Approximate Reasoning in Expert Systems
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SYSTEMIC FOUNDATIONS FOR REASONING IN EXPERT SYSTEMS

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The shift from information processing to knowledge processing in fifth generation computer systems will be a major trend during the next decade. However, the success of expert system developments should not blind us to the very weak foundations on which our current systems are based. We have no overall theory of the nature of knowledge, its representation, its elicitation from experts, its processing by computers and its application to problem solving. This paper proposes systemic principles for knowledge representation and reasoning in expert systems based on a calculus of distinctions that generates a variety of logical systems.

Key words: expert systems, logic, system theory, personal construct psychology, fuzzy reasoning.

INTRODUCTION: KNOWLEDGE AND PSYCHOLOGY AS FGCS TECHNOLOGIES

Fifth generation computer systems (FGCS) present new challenges that go beyond the realms of hardware and software to the processes of human reasoning and its underlying logical and philosophical foundations. The first four generations of computers were based on **information processors.** The transition between each generation has involved the introduction of new technologies (Gaines 1984a). The first generation (1948-55) used vacuum tubes and delay lines and this **hardware** became transistors and core stores in the second generation (1956-63). The transition to the third generation (1964-71) was dominated by the availability of **software,** operating systems and compilers. The transition to the fourth generation (1972-79) was one of **person-computer interaction** in which interactive usage and personal computing became common. The transition to the fifth generation (1980-87) is now seen to be one of **knowledge processing** with the development of expert systems (ES).

FGCS have two main distinctive features (Moto-oka 1982):

a) they will be based on **knowledge processing** rather than information processing;
b) they will offer natural **human-computer interfaces.**

These objectives have been accepted as realistic because of the successful development of **expert systems** (ES) (Reitman 1984) that encode human knowledge and cognitive skills for the computer and make them accessible to others. These objectives both imply that human reasoning is the focus of

both the design and application of FGCS. They have been peripheral considerations in the design of previous generations of computers, although their significance has grown (Gaines 1984b), but they play such a key role in FGCS that new questions of major importance arise:

i) do we have an adequate theory of knowledge on which to base knowledge processing systems?

ii) do we have an adequate theory of human psychology on which to base human-computer interface design?

We emphasize that these are not just questions of general relevance to the next generation of computer systems but that, if the objectives of the ICOT project are accepted (ICOT 1983), knowledge and psychology become key technologies on a par with VLSI and software engineering. Failure to provide adequate foundations and tools in these areas will imply failure of the main objective, although not necessarily failure to innovate and extend the state of the art.

This dependence has been recognized in the Japanese FGCS program and the question:

"Are you saying that the design of the fifth-generation may be modeled by learning more about the human thinking process?"

has been answered:

"Yes, we should have more research on human thinking processes, but we already have some basic structures. For more than 2000 years man has tried to find the basic operation of thinking and has established logic. The result is not necessarily sufficent; it's just the one that mankind found. At present we have only one solution - a system like predicate calculus. It is rather similar to the way man thinks. But we need more research. What, really, is going on in our brain? It's a rather difficult problem." (Fuchi, Sato & Miller 1984 pp.14-15)

This leads to a pragmatic approach to developing FGCS, basing them on the best available foundations for knowledge and psychology, even if these are inadequate. Technology is often in advance of science and the pressure to develop FGCS may be just what is needed to advance the sciences of knowledge and psychology. This approach leads to additional questions:

iii) how adequate is predicate calculus as a science of knowledge?

iv) how adequate is classical logic as a foundation for psychology?

This paper addresses these questions at a constructive, operational level: what do we know about knowledge and psychology that might be relevant to FGCS; where might we expect problems in basing FGCS on standard predicate calculus; what theories currently exist that might be used as a basis for FGCS knowledge and psychology technologies? In the "Conceptual Diagram" of FGCS (Moto-oka 1982 p.8) there are three rings for the hardware, the software and the human. The first two rings are full of detailed descriptions but the third ring is empty. This paper is concerned with filling that third ring.

THE DIVERGENCE OF PSYCHOLOGY AND LOGIC

A philosophical dictionary definition of "knowledge" is that it is "apprehended truth" and that "certain knowledge is more than opinion, less than truth" (Runes 1960 p.161). Knowledge stands between opinion which is in the domain of psychology (the study of mental phenomena) and truth which

is the domain of logic (the study of truth preserving inferences); the underlying discipline is epistemology (the study of truth ascription). It would be reasonable to suppose that psychology and logic would be closely related aspects of a science of knowledge. Until recent times this was so, but in the late nineteenth century psychology and logic diverged and an attempt was made to set up a system of logic that stood alone, independent of any processes of human reasoning. The divergence stemmed from attempts to establish formal foundations for mathematics, particularly those of Frege (1884) and Husserl (1891).

The stimulus for Frege's work was to re-establish irrevocably the position that mathematics was a priori (independent of experience) and analytic (based on inferences in which the conclusion is part of the premise), in contradiction to Mill's (1843) position that arithmetic is not **a priori** but empirical and induced from experience, and Kant's (1781) position that it is **a priori** but synthetic and made known through experience. Husserl's work shows the arguments most strongly because, in response to Frege's (1894) critical review of his 1891 book, he became concerned with the role of psychology in logic and formulated the basis of pure logic clearly demarcated from processes of the mind (Husserl 1900). In his discussion and the distinctions he makes Husserl generates a model of relationships between logic, psychology and knowledge which underlies the development of modern epistemology (Mohanty 1982). Similarly, Frege generated a notion of pure logical inference that underlies the development of modern formal logic (Kneale and Kneale 1962).

These classical discussions may appear remote from modern computing and artificial intelligence (AI). However, a recent paper by Lenat and Brown (1983) on **Why AM and Eurisko appear to work** puts forward the Kantian argument exactly. The problem is why AM succeeded in the first place and why it is so difficult to use the same paradigm to discover new heuristics. Their conclusion is that AM's success in making conjectures in basic mathematics was because set- and number-theoretic results are simply coded in LISP. The conjectures were to a large extent available **a priori** but were **synthetic** because AM needed its empirical investigations to trigger off their discovery. However, while the metarules of logic and arithmetic are embedded in LISP, those about discovery heuristics are not and could not be thus triggered. This not only demonstrates the Kantian argument but also suggests a line of attack that investigates the discovery heuristics as primitives in some operational calculus -- a formal epistemology.

THE CONSEQUENCES OF ANTI-PSYCHOLOGISM IN LOGIC

The anti-psychologistic basis of modern logic is natural in the light of the objective of formalizing arithmetic as a demonstration that it is **a priori** and synthetic. It rejects as irrelevant the questions:

1) How do we come to know arithmetic?
2) Why is arithmetic instantiated in real-world phenomena?

although a variety of answers are part of Frege's and Husserl's discussions. It also does not take into account the distinction between what is known and what might be inferred from this; Wittgenstein notes:

> "If I know an object I also know all its possible occurences in states of affairs." (Wittgenstein 1921, 2.0123)

drawing attention to the gap between formal logic, where all consequences are "known", and human reasoning where they are not. It raises the questions:

3) What is the significance of not knowing all the logical consequences of a state of affairs?
4) How do we come to know particular consequences?

All of these questions are highly significant for knowledge-based systems yet outside the framework of standard formal logic. Questions 1 and 4 may be regarded as primarily within the domain of psychology and question 2 within the domain of philosophy. The significance of question 3 was not realized until the notion of **computational complexity** was developed and formalized. The super-exponential combinatorial explosion of any consequence derivation system creates a boundary that is real and extremely "hard"; the notion of a hard proof is not just psychological, a result of human frailty, but is systemic, a property of the problem for any derivation system.

The boundary created by computational complexity means that existence proofs relating to inference mean little in practical terms. It is not sufficient to know that solutions are eventually accessible; we need to know they can be reached using reasonable resources. The knowledge representation and inference schema used must make the types of inference required easy. This is an extra-logical requirement but a critical one in practice. Hardware parallelism and speed increases cannot be used to overcome the problem because super-exponential growth overwhelms even large multiplicative factors. A danger in developing FGCS is that any logic we build into the hardware may prove inappropriate to emulate human inference.

These considerations suggest that we should regard with some suspicion formal logics developed as foundations for mathematics and deliberately disregarding psychological considerations. It could be that mathematics epitomizes human intellectual achievement and standard predicate calculus (SPC) captures all that is significant. Even this is suspect since we know of many problems with SPC: in the foundations of set theory (Martin 1970); relevance of implication (Anderson & Belnap 1970), ontology of existence (Schock 1968); and extension beyond first order (Kneale & Kneale 1962).

However, while one may criticize SPC for its known faults, it is not easy to suggest an alternative system for knowledge representation and inference. There are many studies of human reasoning and alternative logics but there has not been the intensive study of a coherent system for knowledge in general as there has been for that sub-set which is mathematics. Such a study has its place in the development of FGCS, and in the remainder of this paper we survey some possible bases for such a system with strong logical and psychological foundations.

PSYCHOLOGICAL AND SYSTEMIC FOUNDATIONS

Kelly's **Personal Construct Psychology** (PCP) develops a complete theory of the normal and abnormal, which has strong systemic foundations (Gaines & Shaw 1981a, 1984) and has been operationalized through computer programs (Shaw 1980). PCP models a person as using **personal constructs** as

distinctions made about experience:

> "transparent templets which he creates and then attempts to fit over the realities of which the world is composed"

and emphasizes the use of constructs for knowledge acquisition:

> "Constructs are used for predictions of things to come, and the world keeps rolling on and revealing these predictions to be either correct or misleading. This fact provides a basis for the revision of constructs and, eventually, of whole construct systems." (Kelly 1955)

When Kelly developed his theory there was neither the mathematics to formalize it nor the computer technology to operationalize it. Despite this, PCP has developed to become a major psychological theory and to provide a variety of techniques used in clinical, educational and managerial psychology (Shaw 1981, Mancuso & Adams-Webber 1982). PCP has strong links with Brown's logical system in **Laws of Form** based on the notion underlying personal constructs of **making a distinction:**

> "The theme of this book is that a universe comes into being when a space is severed or taken apart...By tracing the way we represent such a severance, we can begin to reconstruct, with an accuracy and coverage that appear almost uncanny, the basic forms underlying linguistic, mathematical, physical and biological science, and can begin to see how the familiar laws of our own experience follow inexorably from the original act of severance." (Brown 1969)

Kelly's psychology and Brown's logic both take as primitive an axiom of unrestricted predication. In set-theoretic terms they take **comprehension** (Fraenkel, Bar-Hillel & Levy 1973) as **a priori** and derive all other concepts from this. This is not the standard and familiar approach, although logicians such as Fitch (1952) have argued for it, and this makes it misleading to translate the Kelly/Brown discussions into logic and set theory; they are defining a basis of knowledge which is prior to both and from which logic and set theory must be derived. The key questions are: to what does a construct apply; what is it that is distinguished? We fall into a trap if we have any answer based on prior knowledge. The proper answer is that what is distinguished is defined only by being distinguished; it requires an auxiliary ontological postulate to reify this by assuming some entity is thus defined.

We have suggested (Gaines 1980) that what is distinguished is a **system** and that this notion defines a system. To distinguish some entity as being a system is a necessary and sufficient criterion for its being a system and this is uniquely true for systems. This definition may appear too weak in that it does not involve the expected properties of a system. The Oxford English Dictionary notes that a system is "a group, set or aggregate of things, natural or artificial, forming a connected or complex whole." However, these are properties that derive from our definition: a set of things is treated as distinct from another and it is this which gives it coherence; it is also this which increases its complexity by giving it one more characteristic than it had before, that it has now been distinguished.

A LOGIC OF KNOWLEDGE SYSTEMS

Kelly's personal construct psychology and Brown's calculus of distinctions

both point to a knowledge representation system based on unrestricted predication as a primitive. The significance of such an axiom is that it forces us to develop system theories that do not run into the problems of this axiom in conventional mathematics. In set theory such predication leads to the inconsistency that Russell discovered in Frege's (1884) **Foundations of Arithmetic**, and requires the axiom of comprehension to be severely restricted by a complex set of rules. However, it has long been speculated that the inconsistency may be better ascribed to the law of contradiction in standard logic: that the same predicate cannot be both true and false about the same proposition. Maydole (1975) proved that most contenders for an alternative logic led to inconsistencies in set theory, and White (1979) showed that Lukasiewicz infinitely valued logic gives a consistent set theory.

This was a particularly important result in bringing theory and practice together because it was just this logic that Zadeh (1965) takes as a basis for fuzzy sets theory, Mamdani and Assilian (1981) used in their expert system for linguistic control and Shortliffe (1975) discusses as a formal basis for MYCIN. The links from Brown's calculus of distinctions to Lukasiewicz logic have been established: Varela (1975) used the calculus to analyse self-referential systems using a construction based on Russell's paradox which gave a 3-valued logic; Gaines (1976) used a recursive form of this construction to generate the infinite valued Lukasiewicz logic; and Gaines (1983) shows that the Lukasiewicz axioms encompass modal, probability and fuzzy logics. The significance of this construction is that the axioms are taken first as defining a non-truth-functional **standard uncertainty logic**, fuzzy logic is then derived by adding the constraint that the logic be truth functional, and probability logic is derived by the alternative constraint that the law of contradiction apply. Figure 1 shows the relationships between the various logics of uncertainty that may be derived from the Lukasiewicz axioms for a system of distinctions underlying the constructs representing a person's knowledge.

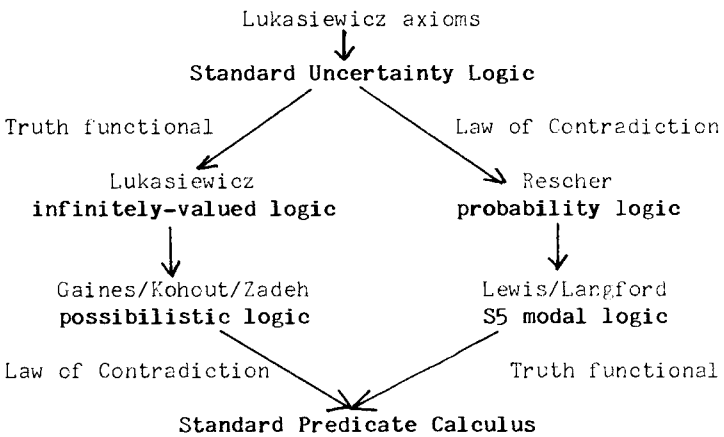

Fig. 1 Logics of uncertainty generated from calculus of distinctions

The need for a system adequate to represent knowledge to encompass both imprecision and non-truth-functionality is obvious in retrospect. Most of the distinctions we make in everyday life do not have hard boundaries. The notion of a red rose is totally unambiguous and acceptable in human communication and reasoning. However, the set of red roses is not a standard set. It has boundary cases which are neither precisely red nor not-red. Yet we can not exclude these borderline cases from being considered as red roses. The laws of contradiction and the excluded middle do not apply.

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

AN EPISTEMOLOGICAL HIERARCHY

Distinctions are not just static partitions of experience. They may be operations: actions in psychological terms; processes in computational terms. This shows in Goguen's (1974) category-theoretic formulation of fuzzy sets, Ralescu's (1979) application of these to a general theory of modeling, and Goguen and Meseguer's (1983) development of **OBJ**, a category-theoretic programming language. The role of distinctions at the base level of all models is evident in Klir's (1976) hierarchy of modeling shown in Fig. 2. The loop from events through distinctions up through the modeling hierarchy and then down again to predictions and actions characterizes what Shaw (1980) has termed the **personal scientist.** Note that the upper levels of modeling are totally dependent on the system of distinctions, or personal constructs, used to express experience through the source system. Klir developed this hierarchy for work on symbolic modeling systems and Gaines (1977) has shown that it leads to general knowledge acquisition algorithms.

This hierarchy does not introduce any additional primitives beyond that of making a distinction. The levels of the hierarchy are the results of distinctions that we make. Thus the source system is distinguished as those distinctions that the particular personal scientist makes; it is a distinction about distinctions defining the construct system of an individual. The data system is distinguished as those distinctions that have been made about a particular event; again a distinction about

distinctions defining an event. The generative system is distinguished as a set of distinctions that also defines an event; these are model-generated rather than event-generated. It is the match between the model-generated and event-generated distinctions that determines the degree of approximation of the model to the world; this is a distinction about distinctions among distinctions that defines goodness of fit.

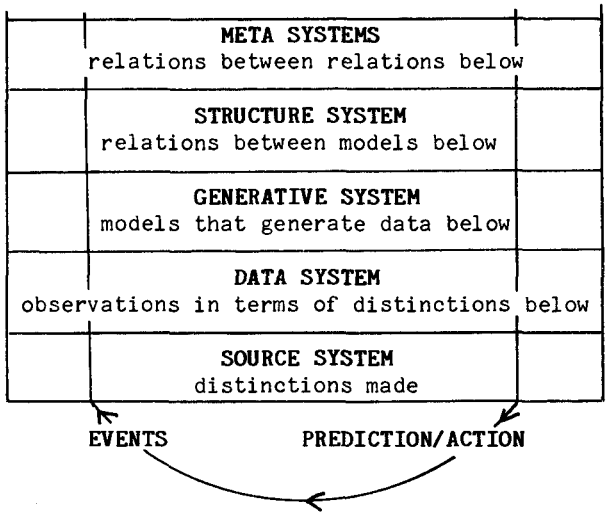

Fig. 2 Epistemological hierarchy of a personal scientist

A modeling schema results from distinctions about distinctions at each level in the hierarchy. In prediction the key distinction is whether a level accounts for the information flowing through it and we may term this distinction one of **surprise** (Gaines 1977). Surprise goes in opposition to the degree of membership of a predicted event to an actual event and the expected surprise is a form of entropy. Surprise at the lowest level of the hierarchy corresponds to distinctions being inadequate to capture events; surprise at the next level to inadequate variety to experience events; at the next to inadequate approximation to predict events; at the next to inadequate simplicity to explain events; and at the next to inadequate comprehensiveness to account for events. AM's "interest" (Davis & Lenat 1982) may be explicated as surprise generated when rules such as property inheritance are violated.

The hierarchy is strongly idiosynchratic and formalization does not imply uniformity. The construct system is subject to change according to feedback from failure to anticipate events. It is individualistic in the constructs used, in the vocabulary used to name the constructs, in the relations between constructs in the hierarchy, and in those constructs most likely to change when necessary. Knowledge engineering for expert systems may be seen as a process of making overt the construct system of the expert. Personal construct psychology provides the technical framework for this and its operationalization in computer programs using the mathematics of fuzzy reasoning provides practical tools for knowledge engineering (Gaines & Shaw 1981b, Shaw & Gaines 1984) which have been shown to be effective in applications (Shaw & Gaines 1983, Shaw 1984, Boose 1983).

SUMMARY AND CONCLUSIONS

The dependence of expert systems and fifth generation computing systems on knowledge processing and the human-computer interface, coupled with the assumption that logic programming will be a key technology, suggests that we should examine the rationale behind standard logic. Modern formal logic was developed as a foundation for arithmetic and psychological considerations were ruled out as irrelevant. Many aspects of the debate about this decision are relevant to developments in artificial intelligence.

Non-standard logics and models of human knowledge processing are recent developments that lack the extensive, coherent literature of standard logic. However, it is important to consider, particularly in hardware design, that there may be systems of logic more appropriate to knowledge processing. An inappropriate system will not just be slower but may run up against computational complexity barriers that make useful inference impossible.

Logical and psychological system theories based on an axiom of unrestricted predication are plausible and attractive alternatives to standard logic. In conclusion, it is suggested that the architecture of logical inference processors should take such systems into account, and that further investigation of the logical, psychological and systemic foundations of knowledge should be a major component of fifth generation computer system development.

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