Shaw, M. L. G. and Gaines, B. R. (1993). Personal construct psychology foundations for knowledge acquisition and representation. In Proceedings of EKAW-93: Seventh European Workshop on Knowledge Acquisition for Knowledge-Based Systems Aussenac, N., Boy, G., Gaines, B., Linster, M., Ganascia, J. G. and Kodratoff, Y., eds., pp. 256-276.

Personal Construct Psychology Foundations for Knowledge Acquisition and Representation

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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 as a basis for a comprehensive theory of knowledge acquisition and representation.

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 [38] 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 with applications mainly in educational, clinical and management studies [59]. Gaines and Shaw suggested that repertory grids would provide a useful development technique for expert systems [23], and later published a validation study of the elicitation of the BIAIT methodology from accountants and accounting students using computer-based repertory grid elicitation [62]. Boose in an independent parallel study reported success in a wide range of industrial expert system developments using computer elicitation of repertory grids [4], and since then many knowledge acquisition systems have incorporated repertory grids as a major elicitation technique [6, 13, 17, 30, 63].

The 'repertory grid' methodology has evolved in the light of application experience and now has major differences from that described by Kelly. Shaw 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 [60]. 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 introduced new forms of analysis of the repertory grid based on fuzzy sets theory [59] which became the basis of rule extraction [26]. Boose and Bradshaw made changes to the grid structure introducing hierarchical data structures to cope with more complex domains [6]. Bradshaw, Boose, Covington and Russo showed how many problems that did not seem appropriate to repertory grids could be formulated in terms of them [11].

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 [20], 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 developed a technique of *laddering*, based on "why" and "how" questions, for investigating ordinal relations between constructs [34], and Boose incorporated a laddering tool in ETS [5]. 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 [6], 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 [28]. Recently, the intensional logic underlying the psychological primitives of personal construct psychology has been developed in detail [27], and this has been used to develop knowledge acquisition tools based on a visual language that corresponds to a formal semantics for semantic nets [22].

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 [15], KNACK [42], SALT [51], Cognosys [68], KEATS [55], and CAMEO [37]. 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 [24, 25] 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.

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 [18] and related tools [49] and another major literature on personal construct psychology [48], 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 [47].

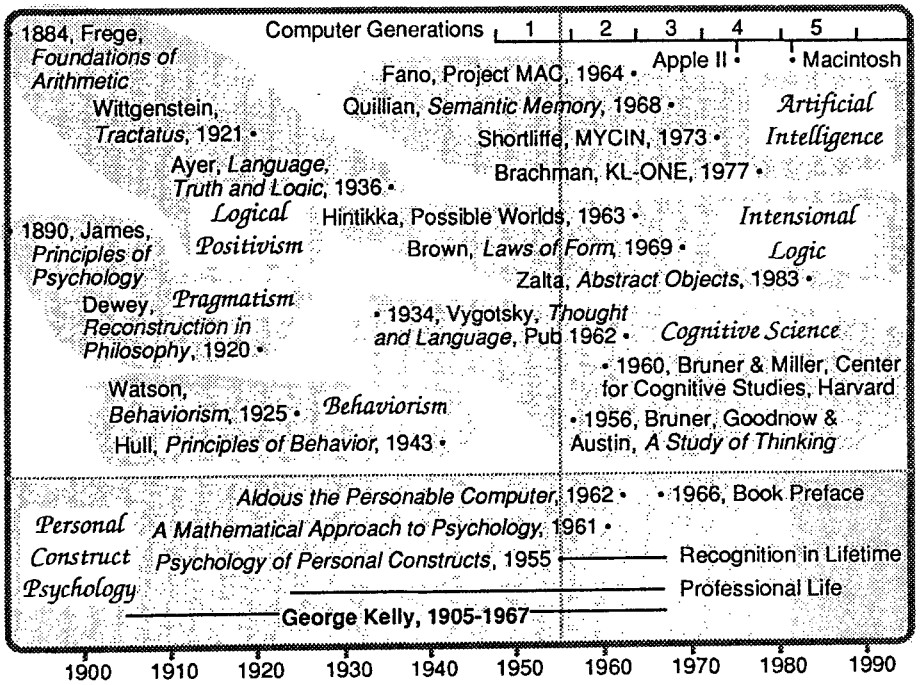

Figure 1 The intellectual setting of personal construct psychology

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 [64, 65]. 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 [40]. Kelly was working on a second book when he died of which, unfortunately, only the preface has been published [41], and he also began to become involved with the computer simulation of personality [39]. 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 [61].

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 [57]. 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* [43].

The standard translation of the *Elements* used for geometry classes in schools contains a deep philosophical discussion of the nature of Euclid's reasoning [16]. 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* [40], 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 [46]. 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 published the model sets formulation that gave intensional logic its *possible worlds* formal foundations [36]. Logics of knowledge and belief are essentially intensional [35] 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 [8, 58, 67], and their philosophical and logical structure as cognitive models has been detailed by Zalta [71].

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 [38] was that:

> "A person's processes are psychologically channelized by the way in which he anticipates events." (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." [40]

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" [41]

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:

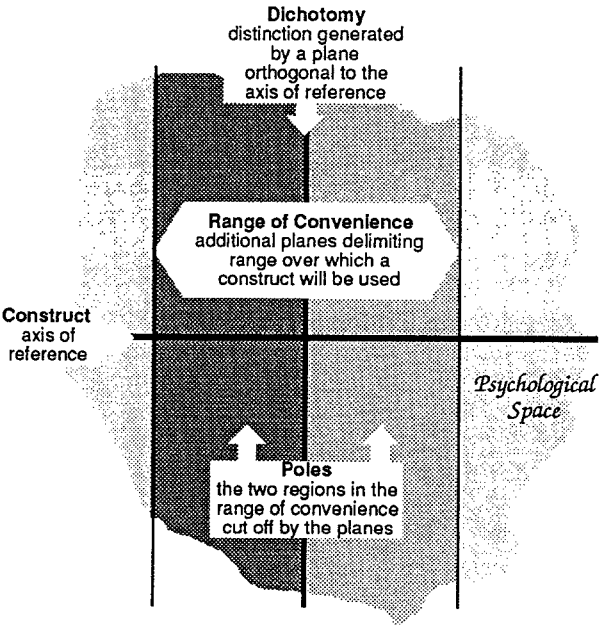

Figure 2 The geometry of psychological space

"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" [41]

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." [41]

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" [38]

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:

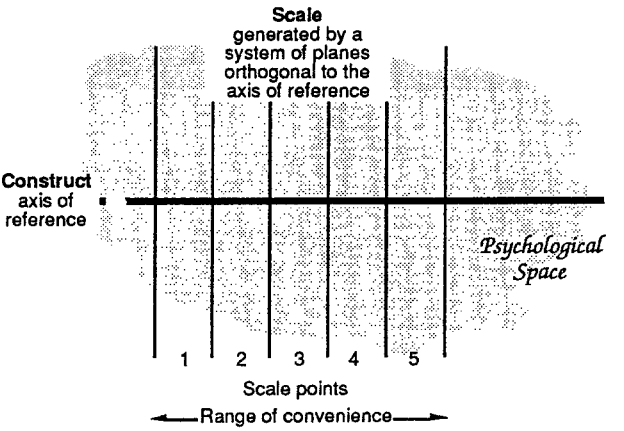

Figure 3 Scales in psychological space

"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" [41]

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" [38]

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" [38]

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." [40]

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" [38]

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." [38]

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 [38]:

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

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 [45] and common across many cultures [52]. 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 [32].

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 introduction of the notion of the *state* of a system as an imputed parametrization

accounting for a system's behavior [69]. 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." [3]

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 [54]: 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 distinction in his intensional logic of abstract objects that "abstract objects *encode* properties whereas existent objects cannot encode properties but do *exhibit* them" [70]. 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 $\forall \mathbf{x}$ 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 $\forall \mathbf{x}$. Marcus' non-standard, *substitutional* reading of the universal quantifier [50]

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**" $\quad \mathbf{a}\text{—}\mathbf{b} \Leftrightarrow \vdash \mathbf{xa} \Rightarrow \neg \vdash \mathbf{xb}$ (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 as 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 $\neg \vdash \mathbf{xb}$. 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 has observed in the use of the, apparently symmetric, poles of a construct [2].

The $\rightarrow$ and — relations are complementary in establishing four possible binary relations between distinctions, that $\mathbf{a}\rightarrow\mathbf{b}$, $\mathbf{b}\rightarrow\mathbf{a}$, **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:

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

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 [44]. 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 [22] 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 [10] or KRS [21], but it has well-defined logical semantics as defined above, and also strong psychological foundations in personal construct psychology.

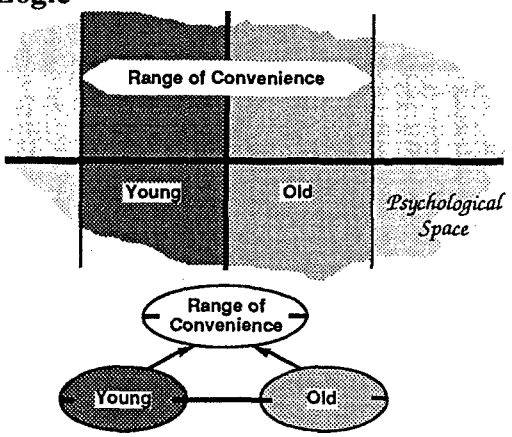

Figure 4 A visual language for the logic

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" [38]

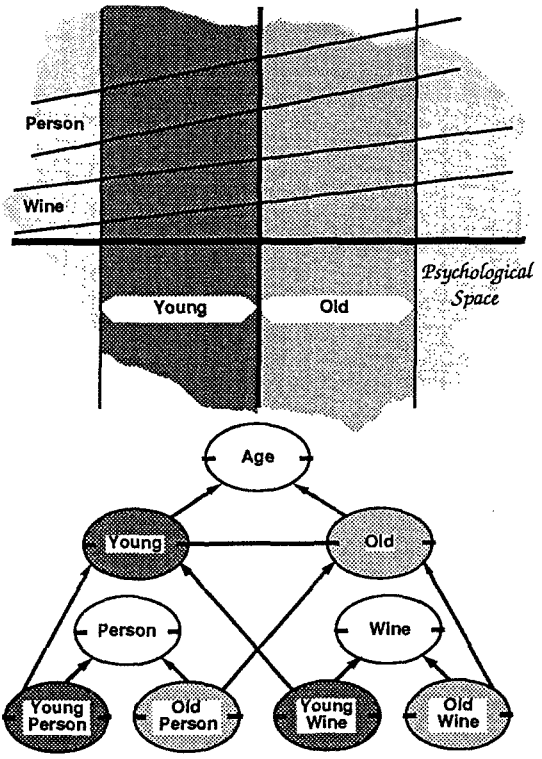

Figure 5 Logic of subsumed foci of convenience

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.

Multiple constructs in psychological space correspond to multiple axes of reference, and the planes 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.

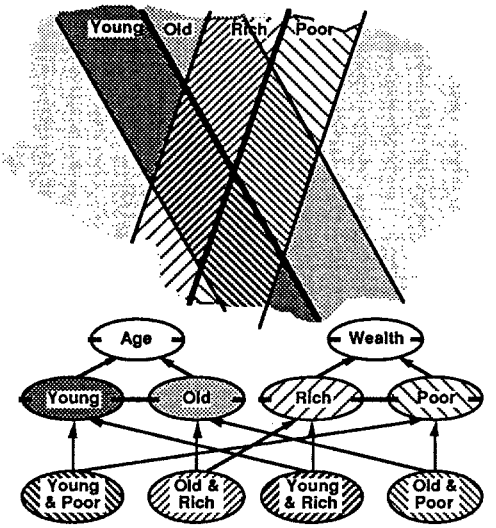

Figure 6 Logic of overlapping distinctions and their intersections

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* [7].

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 [9].

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" [38]

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.

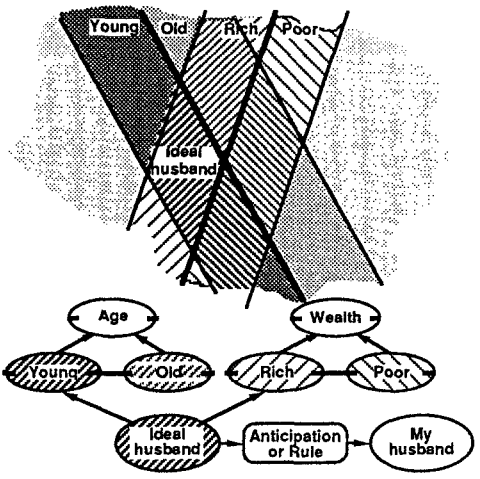

Figure 7 Logic of anticipation through rules

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 [1]. 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 [14].

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 [12]. 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.'

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 who notes that traditionally individuals are characterized by five properties; they are entities which [31]:

(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;

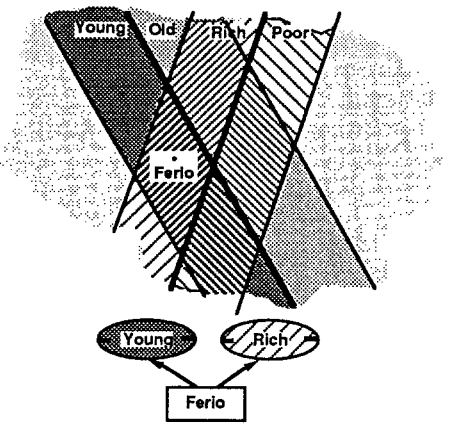

Figure 8 Representation of individuals

(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 [19], Meinong [53] and Russell [56], 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 [66] 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 [67].

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* [33], 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.'

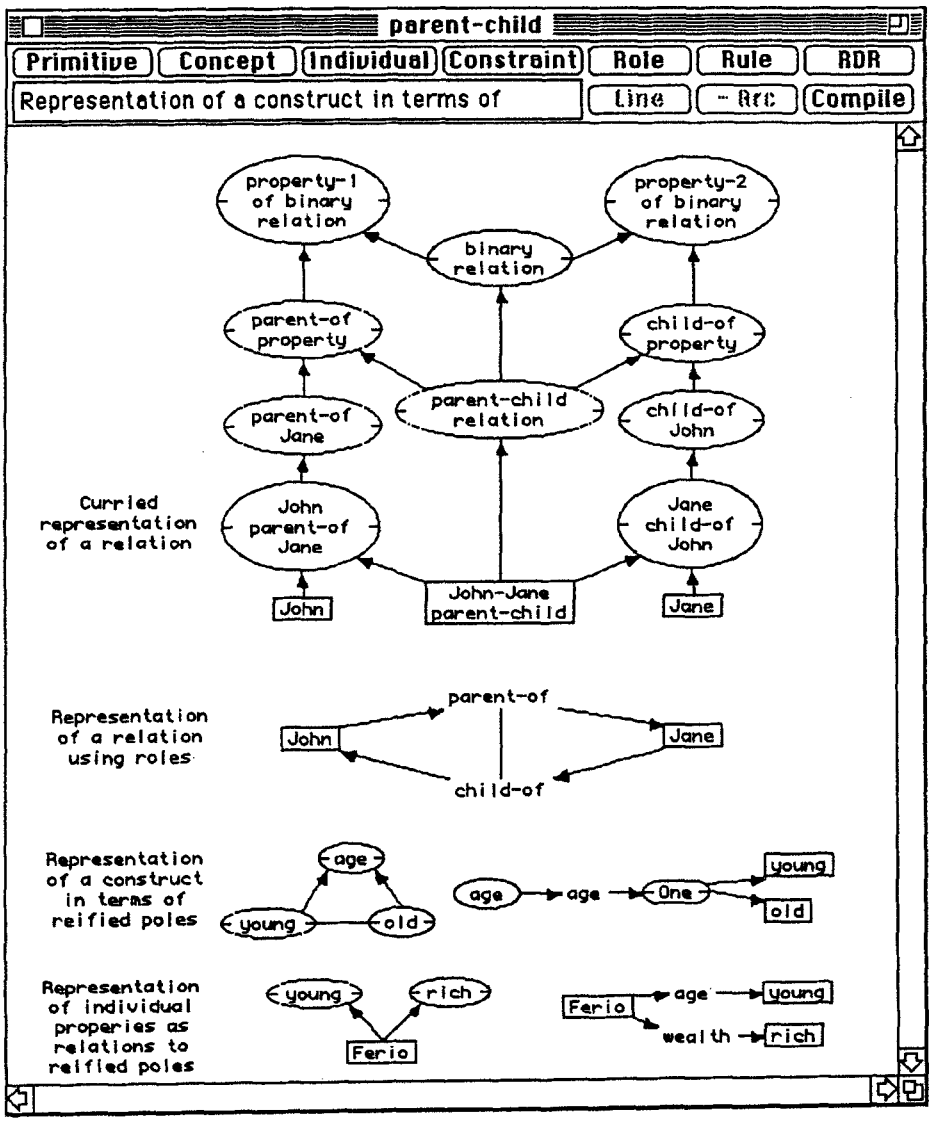

Figure 9 Representation of relations

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 they are inverse to one another.

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.

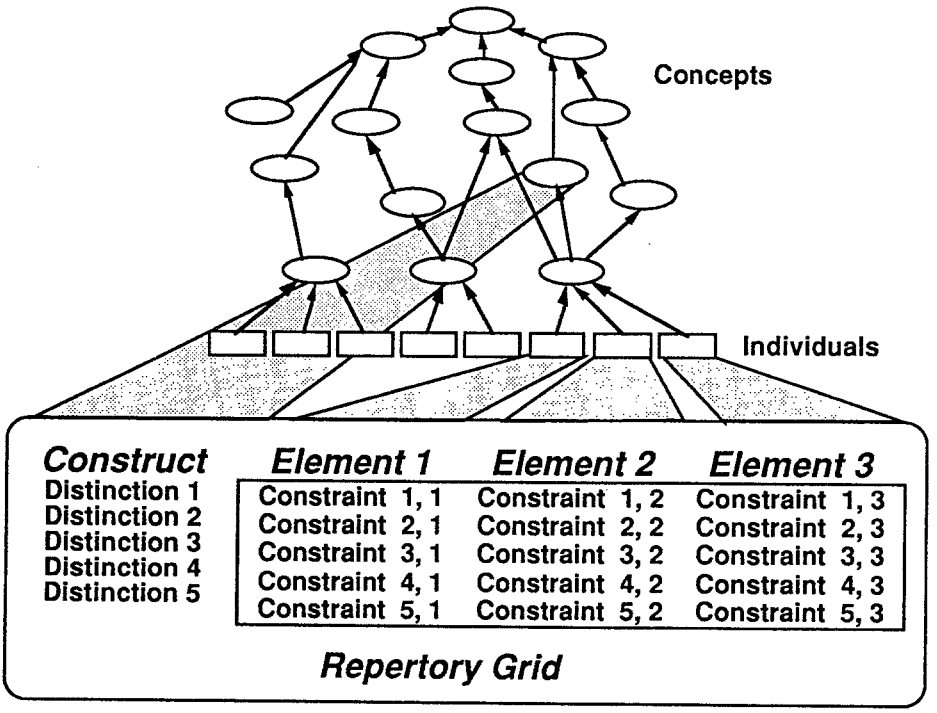

Figure 10 The repertory grid as a matrix of concepts, individuals and constraints

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.

This coordinate system is the basis of Kelly's [38] "repertory gird" representation of the properties of individuals which has been widely used in knowledge elicitation. 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 summary, 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 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 [29].

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.

Acknowledgements

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

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