we have complete freedom of choice as to where to place an element relative to the planes defining their distinction and range of convenience. However, no such freedom exists for non-primitive concepts since they are defined as the intersection of primitive concepts. Logically, we have to *assert* that a primitive concept applies to an element, whereas we can either assert that a non-primitive applies or *recognize* that it applies through the previous assertion of the primitives that define it. In knowledge representation this recognition is termed *classification* (Borgida, Brachman, McGuinness & Resnick, 1989).

The definition of subsumption in (1) applies to non-primitive concepts, but it is no longer a matter of direct commitment but rather of derivation from the composition of commitments for concepts defining the intersection. In knowledge representation terms, the "is-a" relation for non-primitive concepts is computable rather than definable—the commitment to their definition in terms of their structure entails a commitment to a derived, rather than a defined, "is-a" relation. Confusion about these two forms of concept, and associated "is-a" relations, caused problems in early developments of semantic nets (Brachman, 1983).

Kelly's theory of anticipation is based on attaching significance to such recognizable intersections:

> "What one predicts is not a fully fleshed-out event, but simply the common intersect of a set of properties" (Kelly, 1955)

The logic remains intensional because there is no implication that elements have already been construed within the intersections. For example, in the marriage anticipation example given above, the predicted husband 'exists' only as the "intersect of a limited number of conceptual dimensions." The attachment of an anticipation to this intersect corresponds to a commitment to place an element that falls in this intersect in the region defined by the pole of some other construct also. In logic this is a *material implication* rather than an entailment in that it is not necessitated by the way in which the distinctions are defined but is instead an auxiliary commitment or *rule*.

Rules allow a cognitive system to be anticipatory in containing structures which from one set of distinctions made about an event will imply that others should be made leading to prediction or action. Rules play a similar role in computational systems in generating recommendations for decision or action. Overtly modeling the conceptual system of an expert as such a structure is a basis for emulating the expert's performance in a knowledge-based system.

As shown in Figure 7, Kelly's model of anticipation is represented in the visual language by an additional primitive, a rounded corner rectangle, representing material implication or a rule. This is not so readily represented in the geometry because it is a dynamic principle, "if you place an element in this intersection then move it to this sub-intersection." A rule corresponds to an *attractor* in dynamics, that an element placed in a region of space is unstable and falls into the basin of an attractor (Abraham & Shaw, 1984). This can be represented in the geometry but the diagrams for activities of any reasonable complexity become very difficult to visualize and understand. It does, however, provide a nice link to the corresponding phenomena in the geometrical dynamics of neural networks underlying the phenomenon (Domany, Hemmen & Schulten, 1991).

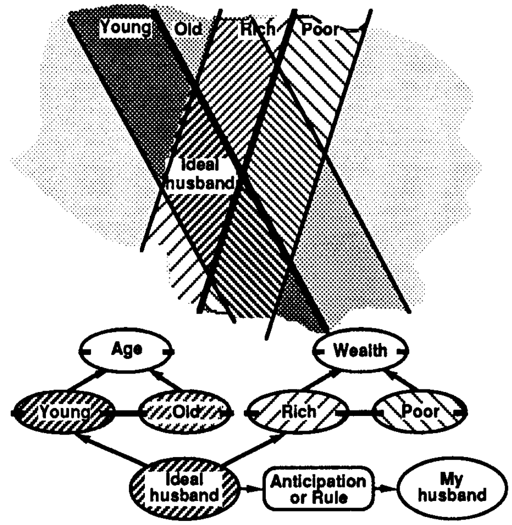

Figure 7 Logic of anticipation through rules

The abstraction of the geometry in the visual language of the logic corresponds to taking multiple cross sections of the geometrical representation from different perspectives and presenting them together. It is way of dealing with the visualization of a high-dimensional space.

7 ELEMENTS AND LOGICAL INDIVIDUALS

The discussion so far has focused on the conceptual architecture of psychological space rather than its application to the construing and anticipation of events. Concepts are distinctions as mental entities without any prescribed link to what is distinguished or represented. For Kelly representational links are established by construing elements of experience as being placed at points in psychological space. In logical terms his elements are *individuals* intended to rigidly designate something in a world of experience. An element or individual acts a *surrogate* in psychological or logical space for some thing in the represented world (Copeland & Khoshafian, 1986). In the visual language such surrogates are represented by a rectangle as shown in Figure 8 and termed *individuals*. Ferio has the properties of 'ideal husband' in figure 7 and hence the placement of a token representing his surrogate in psychological space would be unstable unless it was also in the region 'my husband'—or, in the logic, the rule shown would 'fire.'

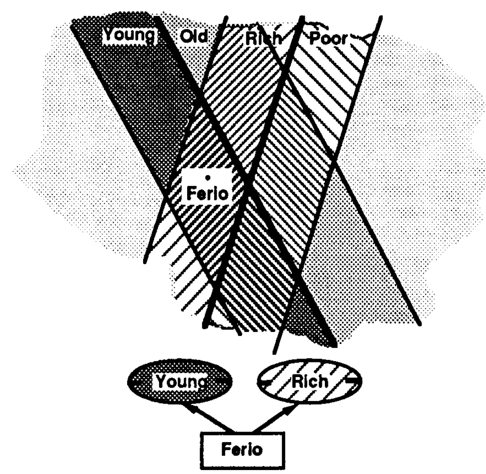

Figure 8 Representation of individuals

In terms of the primitives of distinctions, individuals are defined to be those distinctions which are initial in that they cannot be preceded by other distinctions. They are necessarily leaf nodes in graphs in the visual language. This corresponds to philosophical analyses such as those of Gracia (1983) who notes that traditionally individuals are characterized by five properties; they are entities which:

(a) lose their fundamental character if they are divided into parts;
(b) are distinct from all other entities, even those that are of their same type or kind;
(c) are part of a group type or class which has or can have several members;
(d) remain fundamentally the same through time and various changes;
(e) are the subject of predication but not predicable of other things.

Gracia argues against each of these in turn as being a necessary or sufficient feature to characterize individuals and suggests instead that it is *non-instantiability* that characterizes an individual; that is we cannot instantiate an individual. This corresponds to an initial distinction which cannot have another, an instance, to its left in the algebraic notation of (1).

Thus, while a distinction is the sole primitive, the difference between initial and non-initial distinctions is important. Individual concepts cannot be applied to other concepts and hence have no extensions or instances and cannot subsume one another. However, since individuals are concepts it is possible to have knowledge representation schemas which do not make the distinction explicitly. It is also possible to treat non-initial concepts as *abstract individuals* that represent the individuals that might be distinguished by them. When such an abstract individual has no extension, that is, there are not, or cannot be, any individuals that it distinguishes, then the paradoxes of sense and reference studied by Frege (1892), Meinong (1910) and Russell (1905), can arise. The "morning star, evening star" and "Scott, author of Waverley" equivalences are not problematic as they corresponding to two concepts subsuming the same individual. Non-existent objects such as "the present King of France" are also not problematic because there is no dependence on their empty extensions. They are interesting because, like fictional objects (Woods, 1974), they mimic individuals in that they do not (rather than cannot) have another distinction to their left. This underlies Meinong's intuition that, in some sense, they correspond to real objects, but also leads to the confusion that was a problem in differentiating the definition of concepts from the assertion of those applicable to individuals (Woods, 1975).

8 RELATIONS AS CONSTRUCTS

In his own applications of personal construct psychology, Kelly was primarily concerned with individually-centered construct systems. Hence he usually treats relations to others as attributes of one entity in the relation, that is if John is a parent of Jane, 'parent-of-Jane' is treated from John's viewpoint as an attribute of John. This is equivalent to the technique in combinatorial logic of treating multi-place functions as predicates through *Currying* (Hindley & Seldin, 1986), that is of combining one or more arguments with the function to define a new family of single argument functions. The equivalent construction in the geometry is to treat the relation 'John-parent-of-Jane' as itself an element in psychological space that acts as a place marker linking John to Jane by being distinguished in three ways: as a 'John-relation-', as a '-relation-Jane', and as a 'parent-child-relation.'

Figure 9 shows this and related constructions in the visual language of the logic using a knowledge acquisition tool that operationalizes the visual language and is described in Section 14. The Curried representation of 'John-parent-of-Jane' is shown at the top together with a set of superordinate concepts of increasing abstraction. Through these, for example, general properties of any child of John may be defined by an arrow out of the concept 'has-parent John', and similarly for properties of any parent of Jane by an arrow out of the concept 'has-child Jane.'

In computational applications the representation of complex objects and situations as 'objective knowledge' not individually-centered requires relations to be simply represented and it is convenient to introduce a new primitive in the visual language specifically for relations. This is what is termed a "role" in KL-ONE as a generic term for relations and attributes, that also has connotations of individuals acquiring properties because they play a role in relation to another individual. A role in the visual language is shown by unboxed text as is apparent in the representation of the John-Jane relation just below the Curried form. A line between roles indicates that they are inverse to one another.

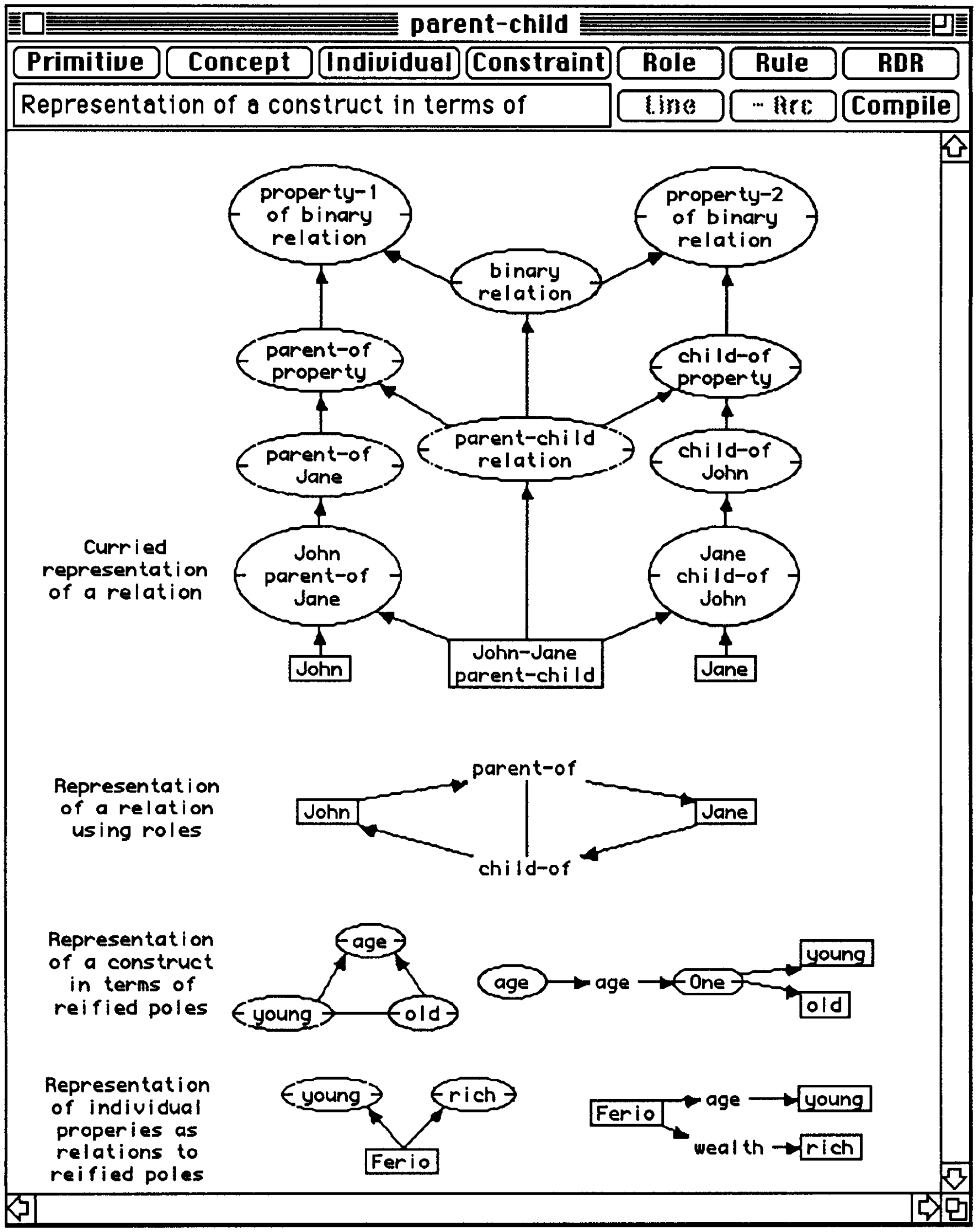

Figure 9 Representation of relations

The availability of the role construction for relations allows properties to be expressed as attributes rather than as concept instantiation. One can *reify* the poles of a construct as if they were individuals and define a concept in terms of a relation to the reified poles. For example, near the bottom of Figure 9 is a bipolar construct, 'young—old' from Figures 6 and 7, and on its right is an equivalent representation in terms of reified poles. The new primitive introduced in the visual language is the constraint "One" meaning that the role is constrained to be filled by just one of the specified set of individuals.

There is a difference in the concept 'age' on the left of Figure 9 and that on the right. The left definition stands alone as a primitive whereas that on the right is actually defined in terms of a role with one of two possible values. One can say that the definition on the right has *internalized* the structure of the construct. This gives rise to a natural coordinate system for specifying the properties of individuals. At the bottom of Figure 9 is shown how the properties asserted of Ferio on the left may be represented as his relations to the reified poles of the corresponding constructs on the right—his values on the coordinates of 'age' and 'wealth.' The constructions on the right for 'age' and 'Ferio' in Figure 9 are visually and conceptually similar, but the first is definitional and the second is assertional. This is an example of the 'encoding-exhibiting' distinction already discussed.

The development of Kelly's geometry of psychological space with individuals (individual constants), concepts (predicates), subsumption (entailment), disjoint (relative negation), rules (material implications), and roles (relations), makes available a complete intensional logic of conceptual structures and their application. The visual language for the logic gives a formal semantics for semantic networks. The close relation between the psychological structures and notions and those of the intensional logic make it possible to build knowledge structures that are interpretable both psychologically and logically. This is the strength of personal construct psychology as a basis for knowledge acquisition tools.

9 THE REPERTORY GRID

Kelly (1955) introduces the "role repertory grid" as a means for investigating a person's conceptual structure relevant to inter-personal relations by having them classify a set of people significant to them in terms of elicited personal constructs. Figure 10 shows the general form of a repertory grid and its relation to the conceptual structures already discussed. If one takes a particular concept somewhere in the lattice, and a set of individuals asserted to fall under that concept, then each distinction that may be made about individuals falling under that concept forms the rows of a matrix, the individuals form the columns, and the constraints applying to a particular individual relative to a particular distinction form the values in the matrix.

In simple applications of the repertory grid these constraints are taken to be the values of the individuals on the roles corresponding to the distinctions. However, it is apparent from Figure 10 that concepts subordinate to those defining the scope of the grid may also be used as if they were individuals, and these may be expected to have more general constraints than single values. Hence in extended repertory grid elicitation, such as that of AQUINAS (Boose & Bradshaw, 1987) the 'values' in the matrix can in themselves be complex constraints.

Figure 11 shows a basic repertory grid elicited from a geographer about spatial mapping techniques. The mapping techniques used as elements are listed as column names at the bottom. The poles of the constructs elicited are listed on the left and the right as row names. The ratings of the mapping techniques along the dimensions of the constructs form the body of the grid. A 1-9 scale has been used based on a construction similar to that of Figure 3. For example, "probability mapping" is rated 8 on the dimension "qualitative and quantitative—quantitative" which means that it is construed as primarily "quantitative." Note that the predicates defined by the pole names may through their linguistic labeling indicate that they themselves are compounds of more primitive predicates. The grid is the starting point for analysis and refinement, not necessarily in itself a conceptual structure but rather a set of data that must be accounted for by any conceptual structure developed. The grid of Figure 11 is a typical one based on Kelly's original specification. Later developments allow structural relations between elements and between constructs to be specified, and the ratings to be extended to more complex constraints.

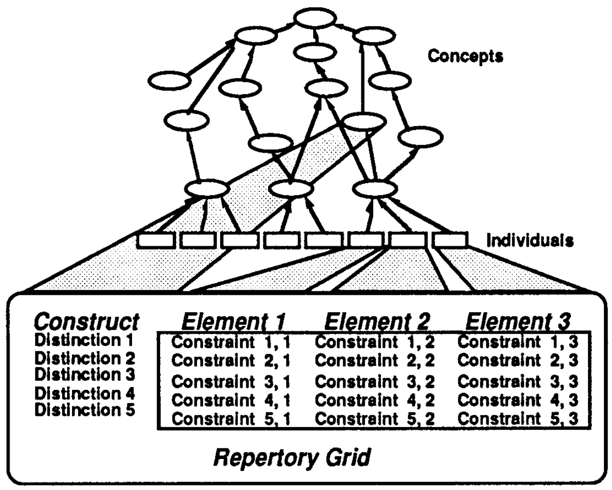

Figure 10 The repertory grid as a matrix of concepts, individuals and constraints

		1	2	3	4	5	6	7	8	9	10	11	12		
qualitative and quantitative	1	8	8	6	9	1	9	8	8	9	4	4	4	1	quantitative
local	2	9	9	6	3	5	1	9	9	1	4	4	4	2	global
autocorrelation not considered	3	1	1	5	4	7	2	3	1	2	9	9	9	3	autocorrelation considered
doesn't honour data points	4	2	1	3	5	9	9	1	1	9	8	7	7	4	honours data points
multiple variables considered	5	9	9	9	9	9	9	9	1	9	9	9	9	5	usually one variable considered
mathematical curve fitting	6	4	4	8	9	9	1	2	4	9	5	8	8	6	doesn't fit a mathematical curve
nonparametric	7	9	8	6	1	1	3	6	8	3	8	8	1	7	parametric
interval or ratio data	8	9	1	1	5	5	1	1	1	1	1	1	1	8	nominal data
requires periodicities	9	6	6	9	9	9	9	1	6	9	9	9	9	9	doesn't require periodicities
doesn't fit a trend	10	9	9	1	1	8	1	7	9	1	6	1	1	10	fits a trend to the data
heavy computing load	11	7	6	7	8	9	4	4	5	3	1	2	3	11	no computing load
assumes isotropic surface	12	1	1	4	3	8	9	1	1	9	7	6	6	12	assumes anisotropic surface
not as susceptible to clusters	13	8	8	6	9	3	4	7	8	5	1	2	2	13	estimates susceptible to clusters
doesn't incorporate geologic model	14	2	2	3	1	9	1	2	2	1	6	6	6	14	incorporates geologic model
interpretive	15	9	9	5	9	1	7	9	9	7	3	4	4	15	representative
not very important	16	4	5	2	1	9	1	1	6	7	8	9	9	16	very important
not very effective	17	4	5	3	1	9	2	4	6	7	9	8	8	17	very effective
not widely used	18	3	8	7	5	9	3	3	4	6	2	2	1	18	widely used
		1	2	3	4	5	6	7	8	9	10	11	12		

12 Nonparametric kriging
11 Punctual kriging
10 Universal kriging
9 Triangulation
8 Most predictable surface
7 Double Fourier series
6 Bicubic splines
5 Hand contouring
4 Proximal mapping
3 Distance weighted averaging
2 Trend surface analysis
1 Probability mapping

Figure 11 A repertory grid about spatial mapping techniques

The psychological function of the repertory grid is to provide a technique for building the conceptual structure without direct elicitation of concepts and their structures and relationships. The assumption is that it may be easier for a person to provide exemplary individuals in the domain of interest, and then to state in fairly concrete terms how they would distinguish them in terms of properties relevant to the purpose of eliciting the grid. In terms of the intensional logic of the concept structure, the extensional specification of how concepts apply to individuals is clearly inadequate to fully specify the concept structure. However, the structure must be consistent with its model and hence it is possible through suitable analysis techniques to approximate the structure from the extensional data, as is discussed in the next Section.

The use of the repertory grid to elicit concept structures thus involves a variety of psychological and analytical techniques, including:

1. Careful definition of the purpose of the elicitation and the appropriate sub-domain to be considered. Maintaining this context so that the purpose and domain do not tacitly change during elicitation is also very important (Shaw, 1980).
2. Choice of exemplary individuals that characterize the relevant features of a domain. This choice is very important and is a major focus of attention in both tool design and application. Fortunately, experts often find it natural to discuss a domain in terms of stereotypical cases, but much care is required to elicit a full range of stereotypes adequate to characterize a domain (Shaw, 1980).
3. Various techniques may be used for initial element elicitation including interviews, protocol analysis, brainstorming with groups of experts, and keyword extraction from relevant textual material (Shaw & Gaines, 1987; Shaw & Woodward, 1990).
4. Online analysis of the interim conceptual structures may be used to detect closely related distinctions and use this to request information on potential stereotypes that might specifically reduce the closeness of the distinctions (Shaw, 1980).
5. The elicitation of some initial distinctions may again derive from interviews, protocols, brainstorming and text analysis.
6. When no prior information is available, triadic elicitation in which a randomly selected set of three individuals is presented with a request to state in what way are two alike and differ from the third can be effective (Shaw, 1980).
7. Online analysis of the interim conceptual structures may be used to detect closely related individuals and use this to request information on potential distinctions that might specifically reduce the closeness of the individuals (Shaw, 1980).
8. The conceptual structure can be developed through various forms of hierarchical and spatial cluster analysis such as FOCUS (Shaw, 1980) and principal components analysis (Slater, 1976, 1977).
9. Rule induction may be used both to derive potential implications between concepts and also, since the premise of a rule is itself a concept, to develop non-primitive concepts and their subsumption relations (Gaines, 1990).
10. Direct elicitation of the concept structure may be mixed with indirect development of the grid (Boose & Bradshaw, 1987).

In clinical psychology repertory grids have been used extensively without computer support, and techniques for manual elicitation are well-documented (Fransella & Bannister, 1977). Repertory grid methodologies are difficult to undertake manually as they require feedback and management from the elicitor while at the same time attempting to avoid inter-personal interactions that would distort the elicitee's conceptual structures. Hence the advent of the personal computer in the mid-1970s and its evolution into the graphic workstations of the 1980s has been very significant for the practical application of the approach (Shaw, 1980, 1981; Mancuso & Shaw, 1988).

10 DISTANCE MEASURES, CONCEPTUAL CLUSTERING AND INDUCTION

In analyzing repertory grid data, distance measures play an important role in conceptual clustering and induction. In terms of the logic and visual language, there is a natural construction of a distance between two concepts, **x** and **y**, as shown on the left of Figure 12. Let **u** be some minimal upper bound of **x** and **y** subsuming both of them, and **l** some maximal lower bound subsumed by both of them, and **U** be the extension of **u** and **L** the extension of **l** over some universe of individuals. If **x** and **y** are identical so will be **U** and **L**, whereas if they are disjoint **L** will be empty. Hence a natural distance measure is the number of individuals that are in **U** but not **L**:

"**x** distance **y**" $\quad d(\mathbf{x}, \mathbf{y}) = \mathcal{C}\mathbf{U} - \mathcal{C}\mathbf{L}$ (4)

where $\mathcal{C}\mathbf{U}$ and $\mathcal{C}\mathbf{L}$ are the cardinalities of **U** and **L** respectively. This measure satisfies the triangle inequality and can be normalized by dividing by its maximum possible value, $\mathcal{C}\mathbf{U}$. It is clearly dependent on the universe of individuals involved, but this is appropriate to measuring concept distance in an extensional context. Intensional concept "distance" independent of context is reflected in the relational structures already developed.

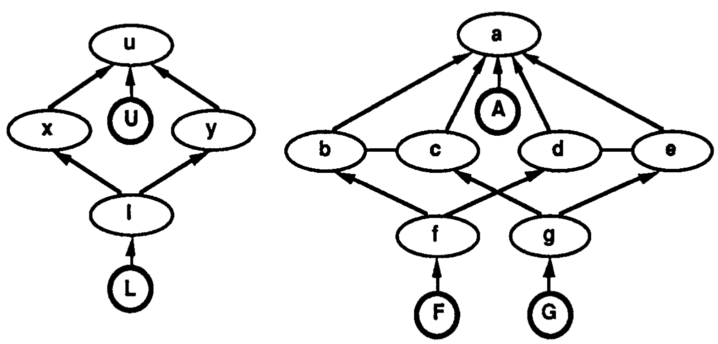

Figure 12 Calculation of distance measures between concepts and between constructs

The distance measure defined readily extends to dichotomous constructs through the comparison of poles as shown on the right of Figure 12:

"**b—c** distance **d—e**" $\quad d(\mathbf{b—c}, \mathbf{d—e}) = \mathcal{C}\mathbf{A} - \mathcal{C}\mathbf{F} - \mathcal{C}\mathbf{G}$ (5)

This measure is a count of the numbers of individuals that fall under the opposite pole of the other construct. Note that it is not invariant if one construct is reversed. This construction generalizes to scales with more than three points. If these scales are numbered linearly it computes a "city block" distance measure—which is precisely that used in construct clustering algorithms such as FOCUS (Shaw, 1980). These distance measures when applied to the constructs of one person enable natural clusters to be seen that may be grouped as part of a coherent concept, for example, in that they are all contributors to an evaluatory dimension. When applied to the constructs of different people in the same domain they enable consensus, conflict, correspondence and contrast in the use of constructs to be measured (Shaw & Gaines, 1989), as is discussed in the next Section.

Figure 13 shows a FOCUS analysis of the grid of Figure 11 in which the distance measure defined in (5) has been used to develop two matrices of inter-element and inter-construct distances. The sets of elements and constructs have then each been sorted to re-order the grid in such a way that similar elements and similar constructs are close together. The hierarchical clusters on the right portray this similarity by developing groups of elements and constructs, starting with the most similar and adding the next most similar, and so on until all the elements and constructs are clustered.

Thus, at the bottom of the construct clusters, it can be seen that the dimension "incorporates geologic model—doesn't incorporate geologic model" is used very similarly to "qualitative and quantitative—quantitative", and that both of these relate closely to "interpretive—representative. This geographer construes mappings that incorporate a geologic model as qualitative and quantitative, as opposed to solely quantitative, and as interpretive as opposed to representative. Similarly in the element clusters, "nonparametric kriging", "punctual kriging" and "universal kriging" are construed as closely related techniques with little distinction between them.

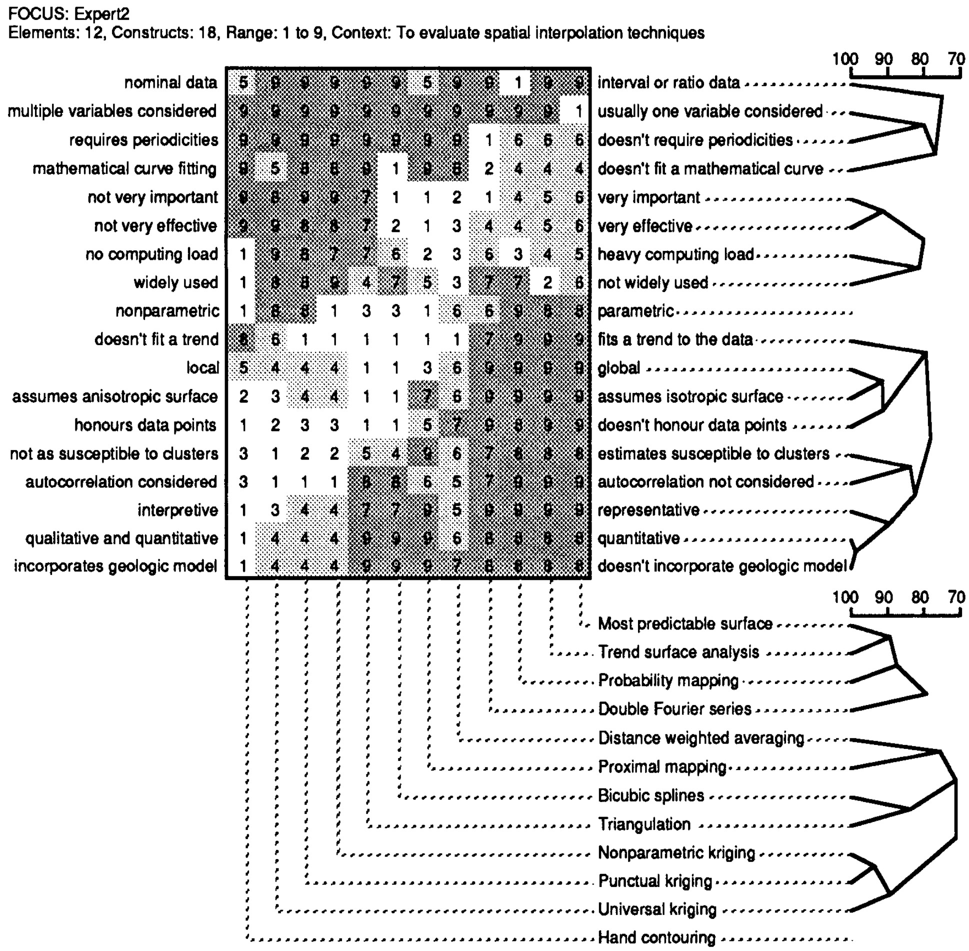

Figure 13 FOCUS hierarchical clustering of spatial mapping grid

The measures used in the induction of a rule linking to concepts are also readily derived as shown in Figure 14. $\mathcal{C}$**X** is the number of "predictions" made by concept **x** as the left hand side of a rule, and $\mathcal{C}$**L** is the number which are correct. Thus, the measures of the validity of inducing the rule, **x**→→**y**, are:

"prior probability of **y**"	$p(y) = \mathcal{C}Y/\mathcal{C}U$	(6)
"probability correct **x**→→**y**"	$p(x \rightarrow\rightarrow y) = \mathcal{C}L/\mathcal{C}X$	(7)
"probability by chance **x**→→**y**"	$c(x \rightarrow\rightarrow y) = I_{p(y)}(\mathcal{C}X - \mathcal{C}L, \mathcal{C}L + 1)$	(8)

where I is the incomplete beta function summing a binomial distribution tail. These measures are precisely those used by Induct (Gaines, 1989) in inducing rules from datasets. In the application to repertory grids Induct searches for potential rules whereby a target predicate may be deduced from some of the others, and constrains the search to rules whereby the probability that they arise by chance is less than some prescribed threshold. The basic search techniques have been well documented by Cendrowska (1987) but for practical applications they need to be controlled by these probabilistic measures, and also to be extended to generate rules with exceptions as these are both more compact and more in accordance with human practice (Gaines, 1991a).

To illustrate rule induction from repertory grids, Figure 15 shows a grid for Cendrowska's (1987) contact lens example involving 5 constructs and 14 stereotypical elements. The objective is to derive the prescription as "hard", "soft" or "none" (this last having been specified as a rating value of 2 on the "hard—soft" dimension). Figure 16 shows the five rules derived by Induct from the contact lens data. The first rule is a default to be applied when none of the others apply recommending "none." The next two rules specify the conditions for "hard". The fourth rule specifies the conditions for "soft", and the fifth specifies an exception to this

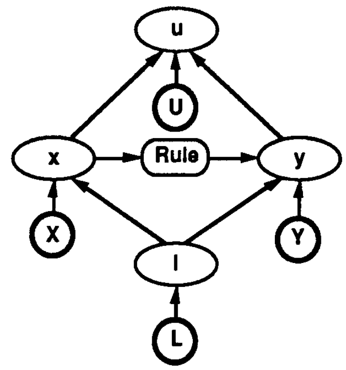

Figure 14 Induction of rules between concepts

		1 Client1	2 Client2	3 Client3	4 Client4	5 Client6	6 Client8	7 Client10	8 Client12	9 Client13	10 Client16	11 Client18	12 Client20	13 Client22	14 Client24		
young	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	1	presbyopic
myope	2	1	1	1	1	3	3	1	1	3	3	1	1	3	3	2	hypermetrope
not astigmatic	3	1	1	3	3	1	3	1	3	1	3	1	3	1	3	3	astigmatic
reduced	4	1	3	1	3	3	3	3	3	1	3	3	3	3	3	4	normal
soft	5	2	1	2	3	1	3	1	3	2	2	2	3	1	2	5	hard

Figure 15 Grid based on Cendrowska's contact lens data

RULE 1: -> lens = none
RULE 2: age = young & astigmatism = astigmatic & tear production = normal -> lens = hard (EXCEPTION TO: 1)
RULE 3: prescription = myope & astigmatism = astigmatic & tear production = normal -> lens = hard (EXCEPTION TO: 1)
RULE 4: astigmatism = not astigmatic & tear production = normal -> lens = soft (EXCEPTION TO: 1)
RULE 5: astigmatism = not astigmatic & age = presbyopic & prescription = myope -> lens = none (EXCEPTION TO: 4)

Figure 16 Induct analysis of contact lens data

Figure 17 shows the construct data in the grid used to define a class of patients together with the rules represented in the graphical notation described in this paper in the grapher implementing the visual language described in Section 14. The only extension to what has been already described is that an arrow from one rule to another means that the first is an exception to the second. The additional terminology has been introduced by having the user specify names for the constructs in the grid, for the central value of the "young—presbyopic" dimension, and for the rules. The graph produced by automatic output from the analysis of grid and rules has been manually edited to give a pleasing appearance but otherwise is a direct analysis of the grid.

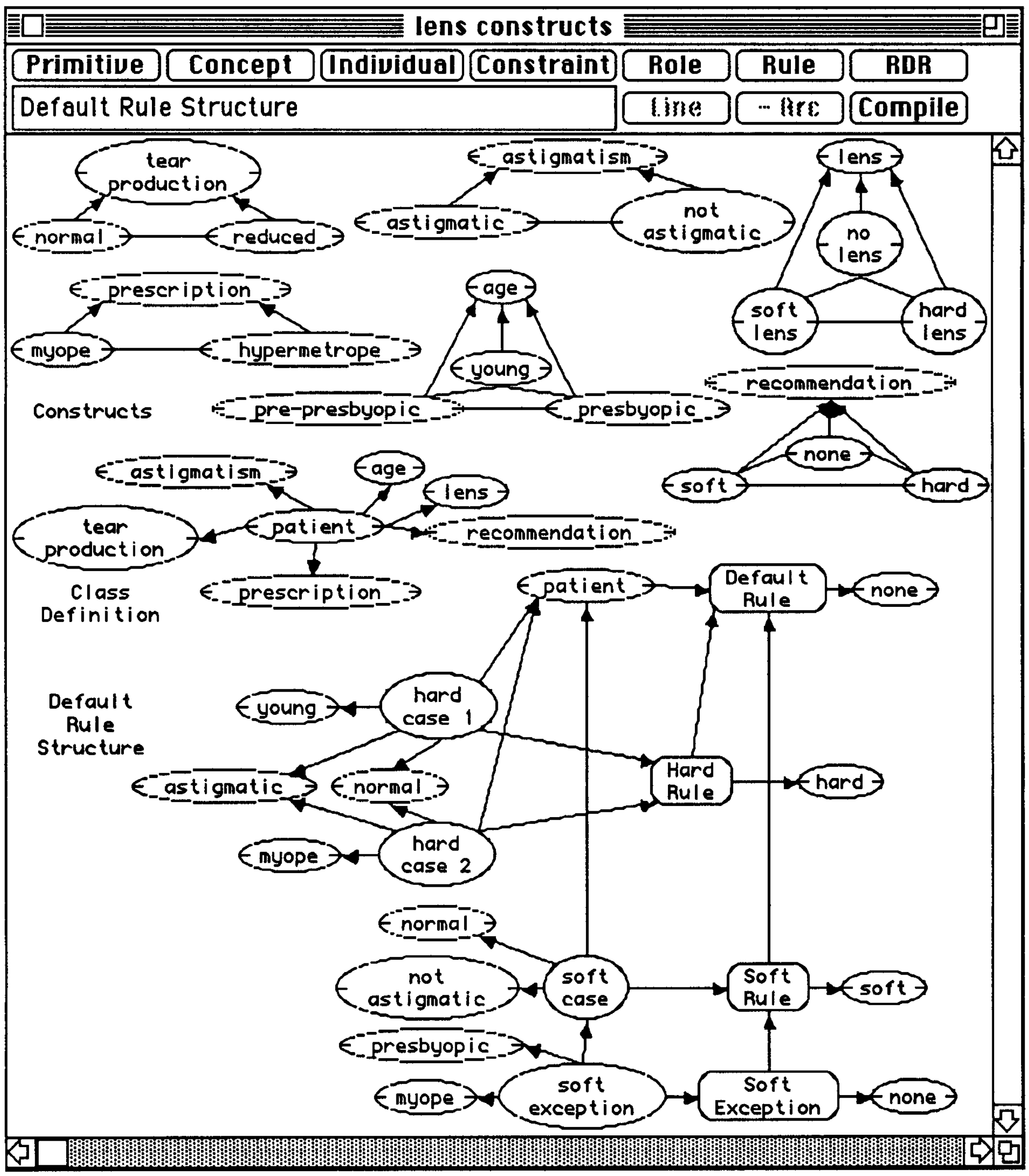

Figure 17 Contact lens domain and rules represented in the visual language

11 ELICITING CONCEPTUAL STRUCTURES FROM GROUPS

In developing knowledge-based systems one becomes aware very rapidly that the required conceptual structures can only rarely be elicited through access to one expert. The basic cognitive agent is not the person but the group. Kelly took group processes into account in personal construct psychology and the psychology and logic described extend readily to the group situation. In fact, as Simmel has noted the relevant cognitive units are not people but the roles within people that they have formed to function within a group:

> "Society strives to be a whole, an organic unit of which the individuals must be mere members. Society asks of the individual that he employ all his strength in the service of the special functions which he has to exercise as a member of it; that he so modify himself as to become the most suitable vehicle for this function....man has the capacity to decompose himself into parts and to feel any one of these as his proper self." (Simmel, 1950, pp.58-59)

Pask goes beyond Simmel in conceiving that a cognitive entity, which he termed a psychological individual or P-Individual, is not just what we conventionally term a 'role' within a person but may itself be composed of a number of roles coming together to form a unity that we conventionally term a group or organization:

> "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. However, it is quite exceptional to discover the (usually assumed) one to one correspondence between M-Individuals and P-Individuals." (Pask, 1975, p.302)

Popper (1968) focused on the knowledge structures that one may be derived from a well-functioning P-Individual in terms of Frege's notion of a "third world" of "statements in themselves". The third world of knowledge is a useful representation of that which we elicit in developing knowledge-based systems, particularly when we note its distinct 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 unforeseeable 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, 1974, p.148)

Shaw (1985) has developed these notions within the framework of personal construct psychology to show how it may be used to account for the psychological processes not only of individual people but also for that of functional groups such as a nuclear family or a product executive. Figure 18 illustrates these ideas. Anne is shown as having three roles, wife, mathematician and technical vice president. John is also shown as having three roles, husband, golfer and sales vice president. The wife role in Anne together with the husband role in John together constitute a new P-Individual or cognitive entity, a nuclear family. This has behavior, language, legal rights, and a model of the world, that are distinct from those of Anne and John in their other roles, and goes beyond those of the participating roles in Anne or John alone. Similarly, the technical VP role in Anne, the sales VP role in John, the finance VP role in Mark and the production VP role in Sue constitute another P-Individual or cognitive entity with again behavior, language, rights and models that are distinct from its participants and other cognitive entities in which they participate in other roles.

The conceptual systems imputed to the roles within people constituting the product executive, and applied by them to make distinctions within a world of products and associated items, are shown in the center. Popper's three worlds distinctions have been used to label the sub-systems within Figure 18, emphasizing through the "world 3" label that the imputed conceptual systems are modeled within an overt, shared world of discourse, subject to encoding in media. "World 1" has been termed one of *reified systems*, rather than of "physical systems" since it can be any subsystem that is imputed to have some special status of inter-subjective availability, that is, to be "real" in some sense.

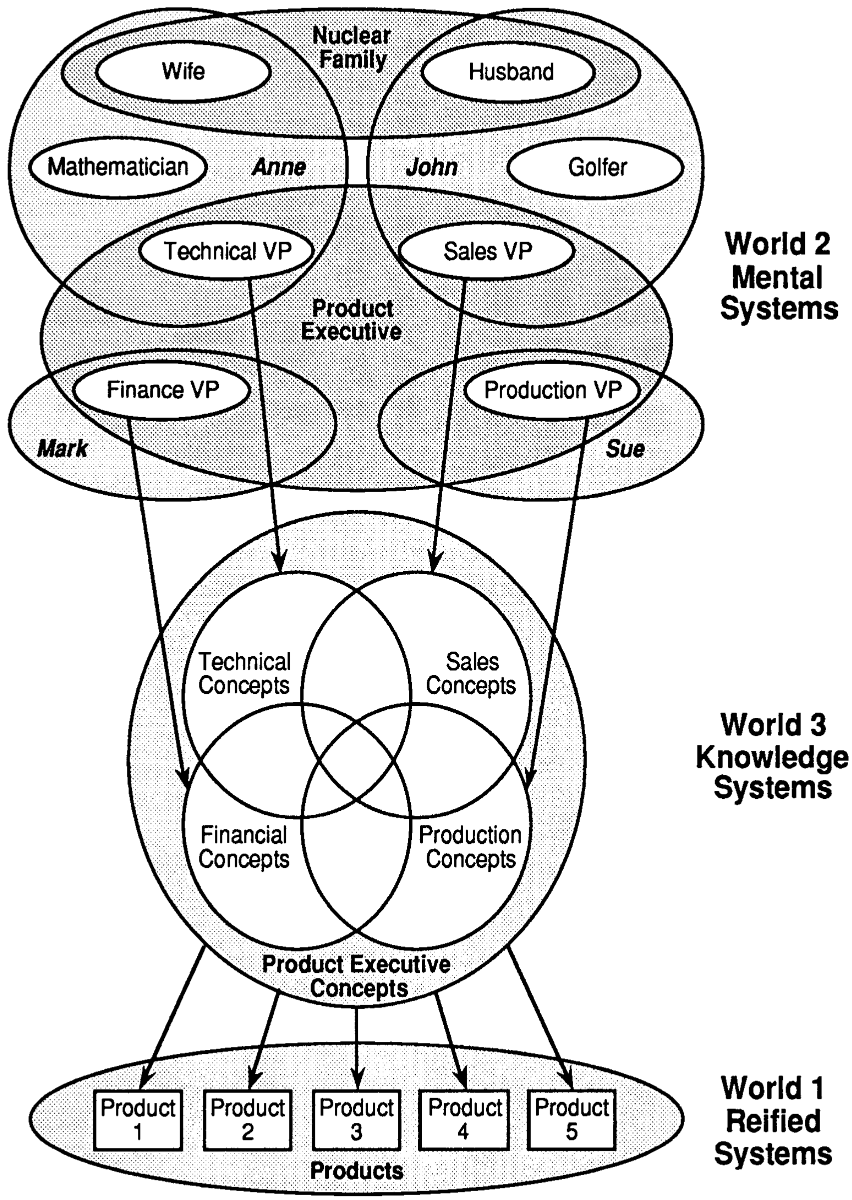

Figure 18 Concept structures as systems of distinctions imputed to cognitive systems to mediate their interaction with a world

A new issue raised by Figure 18 is a linguistic one. We have so far assumed that the terminology used for distinctions is well-defined and unambiguous. This is not reasonable in a group situation. People may use the same term for different distinctions, and different terms for the same distinction. Elicitation methodologies for the group situation are much the same as those for the individual situation except for the need to track such terminological differences. Figure 19 shows the four situations that may arise through interactions between terminology and distinctions (Shaw & Gaines, 1989).

The recognition of consensual concepts is important because it establishes a basis for communication using shared concepts and terminologies. The recognition of conflicting concepts establishes a basis for avoiding confusion over the labeling of differing concepts with same term. The recognition of corresponding concepts establishes a basis for mutual understanding of differing terms through the availability of common concepts. The recognition of contrasting concepts establishes that there are aspects of the differing knowledge about which communication and understanding may be very difficult, even though this should not lead to confusion. Such contrasts are more common than is generally realized. For example, it is possible to derive the same theorem in mathematics either by using an algebraic perspective, or a geometric one. There is nothing in common in these two approaches except the final result. It may still be possible to discuss the same domain using consensual and corresponding concepts that were not fundamental to the problem solving activities.

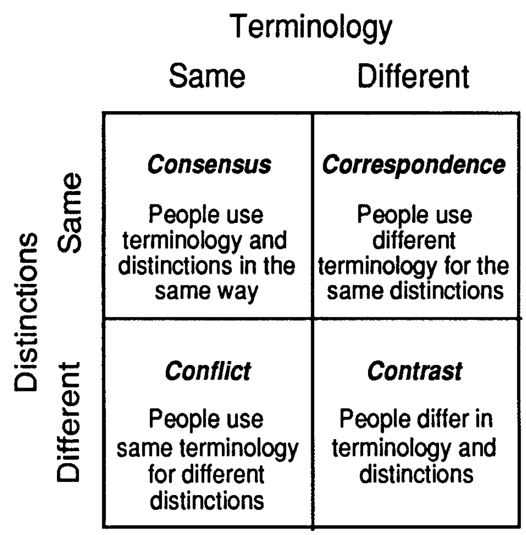

Figure 19 Four-quadrant representation of consensus, correspondence, conflict and contrast between distinctions in conceptual systems

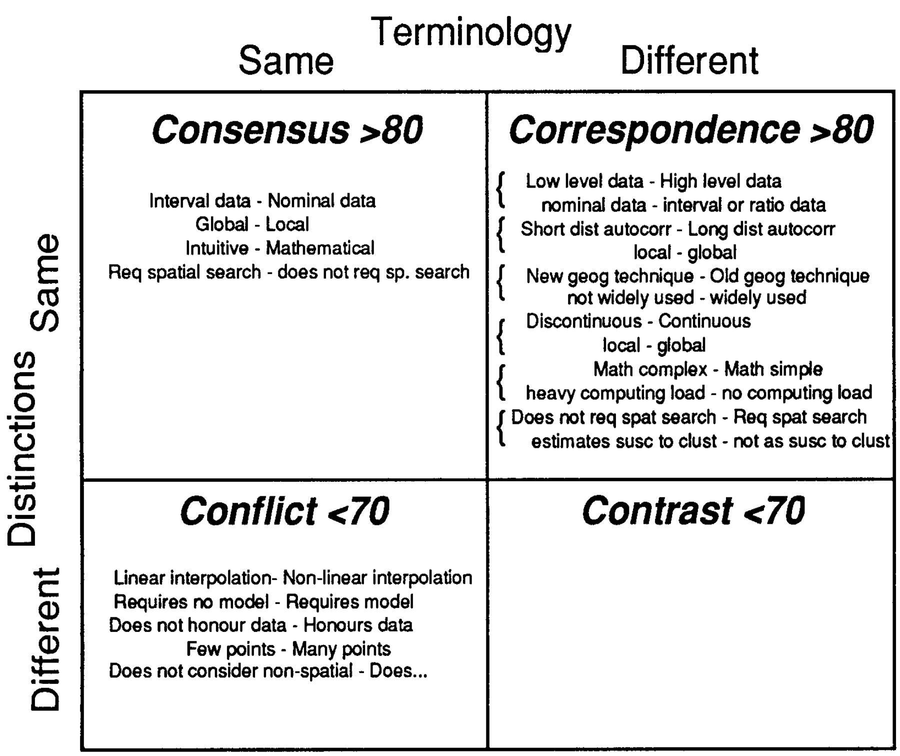

Figure 20 Four-quadrant analysis of grid data from two experts in spatial mapping

Figure 20 shows grid data elicited from two geographers on spatial mapping techniques analyzed in terms of consensus, correspondence, conflict and contrast. Some raw data and its individual analysis has already been shown in Figures 11 and 13. There is no significant example of *contrast* in this data, possibly because the two experts work very closely together. The basis of the consensus and conflict analysis is shown in detail in the difference analysis of Figure 21 where rating values (in this case 1 to 5) for expert B's ratings of expert A's elements on his constructs are subtracted from expert A's similar rating values respectively. Figure 21 shows this with the elements and constructs about which they agree the most in the top right corner, shown by no difference or a difference of only 1; and those with most disagreement towards the bottom left, shown by the maximum difference of 4 or a large difference of 3. The darker gray areas indicate the greater difference. The graphs on the right show the declining matches and may be used to decide where to place thresholds distinguishing consensus and conflict. From this difference grid, the consensus and conflicts can easily be identified and discussed by the experts.

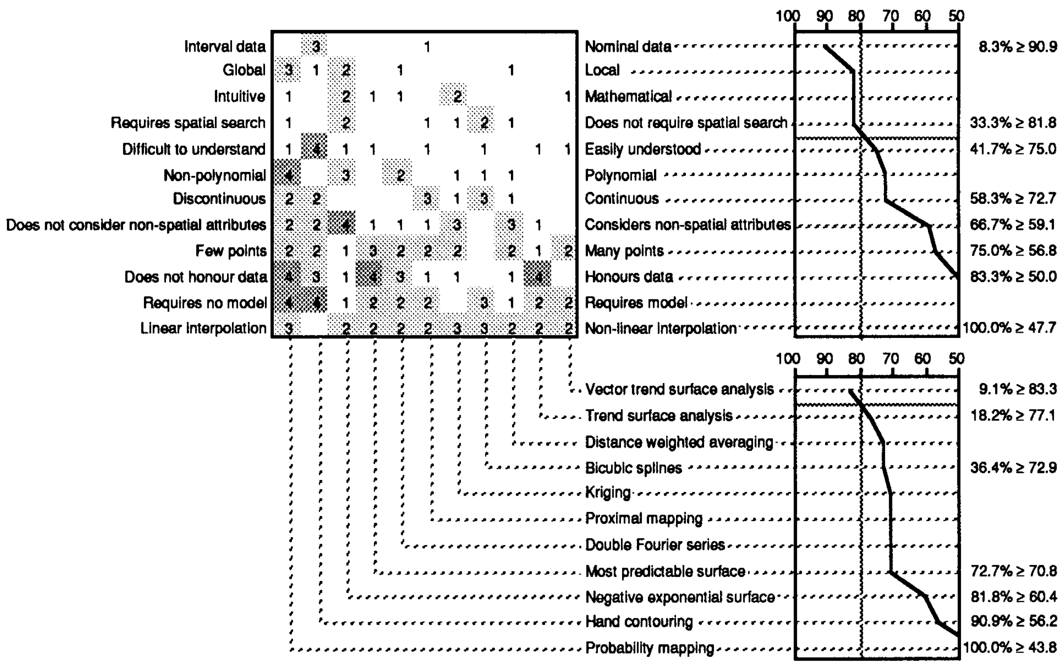

Figure 21 Difference analysis for two spatial mapping experts

The basis of the correspondence and contrast analysis is shown in detail in the construct comparison analysis of Figure 22 in which construct matches are sorted with highest first. The cumulative percentage is given of those with matches greater than the value shown, and the construct from one expert which best matches each from the other is shown beneath it. It can be seen that:

- Both experts are using the construct *local-global* in the same way. This is an example of *correspondence*. It is not an interesting one because we can see that the terms used are the same and it is effectively arising from a *consensus*.
- When one expert uses the term *low-level-data—high-level data,* the other is using the term *nominal data—interval or ratio data*. This shows a difference in terminology which can be interpreted as their *levels of abstraction* being different in their construing of this topic, and is an interesting *correspondence*.

- The construct *heavy computing load—no computing load* is being used by one expert to correspond to *mathematically complex—mathematically simple* used by the other. We can interpret this as a difference in terminology corresponding to a correlation in the real-world.

```
G1<:G2 62.5% over 80.0 (ExpertA construct-construed-by ExpertB)
  1:    6.2% ≥ 88.5    G1A2: Local - Global
                       G2A2: local - global
  2:   12.5% ≥ 87.5    G1A3: Low level data - High level data
                       G2A8:   nominal data - interval or ratio data
  3:           86.5    G1A1: Does not honour data points - Honours data points
                       G2A4: doesn't honour data points - honours data points
  4:           86.5    G1A7: Short distance autocorrelation - Long distance autocorrelation
                       G2A2:                          local - global
  5:   31.2% ≥ 86.5    G1A9: New geographical technique - Old geographical technique
                      G2A18:            not widely used - widely used
  6:   37.5% ≥ 85.4   G1A16: Not widely used - Widely used
                      G2A18: not widely used - widely used
  7:   43.8% ≥ 83.3    G1A5: Discontinuous - Continuous
                       G2A2:         local - global
  8:   50.0% ≥ 82.3    G1A4: Mathematically complex - Mathematically simple
                      G2A11:   heavy computing load - no computing load
  9:           81.2   G1A10:   Hard to adapt to multivariate - Easy to adapt to multivariate
                       G2A5: usually one variable considered - multiple variables considered
 10:   62.5% ≥ 81.2   G1A12:   Does not require spatial search - Requires spatial search
                      G2A13: estimates susceptible to clusters - not as susceptible to clusters
```

Figure 22 Construct comparison for two spatial mapping experts

12 TOOLS BASED ON PERSONAL CONSTRUCT PSYCHOLOGY—KSS0

The preceding sections have given the historic, psychological and technical foundations of personal construct psychology, and illustrated some of the techniques that are used in its application to knowledge acquisition. In doing this, some aspects of repertory grid and semantic net elicitation and analysis tools based on personal construct psychology have also been illustrated. There is not space in this paper to present even the major tools in great detail—the tools have many features, the user manuals are large, and each application in itself requires a long paper to describe. The details are available in the knowledge acquisition literature and in many papers in journals and conference proceedings that have already been cited. This and the following Sections give an overview of the objectives, activities and developmental directions of the two major research groups that have developed a diversity of knowledge acquisition tools: that associated with the authors at the Centre for Person-Computer Studies and the Knowledge Science Institute, and that associated with John Boose and Jeff Bradshaw at Boeing Computer Services. A brief history of developments in the first group is given in Gaines (1988) and of the second in Boose, Bradshaw, Kitto and Shema (1989).

KSS0 is a repertory grid elicitation and analysis system running on Macintosh computers that aims to allow end-users, the experts rather than the knowledge engineers, to develop their conceptual structures through direct computer interaction. Hence it focuses on ease of use through attractive user interfaces to both elicitation and analysis. Figure 23 gives an overview of the tools in KSS0 and their interrelations:

- *Elicit* accepts specifications of cases as elements within a sub-domain and provides an interactive graphical elicitation environment within which the experts can distinguish elements to derive their constructs. The resultant class is continuously analyzed to provide feedback prompting the expert to enter further elements and constructs.

The visualization tools consist of an interactive interface to represent the abstractions derived from those elements in terms of hierarchical clusters using FOCUS, and relational diagrams such as a non-hierarchical conceptual maps derived through principal components analysis. The objectives are to validate the raw domain knowledge and suggest further structure:

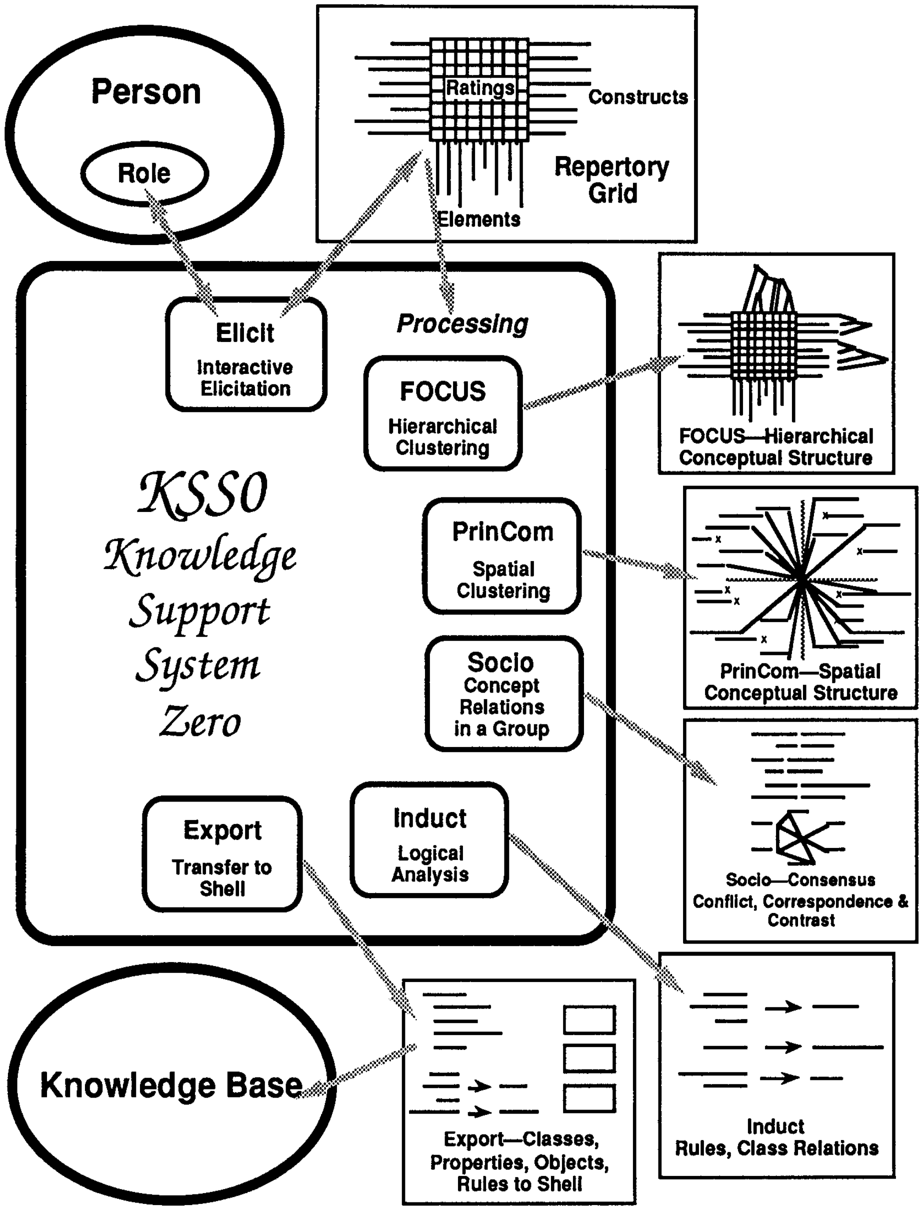

Figure 23 KSS0 architecture

- *FOCUS* hierarchically clusters elements and constructs within a sub-domain prompting the experts to add higher-level constructs structuring the domain.
- *PrinCom* spatially clusters elements and constructs within a sub-domain prompting the experts to add higher-level constructs structuring the domain.

The group comparison tools consist of an interactive interface to represent the relations between the terminologies and conceptual systems of different experts, or experts and clients:

- *Socio* compares the structures for the same sub-domain generated by different experts, or the same expert at different times or from varying perspectives.

The inductive part consists in the derivation of constraints within the conceptual structures through logical entailment analyses. The objective is to suggest further structure at a higher level that translates into concept subsumptions or rules in the expert system shell:

- *Induct* induces logical entailments enabling the constructs applying to an element or the evaluations of a decision-making situation in a domain, to be derived from other constructs.

The generative part consists in the transformation of the knowledge analysis made by the previous tools into formalisms understandable by knowledge-based system shells such as *NEXPERT* (Rappaport, 1987) and *Babylon* (Christaller, Primio & Voss, 1989):

- *Export* formats the specifications of sub-domains as classes, of elements as objects, of constructs as properties, and of entailments as methods, and transfers them to the performance tool.

The main aspects of KSSO that have not been illustrated are *Elicit* module for the interactive graphical elicitation of repertory grids, and the *Export* module for transfer of the results of grid elicitation and analysis to an expert system shell. Figure 24 shows triadic elicitation occurring during the elicitation of a grid on spatial mapping techniques, and Figure 25 shows the elements being rated on the construct elicited in this way. Figure 26 shows a construct match being used to suggest the entry of another element which might break the match. KSSO generates a wide variety of such screens during elicitation to maintain the expert's interest and explore his or her psychological space. Its operation is non-modal so that cluster and induction analyses may be requested during elicitation also.

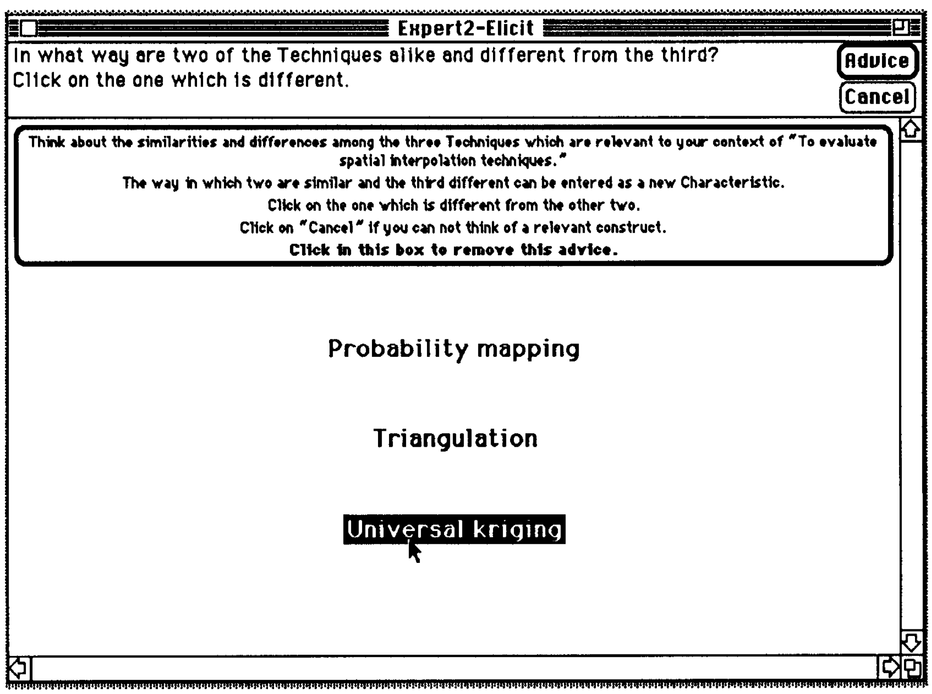

Figure 24 Construct elicitation from a triad

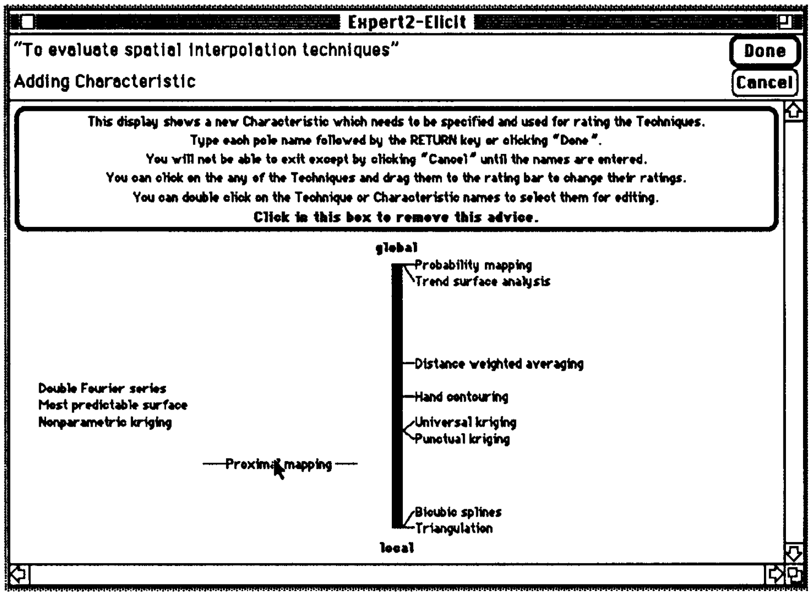

Figure 25 Click and drag rating of elements on constructs

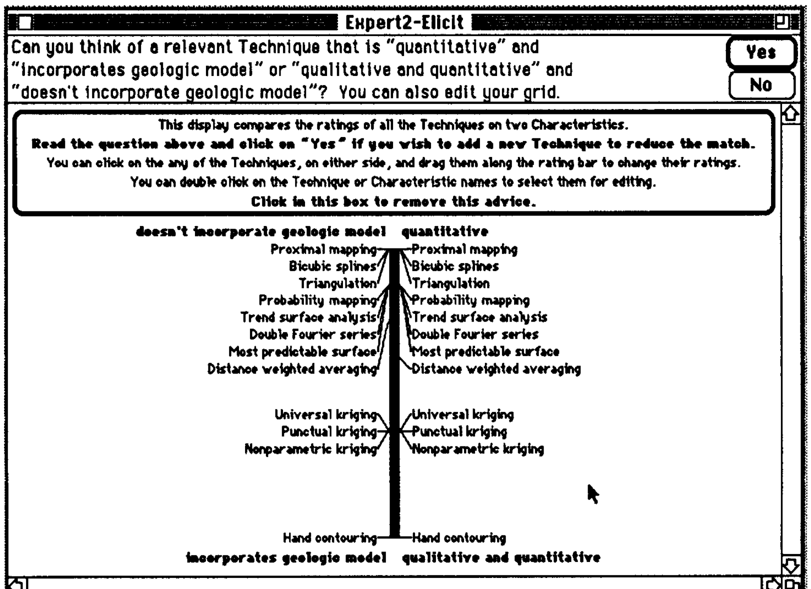

Figure 26 Eliciting an element through a construct match

Figures 27 through 30 are based on the contact lens data of Figures 15 and 16 and show some of the data structures exported from KSS0 to NEXPERT. These are given in detail because experience has shown that the way in which repertory grid data translates into expert system knowledge structures requires considerable attention in implementing knowledge acquisition tools. The structures for another shell such as BABYLON are similar in form but very different in detail.

Figure 27 shows rule class and subclass definitions used to establishment an object-oriented framework for the rules.

```
(@CLASS=      Rules   (@SUBCLASSES=        contact_lens_prescription)
        (@PROPERTIES=
                hypothesis        @TYPE=Boolean;
        )
)
(@CLASS=      contact_lens_prescription
        (@SUBCLASSES=
                lens_recommendation
        )
)
(@CLASS=      lens_recommendation)
```

Figure 27 Rule class and subclass definitions from contact lens dataset

Figure 28 shows the top level control rule generated. It uses the class of Rules defined in Figure 27 in a pattern-matching clause that tests whether the hypothesis of any rule is true. The global hypothesis of this rule is also put on the list of suggestions in the shell so that this rule may be triggered very simply.

```
(@OBJECT=     Global_Hypothesis)
(@RULE=       Global
        (@LHS=
                (Yes    (<Rules>.hypothesis))
        )
        (@HYPO=       Global_Hypothesis)
)
(@GLOBALS=    @SUGLIST=     Global_Hypothesis;)
```

Figure 28 The top level control rule

Figure 29 shows the class definition that transfers the primary knowledge structure about the class of cases defined by the dataset. It is followed by meta-slot definitions, of which one is shown, giving the prompts that the shell should use in requesting the values of attributes. These are followed by the instantiation of one object in the class that may be used as a test case.

```
(@CLASS=      people
        (@PROPERTIES=
                age     @TYPE=String;
                prescription      @TYPE=String;
                astigmatism       @TYPE=String;
                tear_production   @TYPE=String;
                lens_recommendation      @TYPE=String;
        )
)
(@SLOT=       people.age        @PROMPT="Double click on the age from the list
below that applies to @SELF";)
(@OBJECT=     person  (@CLASSES=    people))
```

Figure 29 Case class definition, prompting and instantiation

Figure 30 shows a rule generated by *Induct* translated into *NEXPERT* knowledge base format. The first line instantiates a rule object for the rule. The left hand side tests the premise of the rule with an added test to determine whether the value of the attribute to be set on the right hand side of the rule is already known.

```
(@OBJECT=       Ind_1   (@CLASSES=   lens_recommendation))
(@RULE=         Ind_1
  (@LHS=
        (IsNot  (<people>.lens_recommendation)  (KNOWN))
        (Is     (<people>.prescription)     ("hypermetrope"))
        (Is     (<people>.astigmatism)      ("not_astigmatic"))
        (Is     (<people>.tear_production)          ("normal"))
  )
  (@HYPO=       Ind_1.hypothesis)
  (@RHS=
        (Let    (<people>.lens_recommendation)  ("soft"))
  )
)
(@SLOT=         Ind_1.hypothesis        @INFCAT=        10098;)
```

Figure 30 Induced rule transferred to *NEXPERT*

13 TOOLS BASED ON PERSONAL CONSTRUCT PSYCHOLOGY—AQUINAS

AQUINAS and KSS0 have very similar origins and some related functionality since the two groups have collaborated through very open information interchange. However, there are major differences in the directions of development and objectives that make for very significant variations in the operations and functionalities of the two systems. The major difference in performance objectives is that while ETS, the precursor to AQUINAS, was aimed at knowledge acquisition for expert system development, AQUINAS has been designed as a complete decision support environment. It uses case-based reasoning to provide its own inference engine independent of any expert system shell. The major difference in technical objectives is that AQUINAS, as already noted, greatly extended the basic repertory grid to support hierarchical structures of elements, constructs, multiple experts and multiple tasks, and to allow complex constraints to be specified rather than just rating values.

Figure 31 shows the way in which a rating grid in AQUINAS is essentially a four-dimensional structure indexed by hierarchies of solutions (elements), traits (constructs), experts (elicitees) and cases (application contexts). The particular grid under consideration at any time is determined by the sub-hierarchies selected as indicated in the diagram.

Figure 32 is a concrete instance of these hierarchies developed for a programming language advisor, and Figure 33 shows how a simple grid might be defined through selection in the hierarchies. AQUINAS provides a wide range of user facilities to navigate the multi-dimensional grid structure. In its inference procedures it also provides techniques to use grid data from multiple sources and levels to provide advice in decision support problems. For example, if one expert has not rated a solution on a particular trait then this information may be obtained from the data of another expert. More complexly, ratings available only at higher levels in the hierarchy may be propagated to lower levels, and conversely ratings available at only lower levels may be used to estimate those at higher levels. This need to estimate expert judgements from a variety of sources and to use them directly to support decision making has led to the use of a variety of existing decision-theoretic methodologies in AQUINAS, and also to the development of many novel approaches.

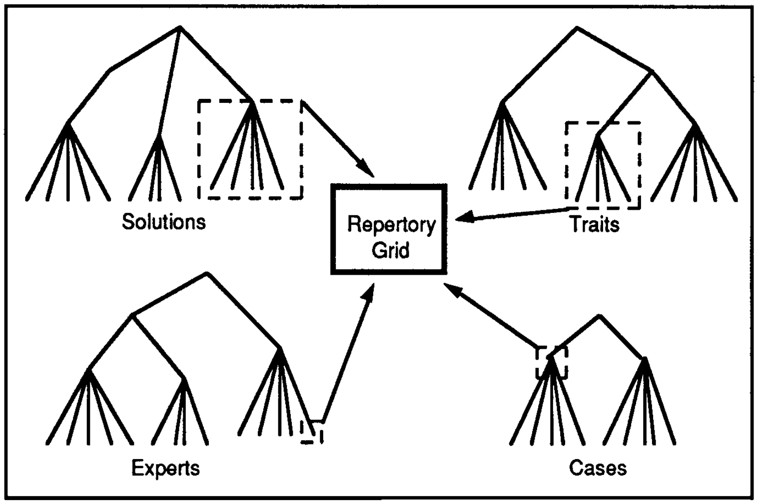

Figure 31 AQUINAS extended repertory grid structure (Boose & Bradshaw, 1987)

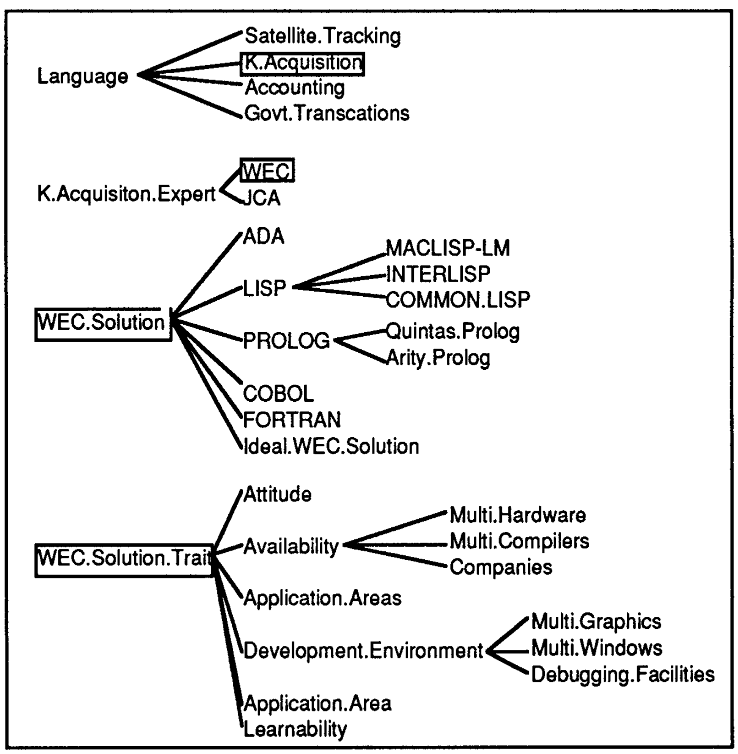

Figure 32 Programming language advisor hierarchies in AQUINAS (Boose & Bradshaw, 1987)

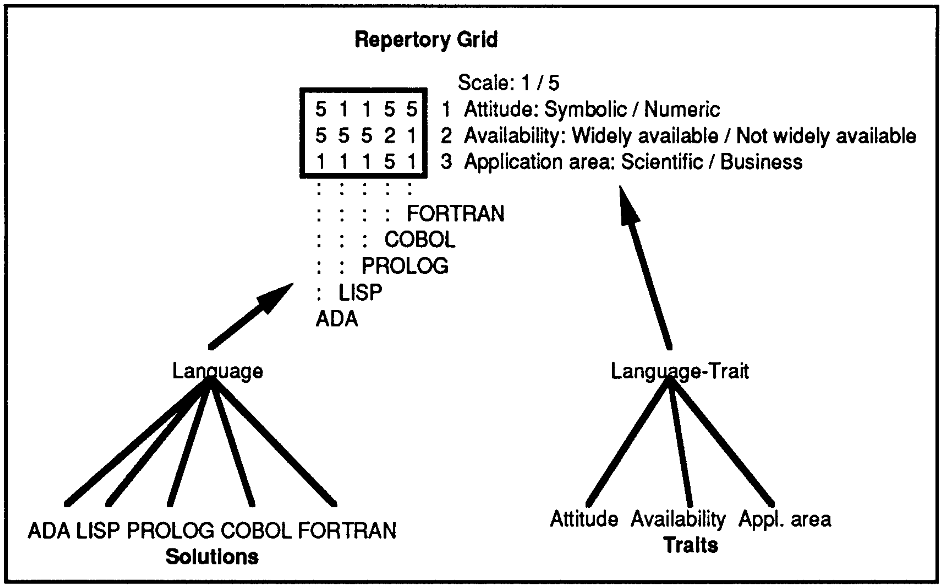

Figure 33 Defining a grid from a hierarchy in AQUINAS (Boose & Bradshaw, 1987)

As Boose and Bradshaw (1987) note, in AQUINAS various trait (attribute) scale types can be elicited, analyzed, and used by the reasoning engine. Traits are currently described according to the level of measurement of their rating scales, which is determined by the expert. The level of measurement depends on the presence or absence of four characteristics: distinctiveness, ordering in magnitude, equal intervals, and absolute zero (Coombs, Dawes & Tversky, 1970). These four characteristics describe the four major levels of measurement, or types of traits: nominal (unordered symbols), ordinal, interval, and ratio. The additional information about trait types gives increased power to analytical tools within AQUINAS and allows experts to represent information at the level of precision they desire.

Ratings may be generated through several methods:

1. **Direct.** An expert directly assigns a rating value for a trait and an element. If an exact value is unknown, AQUINAS helps the expert derive an estimate (Beyth-Marom & Dekel, 1985). If fine judgments are needed, AQUINAS can derive a set of ratio scaled ratings from a series of pairwise comparisons (Saaty, 1980). AQUINAS also contains tools for encoding of probability distributions on specific values. The value with the highest probability is displayed in the grid, but all appropriate values are used in reasoning and may be edited with graphic distribution aids.
2. **Derived.** Incomplete grids can be automatically filled through propagation of rating values from another grid through the hierarchies (e.g. from lower to higher level grids, different experts, or different cases).

One particularly attractive feature of AQUINAS is the way in which the expert hierarchy may be used to provide advice based on the opinion of a particular expert or weighted combinations of experts, and also used to provide an analysis of the extent to which other experts might dissent from this advice (Boose, 1986b). The dissenting opinion is found by computing a correlation score between each member and the consensus; the member with the lowest correlation score is listed as the dissenting opinion. Dissenting opinions show the users the range of opinion about a decision, not just the top rated list and give decision makers confidence that the top rated alternatives were sound choices or point out areas of disagreement for further exploration.

The Boeing group has developed many other decision support tools that have been combined in a variety of ways with AQUINAS. For example, Canard is an engineering design aid that helps synthesize alternatives from potentially large search spaces (Bradshaw, Boose, Covington, & Russo, 1989; Shema, Bradshaw, Covington & Boose, 1990). Canard helps generate and structure complex alternatives in a possibility table. The possibility table representation was adopted from manually developed strategy tables (McNamee & Celona, 1987) and morphological charts (Zwicky, 1969). Canard automates this representation and extends its logic and structure to allow knowledge-based inference and the representation of more complex problems (e.g. hierarchical tables, explicit representation of constraints). Figure 34 shows a Canard possibility table for a portion of a network design problem. The thick horizontal line is a partial solution path linking component alternatives. Shaded cells show hard and soft constraints associated with the path. The left-most column shows classes of solutions associated with paths. Repertory grids "plug in" to each column, recording criteria relationships and enabling analysis. Repertory grid reasoning methods help rank the components in a column. Automated methods combine ranking information with constraints to produce a set of best possible solutions.

DART (Design Alternatives Rationale Tradeoffs) is an application of repertory-grid-based knowledge acquisition techniques to *trade studies* in engineering design. It was originally developed for NASA as part of an effort to capture design knowledge for the Space Station Freedom program (Boose, Shema, and Bradshaw, 1990). In recent years a major focus of activity for the group has become the development of *group decision support systems* based on extended repertory grids and decision analysis (Boose, Bradshaw, Koszarek & Shema, 1992).

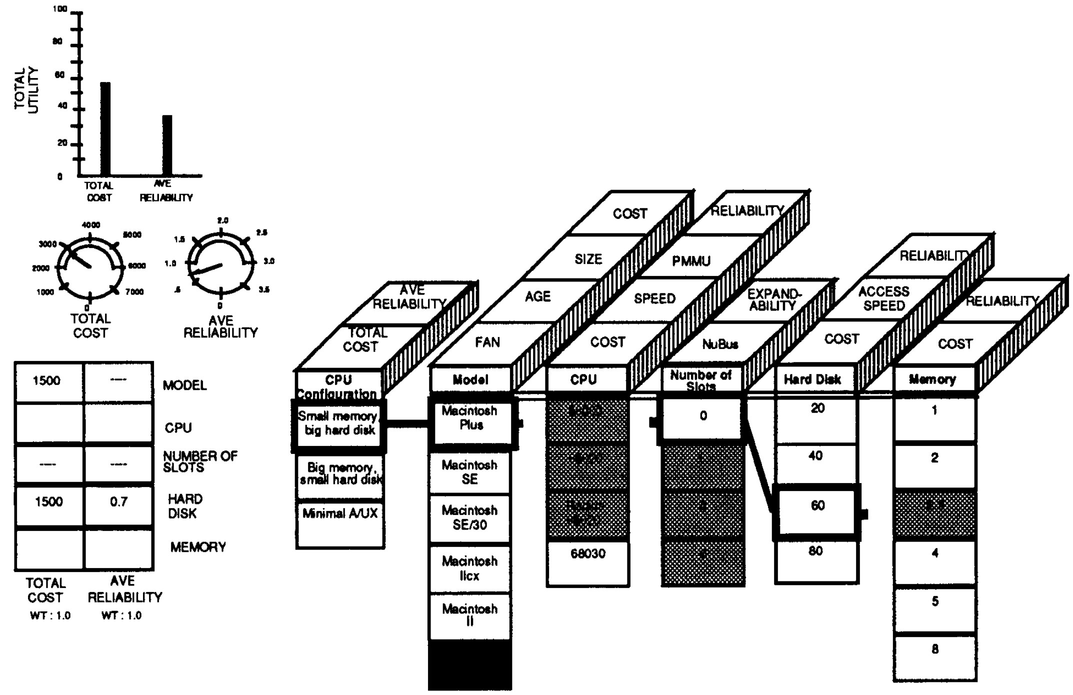

Figure 34 Engineering design in Canard (Shema, Bradshaw, Covington & Boose, 1990)

14 TOOLS BASED ON PERSONAL CONSTRUCT PSYCHOLOGY—KSSn

KSS0 and AQUINAS were both developed commencing with the standard, rating-scale based repertory grid and extending it in various ways. In the light of several years experience with the systems, and with developments in the logical expression of personal construct psychology, it became timely in the 1990s to develop a new range of systems based on the cognitive and logical foundations described in this paper. In particular, the weaknesses of the basic repertory grid in representing more 'objective' data such as categories, numbers, dates, and so on, have restricted methodologies without major extensions to use only in the initial stages of knowledge acquisition. Similar considerations apply to the lack of representation of hierarchical relations between elements and constructs in the basic repertory grid. As knowledge acquisition tools mature it is reasonable to expect them to extend in scope from initial elicitation, through detailed knowledge modeling, to validation and knowledge base maintenance. This has been achieved experimentally through the various extensions already described and also by integration with other systems as described in the next Section. However, it is important that the somewhat *ad hoc* systems developed in this way be used as a basis for a new generation of more principled designs.

KSSn is an ongoing experiment in the development of knowledge acquisition tools based on personal construct psychology. It takes advantage of two recent developments in artificial intelligence and software engineering: new insights into the complexity issues affecting knowledge representation and reasoning (Brachman & Levesque, 1984; Schmidt-Schauss, 1989); and the development of object-oriented programming environments offering precise definition and efficient implementation of extensible abstract data types (Shriver & Wegner, 1987). The advances in artificial intelligence allow requirements specifications to be developed for knowledge representation and reasoning systems with known, and practically applicable, performance curves. The advances in software engineering allow these specifications to be implemented cleanly in such a way that their conformance with the requirements can be verified and their algorithms achieve the best possible performance.

The series of knowledge representation schemes and tools commencing with KL-ONE (Brachman & Schmolze, 1985), developing through KRYPTON (Brachman, Gilbert & Levesque, 1985) and currently culminating in systems such as CLASSIC (Borgida, Brachman, McGuinness & Resnick, 1989) and LOOM (MacGregor, 1988) has reached a maturity of technology which offers the promise of knowledge representation 'services' in Levesque's (1984) terminology. KSSn is designed around a knowledge representation server implemented in C++ (Gaines, 1991b), providing services based on those of CLASSIC augmented with inverse roles, data types for integers, reals, strings and dates, and with rule representation that allows one rule to be declared an exception to others (Gaines, 1991a). The server supports the operations of the intensional logic underlying personal construct psychology as described in this paper, and one of the modules attached to it is a graphic knowledge editor supporting the associated visual language (Gaines, 1991c). This was used to represent the knowledge structures shown in Figures 9 and 17.

The user interfaces to the server in KSSn are designed to extend those of KSS0 to a wide range of data types and to hierarchical knowledge structures, without losing the essential simplicity of the original interfaces which have proved very effective with end users. Visualization interfaces such as those of Figures 24 through 26 are still used initially to capture basic repertory grid data, but the scales can be converted to categories, numbers or dates as the knowledge structures are refined. The elements and constructs are also visually represented not as lists but rather as a knowledge structure in the grapher. Figure 35 shows the grid of Figure 11 during development in the grapher. This is a simple flat structure of individuals instantiating roles, but the grapher allows this basic grid structure to be extended to hierarchical relations. Figure 36 shows the AQUINAS knowledge structure of Figure 32 in the grapher.

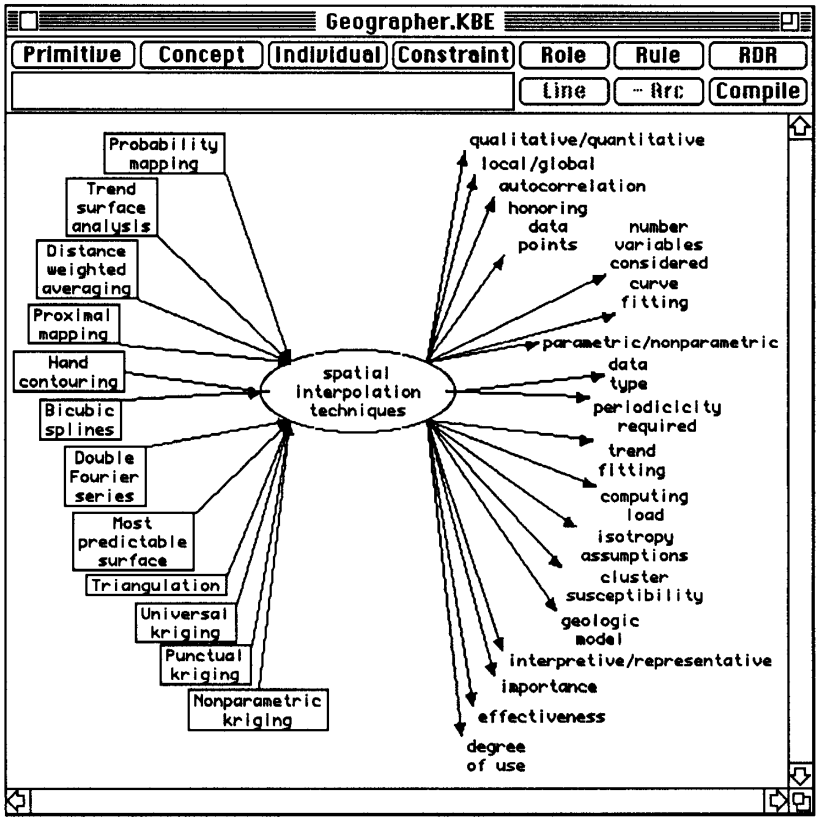

Figure 35 Spatial mapping grid elements and constructs in the grapher

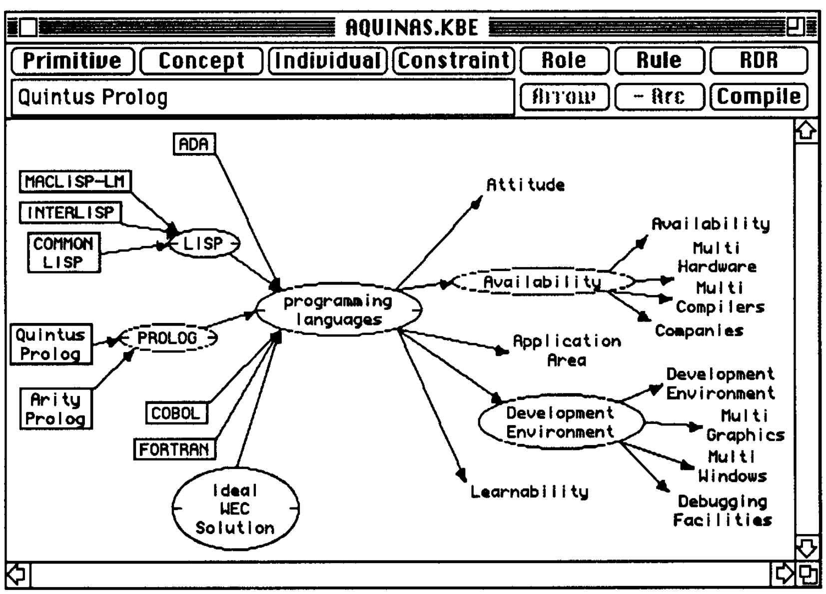

Figure 36 AQUINAS language advisor solution and trait hierarchies in the grapher

While KSSn still provides export facilities to expert system shells, the KL-ONE/CLASSIC inference capabilities of the server allow the system to be used as a complete problem solving environment. For example, Figure 37 shows KSSn in use on a room allocation problem (Gaines, 1991d) derived from an ESPRIT project (Voß, Karbach, Drouven, Lorek & Schuckey, 1990) that has recently been placed in the public domain as part of Project Sisyphus. Sisyphus is research program to encourage international collaboration in knowledge-based system development developed initially by the European Knowledge Acquisition Workshop in 1989. A number of problem datasets have been made available through Sisyphus, and a major part of the EKAW'91 program was devoted to reports on the solution of these problems using different approaches and techniques (Linster, 1991).

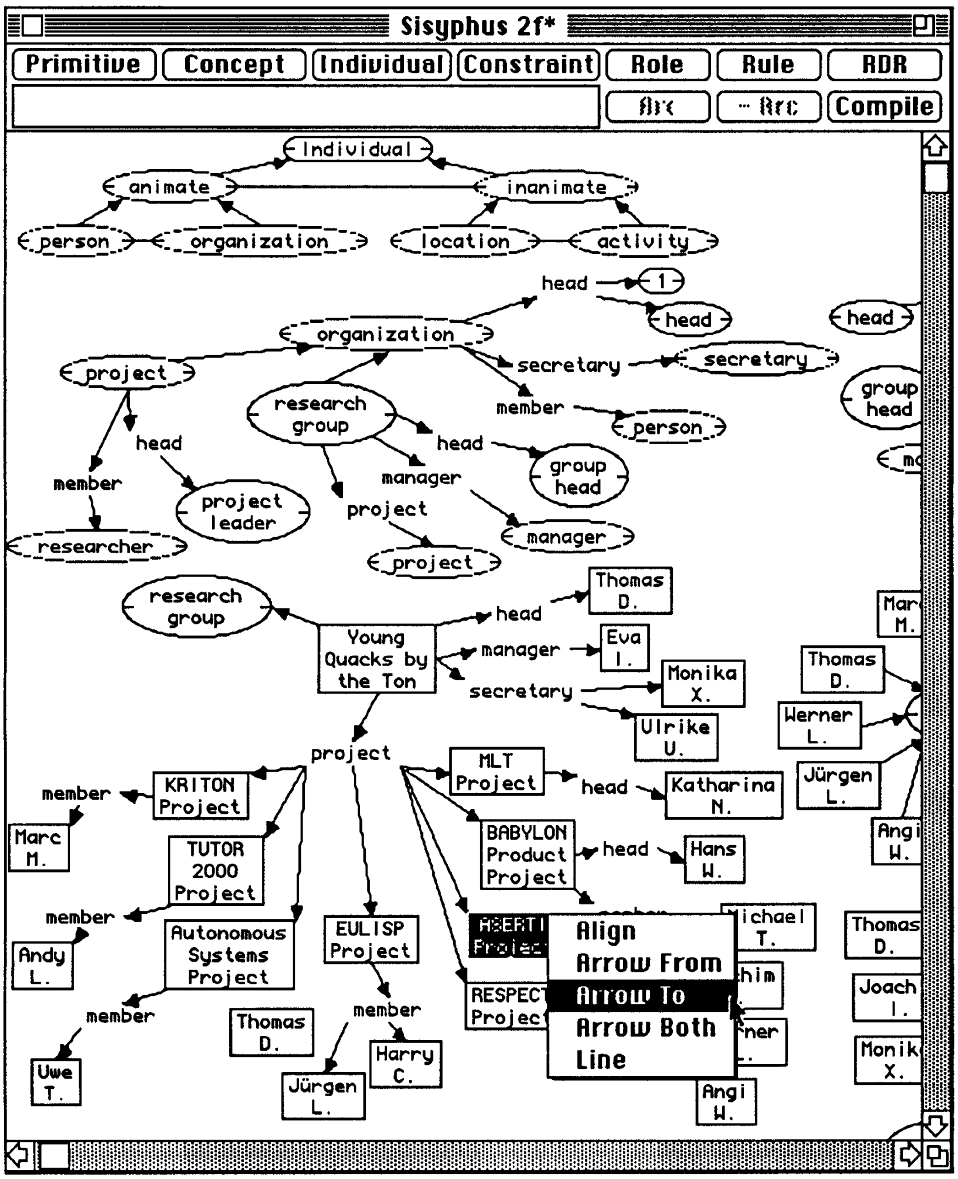

Figure 37 Room allocation task solution in the visual language

At the top, Figure 37 shows the top level conceptual structures of an organizational domain, and at the bottom, the assertion of facts about a particular organization. Human-computer interaction in the editor is modeled on Apple's MacDraw with additional features appropriate to the language such as arcs remaining attached to nodes when they are dragged. A popup menu as shown at the bottom of Figure 37 allows connecting lines to be entered easily. The syntax of possible node interconnections and constraint expressions is enforced—it is not possible to enter a graph that is syntactically incorrect. Cut-and-paste of graphs and subgraphs is supported, and popup menus allow nodes to be connected with the minimum of effort. Updates are efficient and graphs with over a thousand nodes can be manipulated interactively. Scroll, zoom and fit-to-size facilities allow large data structures to be navigated easily. However, partitioning data structures over several screens is encouraged and has proved practical in managing large knowledge structures.

The grapher interface to the knowledge representation server allows the knowledge structures to be used deductively to solve problems and give advice. Other programs such as HyperCard can also access the server and provide additional functionality such as customizable end-user interfaces. Repertory grid data and induced rules, elicited and analyzed through the KSS0-style modules, may be exported to the grapher for visual analysis and editing. Thus KSSn is a step towards a new family of tools that instantiate more aspects of personal construct psychology than those based on repertory grids alone.

15 INTEGRATION WITH RELATED SYSTEMS

The development of Canard as an extension to AQUINAS is an indication of the possibilities of using personal construct psychology-based knowledge acquisition tools as embedded components in larger systems. A particularly attractive combination is to integrate hypermedia tools for informal knowledge acquisition with repertory grid knowledge acquisition tools and an expert system shell. For example, KSS0 has been extended support the informal representations of knowledge that are prior to those within the tool, such as text, pictures, diagrams, semi-structured interviews, protocols, and so on. This has been done by providing an interapplication protocol allowing KSS0 to interact with Apple's HyperCard to provide the appearance of a seamless single application to users. Each element and construct has a card associated with it on which can appear a detailed description, diagrams, or whatever other form of annotation the expert wants to include. KSS0-specific functionality in HyperCard is supported by scripts that allow conceptual structures on the KSS0 side to be linked to informal sources and annotation on the HyperCard side. The same inter-application protocol has also been used to provide run-time integration with the knowledge-based system shells to which KSS0 exports such as NEXPERT (Gaines, Rappaport & Shaw, 1989) and BABYLON (Gaines & Linster, 1990).

Figure 38 shows the distributed knowledge base and inter-application protocols linking the hypermedia, knowledge acquisition and knowledge-based system shell, BABYLON, in such an integrated system. Also shown are the types of interaction which are supported with experts, clients and knowledge engineers. It is important to note that all three types of user see a single, uniform interface, so it is easy for people to change roles. The "expert" can become a "client" for testing, or a "knowledge engineer" for deeper technical development.

The operation of each component of this system is similar to its stand alone use, but the inter-application protocol provides a new level of functionality. For example in the KSS0 analysis and elicitation screens already shown, popup menus become available as one mouses over element and construct pole names. These give access to the HyperCard cards that can be used to annotate these elements and constructs. These same cards may also be used as a decision-support interface to interrogate the shell, and as annotation accessible from the shell.

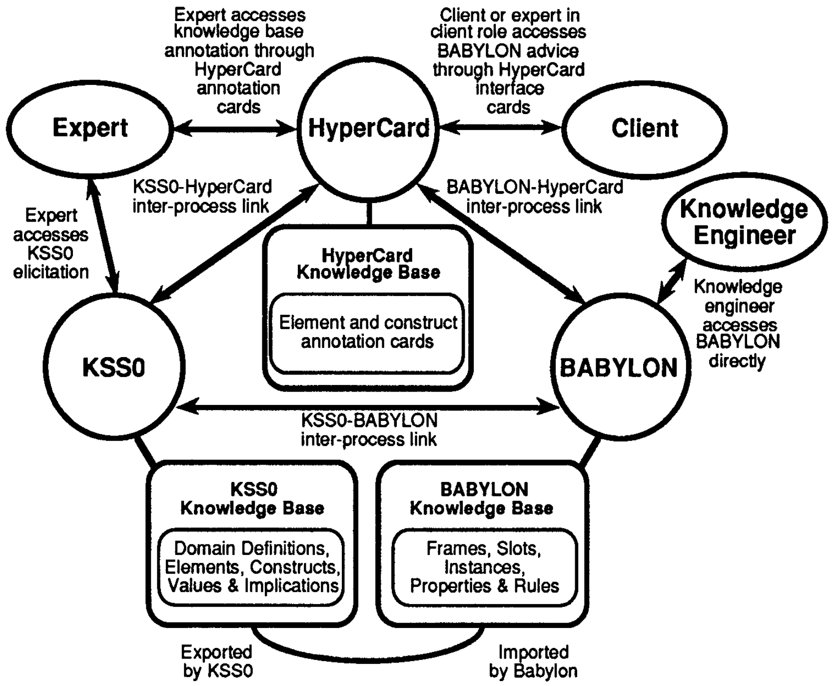

Figure 38 Integration of hypermedia, knowledge acquisition and expert system shell

One important result of on-line integration between the knowledge acquisition and performance tools is that new modes of knowledge acquisition become possible. Figure 39 shows a typical development cycle with the integrated system. The most interesting new mode is that when the knowledge base exported from KSS0 is run in BABYLON it can be tested on new cases and, if these lead to erroneous decisions, the cases may be corrected and posted to KSS0 to extend the grid and hence affect the rule induction and knowledge base generated. This allows knowledge acquisition to be integrated with the validation of the knowledge base in the applications environment.

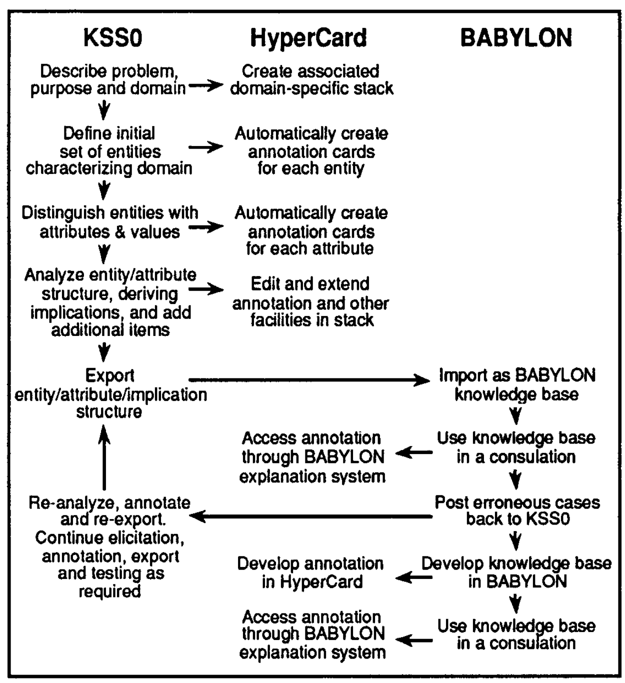

Figure 39 Sequence of activities in using integrated system for knowledge base development

Ideally, the loop between BABYLON, KSS0 and HyperCard could be left in place indefinitely for system upgrade and maintenance. However, since the knowledge acquisition tools do not yet support the full functionality of the knowledge base, particularly its capabilities for procedural attachment and linkage to data-processing subsystems, it is usual for the final system development to take place in BABYLON as shown at the lower right of Figure 39. Note that the links to the HyperCard annotation are retained in the final performance system.

The integration of knowledge acquisition tools based on personal construct psychology with other related tools such as hypermedia and performance systems offers many important possibilities for future research, development and application. Ford, Stahl, Adams-Webber, Novak and Jones (1990) have suggested integration with neural nets as a grid generating technique, and with conceptual maps as a conceptual structure representation. RepGrid-Net combines repertory grids and electronic mail to allow geographically dispersed groups to work together and exchange and mutually develop knowledge structures (Shaw & Gaines, 1991a,b). AQUINAS incorporates its own performance tool and has been used as part of other systems such as Canard through heterogeneous integration. KSSn has an open architecture supporting various forms of integration at different levels, through the C++ class library, through direct calls to the server from associated modules, and through indirect calls, possibly across a network, from heterogeneously integrated programs.

The following Section outlines the types of knowledge acquisition methodologies appropriate to such integrated systems.

16 INTEGRATION OF KNOWLEDGE ACQUISITION METHODOLOGIES

The foundations for personal construct psychology and knowledge representation developed in this paper also provide a framework for the analysis of knowledge acquisition techniques and the design of integrated tools. To use these tools effectively requires the development of knowledge acquisition methodologies that themselves integrate a variety of approaches. Figure 40 illustrates the way in which the techniques described in this paper may be seen as supporting an overall development methodology:

Stage ⓪ consists of the acquisition of informal knowledge from interviews, protocols and media.

Stage ① consists of using the informal knowledge to elicit the major coherent sub-domains that together encompass the significant phenomena in the overall domain.

Stage ② consists of using the repertory grid methodology in each sub-domain to elicit relevant attributes and critical cases.

Stage ③ consists of using the conceptual induction methodology to derive concepts and rules from the grids.

Stage ④ consists of linking the sub-domains together, generally by specifying as a constraint in one domain that some role in that domain has as value an individual in another.

Stage ⑤ consists of testing the overall knowledge base and iterating back through any of the earlier stages in order to develop and refine it further.

The architecture of Figure 40 is not intended to be a rigid framework for integrated tools, but rather to illustrate ways in which the various knowledge acquisition techniques already described may be naturally combined. For example, some sub-domain structures may be developed by direct editing, others by induction from databases, others by text analysis, and others by tools not yet defined or developed. The techniques and tools we have described come together naturally in this framework, and it also provides an open architecture for incorporating further techniques and tools. This paper gives strong theoretical foundations for what is shown. In the longer term, the architecture shown may need major extension, but currently it seems to encompass what is available to us in knowledge acquisition.

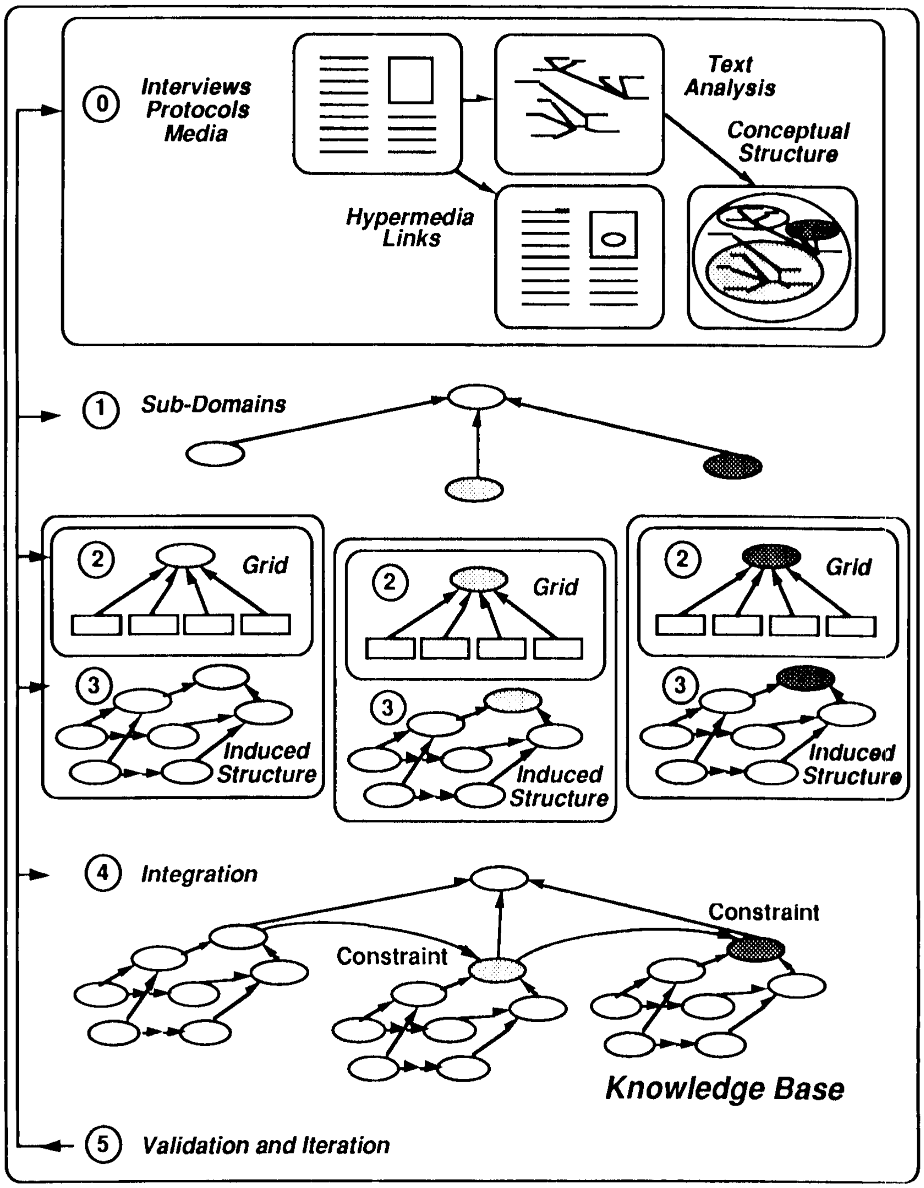

Figure 40 Integration of knowledge acquisition techniques

17 CONCLUSIONS

Personal construct psychology is a theory of individual and group psychological and social processes that has been used extensively in knowledge acquisition research to model the cognitive processes of human experts. The psychology has the advantage of taking a constructivist position appropriate to the modeling of specialist human knowledge but basing this on a positivist scientific position that characterizes human conceptual structures in axiomatic terms that translate directly to computational form.

The repertory grid knowledge elicitation methodology is directly derived from personal construct psychology. In its original form, this methodology was based primarily the notion of dichotomous constructs and did not encompass the ordinal relations between them captured in semantic net elicitation. However, it has been extended in successive tools developed for applied knowledge acquisition and tested in a wide variety of applications.

This paper has given an overview of personal construct psychology and its expression as an intensional logic describing the cognitive processes of anticipatory agents. A theoretical framework has been developed and shown to provide logical foundations for personal construct psychology and computational knowledge representation schema. The framework is generated from the single primitive of "making a distinction." It has been used to provide cognitive and logical foundations for existing knowledge acquisition tools and techniques, and for the design of integrated knowledge acquisition systems.

In conclusion, we suggest that personal construct psychology provides a very attractive foundation for knowledge acquisition methodologies and tools that have to bridge between human cognitive processes and computational knowledge representation. The many tools so far developed based on personal construct psychology encourage this conclusion. However, what has so far been developed taps only a small part of the potential and we may expect to see major new developments in the future. In particular, personal construct psychology offers the opportunity to integrate many different knowledge acquisition and knowledge representation approaches within a single principled framework.

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