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The fuzzy decade: a bibliography of fuzzy systems and closely related topics

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The main part of the paper consists of a bibliography of some 1150 items, each keyword-indexed with some 750 being classified as concerned with fuzzy system theory and its applications. The remaining items are concerned with closely related topics in many-valued logic, linguistics, the philosophy of vagueness, etc. These background references are annotated in an initial section that outlines the relationship of fuzzy system theory to other developments and provides pointers to various possible fruitful interrelationships. Topics covered include: the philosophy and logic of imprecision and vagueness; other non-standard logics; foundations of set theory; probability theory; fuzzification of mathematical systems; linguistics and psychology; and applications.

1. Introduction

This bibliography originated from personal attempts to come to grips with the literature explosion on fuzzy systems. It rapidly became apparent that: (a) there was much more work in progress than any individual involved in the area realized; (b) there was a substantial duplication of effort in some areas and neglect of others; (c) that the rate of growth of the literature was being sustained at a very high level (now known to be 40% a year). Thus, apart from the intellectual challenge, it seemed particularly worthwhile to attempt to publish a complete and comprehensive bibliography with the objective of consolidating a massive new area of study and increasing the awareness of those working in the area of its ramifications and extent.

This paper is the first formal publication of the bibliography. An earlier draft was distributed worldwide to over 200 research workers in some 20 countries, and many corrections and additions have been received. Undoubtedly there are more to be made—we have aimed in the "fuzzy" references for completeness before all else and have included working papers whose date may be dubious and references in which details of publication are unknown—in some cases our classification may be incorrect. Additional items, updates and corrections are still coming in and we welcome them. The bibliography is maintained, analysed and formatted on a computer, and updates, tabulations and printouts are swift and simple. We shall probably be forced to stop maintaining it at some time if the current growth rate of publications is maintained, but there will be at least one further publication of updates and analyses.

The papers are listed in alphabetical sequence of authors' names. We know that some users will prefer alternative arrangements, e.g. chronological order or sub-division by classification, but the name order seemed generally most useful. The year of publication follows the name and classificatory keywords are in bold face at the end of each reference so that it is relatively easy to scan the bibliography on other bases. We found it very difficult to decide whether or not to split the bibliography into classified sections—some 1100 references in a single sequence is not readily searched or assimilated. However, we finally left it as a single list because we felt that classification, even if completely accurate, would make it too easy to skip whole sections—in particular the non-**FUZ** references are a selection intended to link fuzzy system theory to the main body of mathematics, philosophy and system science—they are relevant to the future development of fuzzy system theory, not only building in its own right, but also contributing to parallel developments in other fields.

The organisation of this preamble is aimed primarily at helping those with particular interests to find their way around the bibliography. It notes some of the key references in the main areas of development of fuzzy system theory. However, it is assumed that the majority of papers classified as **FUZ** will indicate through their title and associated keywords their place in the literature—we have not attempted an exhaustive annotation of these. On the other hand, whereas the "fuzzy" part of the bibliography aims at completeness, the "related topics" are very much a personal selection, references that we have found useful in coming to understand the role of fuzzy systems theory and its relationships to other fields of study. To be generally useful, this part of the bibliography needs more annotation than the "fuzzy" part, and we have indicated for each non-**FUZ** paper the reason for its inclusion.

This paper is, and is intended to be, a tribute to one man, Lotfi Zadeh, who initiated the area of study and has been a consistent driving force behind its further development and application. Many of us who saw his original papers in 1965 did not realize their significance until many years later. We were even somewhat disappointed in the change of direction that they represented, from hard system science (in which Zadeh had been a major pioneer) to a deliberate acceptance of imprecision in any real system applications. What was not clear at that time is that an ontology that denies the existence of this imprecision itself introduces such major artefacts that it is not just unreal but definitely false and positively misleading. Zadeh saw this as a fatal flaw in classical system science at the same time as the majority of us were looking for new peaks to conquer with the tools that had been so successful in the past. In retrospect one can see that, in many cases, it was the tools that were building the peaks, not conquering them!

2. Survey of literature

We will first give a brief overview of fuzzy system theory and the related topics, and then cover each of them in a separate section. The compartments are not generally self-contained and there is considerable overlap between them.

In his earliest papers Zadeh (1965*a*) makes clear his *semantic* interest in fuzzy set theory. It is a tool for reasoning with the *inherently imprecise concepts* of systems engineering, and the tool is based upon, and expected to model, *human linguistic reasoning* with such concepts. Thus the attempts by philosophers, logicians and scientists, to come to terms with, and represent, *vagueness*, *imprecision*, and so on, are clearly relevant. So are the more recent attempts by linguists to comprehend actual usage of terms representing, and modifying, *vague concepts*. Human linguistic reasoning seems to make less of a distinction between inductive and deductive reasoning than do logicians, and *inductive generalization* in vague reasoning leads naturally to some contact with studies of *automated induction*. This in its turn is closely related to what may be seen as the classical tool for studying systems about which our knowledge is imprecise, namely *probability theory*. In particular, *logical studies of probability* appear to have strong links with the mathematical foundations of fuzzy logic, and *subjective studies of probability* are relevant to the problems of human decision-making and the source of the numerical values in fuzzy reasoning.

Fuzzy set theory may be regarded either as a foundation for, or as founded upon, a system of logic. The first point of view emphasizes the direct links with classical *multi-valued logics* (MVLs), and the second highlights those studies of the *foundations of set theory* that have used non-classical logics, again particularly multi-valued logics. One MVL in particular stands out as closely related to Zadeh's development and that is Łukasiewicz's infinite-valued logic (here abbreviated as $Ł_1$). However, there are also important links with other non-classical logics, particularly *modal logics*. These in their turn are closely linked with topological structures, and fuzzy system theory has links with both conventional topology and non-standard systems, e.g. without points or with generalized closures, that may be regarded as precursors of *fuzzy topologies*. Many other mathematical structures may also be studied using fuzzy, rather than classical sets, leading to *fuzzy graphs*, *groups*, *algebras*, *automata*, etc.

These two directions of fuzzy system theory, the one orientated to human linguistic reasoning and the other to formal logic and mathematics, come together again in a wide range of applications. We have not attempted to gather background references for these applications because they are so diverse and the individual fuzzy applications papers generally have good bibliographies of the relevant non-fuzzy approaches.

2.1. INTRODUCTORY PAPERS

The newcomer to fuzzy systems theory will probably be appalled by the sheer volume of literature now extant. However, there are a few key references which make it fairly easy to get into the central literature very rapidly and to a reasonable depth. The danger is only in assuming, for research purposes, that this central core fairly represents the current state-of-the-art. There is now a complex, derivative literature, so that many problems are being explored at secondary, or even tertiary, level. Many of the obvious avenues of exploration arising out of Zadeh's papers have now *been* explored and re-explored. This applies particularly to the technicalities and foundations of fuzzy reasoning—it is dangerous to rush into print with a "new" set of connectives or a variant fuzzy logic. Even some applications areas, notably pattern-recognition, clustering, decision-making and control, have been explored on a fairly wide front—it is certainly dangerous to rush out a note re-discovering and eulogizing the potential application of fuzzy system theory to a particular problem area. Such notes already exist in great abundance and what is needed are solid application studies demonstrating actual results. Many such studies do also now exist, particularly in pattern-recognition, simulation and control engineering. Finally, the anti-fuzzy reaction, showing that the concepts are misconceived or the approach wrong, has itself become antiquated, if only because each recipient of the fresh revelation does not realive how many others actively engaged in the field have been through the same process of critical reaction appreciation and constructive re-development. This is not to say that all or part of the literature is completely right, but there is now a wide variety of evidence to show that the concepts and approach are certainly not completely wrong!

As in most areas of study, the best introduction is to go straight back to the source, and Zadeh (1965*a*) is still worth thorough reading. Zadeh (1973*a*) has served a great many workers as a general introduction to the area, and Bellman & Zadeh (1976), the latest paper, is particularly important for its new results on fuzzy reasoning and truth. Bellman & Zadeh (1970) has many interesting speculative remarks about fuzzy multistage decision-making, and Zadeh (1971*d*, 1975*d*) develop interesting technical concepts of fuzzy similarity relations, and fuzzy restrictions, respectively. Zadeh (1972*c*) is probably the most complete exposition of his analysis of *linguistic hedges*, and Zadeh (1975*b*) is a very clear and concise account of the syntax and semantics of multi-term hedges. Zadeh (1972*b*) links this work to studies of formal languages. Zadeh himself has written no book as yet on fuzzy system theory, but the sum total of his papers forms a massive work encompassing a wide variety of topics. The collection is important not only for its technical content but also for expressing the motivation behind the developments in a more powerful form than in books or papers by other authors.

Other key introductory papers are: Lakoff (1973*c*) which gives a linguist's view of Zadeh's analysis of fuzzy hedges [for some later comments see the conversation with Lakoff in Parrett (1974)], and which has been published three times, in a conference proceedings, in a journal (as referenced here), and in a book (Hockney, Harper & Freed, 1975) which also contains some comments by Van Fraassen (1975); Goguen (1969*b*) which has some interesting comments on, and variants of, Zadeh's approach, including the first analyses of some paradoxes and fuzzy quantifiers; and Goguen (1974*b*) which presents axioms for the category of fuzzy sets and relates them directly to a phenomenal analysis of human concept processing. The book of the 1974 joint U.S.A.–Japan conference at Berkeley (Zadeh, Fu, Tanaka & Shimura, 1975) is a particularly useful introduction to the wide range of fuzzy system studies. The book by Negoiţă & Ralescu (1975*a*) is a compact introduction to many technical aspects of fuzzy systems and their literature, whilst the series of three volumes by Kaufmann (1973, 1975*a*, *b*) is remarkable for its coverage at this early stage. No one should be fooled by the book format, however, into feeling that it is possible to put forward a definitive version of fuzzy system theory at present—the area is still developing rapidly and these books are research compendia rather than textbooks.

Apart from those so far mentioned, there is a noticeable lack of expository and survey papers in the literature—perhaps the former because Zadeh has done such a good job, and the latter because the literature explosion has been so rapid and recent! Gusev & Smirnova (1973) is worth reading and the report by Gupta & Mamdani (1976) of the 1975 Boston IFAC round table discussion is a useful survey of some current trends. Aizermann's (1975) paper for that discussion is particularly interesting for its strong motivation of fuzzy systems theory from an independent and eminent source.

2.2. PHILOSOPHY AND LOGIC OF IMPRECISION AND VAGUENESS

Hacking (1975*b*) remarks in his book on the "emergence of probability" that:

> "Europe began to understand concepts of randomness, probability, chance and expectation precisely at that point in its history when theological views of divine foreknowledge were being reinforced by the amazing success of mechanistic models." ". . . this specific mode of determinism is essential to the formation of concepts of chance and probability."

It is reasonable to speculate that interest in the philosophy and logic of vagueness only really originated when the program of *precisiation* in science had gone so far and succeeded so well, i.e. in the twentieth century. Certainly most of the literature is concerned with the eradication of imprecision, not with the study of *inherent imprecision* in its own right. Russell (1923) and the series of publications by Black (1937, 1963, 1968, 1970) are most often quoted as studies of vague reasoning sympathetic to the direction of development of fuzzy system theory, and Machina (1972, 1976) provides an up-to-date account of recent developments.

Mehlberg (1958) analyses the effect of inherent imprecision on meta-theories of scientific knowledge, truth, verification, etc. The so-called Popper–Carnap "controversy" (Popper, 1963, 1972*a*, 1976*b*; Carnap, 1963, 1964; Michalos, 1971) is in fact a far deeper and multi-faceted dialogue than presented by most commentators, and both authors have much to say on inherent imprecision—the first chapter ("on explication") of Carnap's (1950) *Logical Foundations of Probability* presents a clear exposition of the process of precisiation in science, and section 7 of Popper's (1976*b*) autobiography presents the dangers of attempting to carry it too far. A miniature version of the controversy in the context of fuzzy system theory can be found in the Kalman–Zadeh discussion at the end of Zadeh (1974*a*).

The transition from the philosophy of imprecision to an appropriate logic of imprecise reasoning is the subject of all too few papers. Körner (1957, 1959, 1966, 1970, 1971, 1976*a*) has made it a subject of extensive study over many years, and his logical proposals have been developed technically by Cleave (1970, 1974, 1976). Körner (1976*a*) has the very appropriate subtitle, "*a study of practical reasoning*", and is worth thorough reading. There are many background developments in logic also, some emanating from Łukasiewicz's (Borkowski, 1970) 3-valued logic, $Ł_3$, of future contingents which are neither true nor false, e.g. work on *truth-gaps* and *supervaluations* (Van Fraassen, 1968; Wilson, 1975). Susan Haack (1974, 1975) has given particularly clear and perceptive accounts of a range of such "deviant logics" and related them both to the underlying requirements and to classical developments.

It is interesting to note that the 3-valued logic used by Körner was first studied by Kleene (1938, 1952; Rescher, 1969, pp. 34–35) in connection with the recursiveness of arithmetic functions. The meaning of the third value is not true or false but indeterminate, or indeterminable by certain specified decision procedures, i.e. by an effective algorithm—a recent technical paper on this logic is Martin (1975). Another independent development of the same logic has been motivated by work on computerized "*automated systems for generating interesting hypotheses from experimental data*", the GUHA method (Chytil, 1969; Hájek, 1968; Havránek, 1971) which is a generalisation of Hájek, Havel & Chytil (1966). The 3-valued system was first announced in 1969 and is reported in detail in Hájek, Bendová & Renc (1971). H. B. Curry noted in 1970 that the logic used was that of Kleene. The motivation for the third value in this case is to express the *absence of information on some objects and properties.*

The GUHA method is a special instance of a more general family of (infinite-valued) systems, ALIOS, based on work of Hájek and his school (Hájek, 1973*b–d*, 1974*a*, *b*, 1975; Hájek & Harmancová, 1973; Hájek & Havránek, 1976; Havránek, 1974, 1975*a*, *b*; Pudlák, 1975*a*, *b*). A prime thesis of the ALIOS method is that (Hájek, 1975):

> "there are formal systems different from the predicate calculus that are appropriate for hypothesis formation (inductive generalization) and have a satisfactory mathematical theory."

The authors define an *observational structure* as a relational system mapped into rational numbers, and theoretical statements are represented in a real-valued Σ-modal structure. It appears that the theory is sufficiently general to include both stochastic and fuzzy models. The best survey papers are Hájek (1975) and Havránek (1975), and other key papers are Hájek (1973, 1974). Pudlák (1975) provides a link to computational complexity and Hájek (1975) to semisets.

The recent issue of *Synthese* [1975, **30**(3/4)] devoted to vague reasoning had a particularly stimulating and wide-ranging series of papers by Adams & Levine (uncertainties from premise to conclusion), Arbib & Manes (fuzzy systems), Carlstrom (vague quantifiers), Dummett (Wang's paradox), Fine (vagueness & truth), Wright (vague predicates) and Zadeh (fuzzy logic), covering both the philosophy and the logic of inexact reasoning and relating technical developments to classical logics, probability theory, and fuzzy system theory—it is worth acquisition as a reference work in its own right. Earlier significant papers on imprecise reasoning include: Verma (1970) on *vagueness and excluded middle*; Khatchadourian (1965) on *vagueness, meaning and absurdity*; Axinn & Axinn on *ignorance relations*; Kerridge (1961) on *inaccuracy and inference* in a classical framework; Simon (1967) on *the logic of heuristic decision-making*; Morton (1975) on *complex individuals and multigrade relations*; Morgan (1975) on *similarity as a theory of graded equality*; Sober (1975) on *simplicity*; Wiredu (1975) on *truth as a logical constant*; Rescher & Manor (1970) on *inference from inconsistent premises*, Adams (1965) on *inexact measurement*; and the book by Krantz, Luce, Suppes & Twersky (1971) on *foundations of measurement*.

One important paper on vague reasoning that is not generally accessible because it exists only in Polish is Kubiński's (1958) analysis of *vague terms*. Kubiński classifies vagueness in terms of pragmatic, semantic and syntactic definitions, and, in the appendix, analyses some of the ancient paradoxes. His logical system is based on *quasi-ontologies* that are generalizations of Lesniewski's *ontology* originally developed as an alternative to set theory for the foundations of mathematics (Luschei, 1962; Fraenkel, Bar-Hillel & Levy, 1973).

According to Kubiński's syntactic definition, a non-individual term b is vague if there exists an individual term a such that neither the expression: (1) "a is b", nor the expression: (2) "a is non-b" are theses of definite systems called quasi ontologies. The sense of the functor "is" used in (1) and (2) above is determined by an axiom of Lesniewski's ontology. The meaning of "non" in (2) is determined by a special axiom—it neither term-negation of ontology nor the negation of classical logic.

The system on which the work is based is defined by the following syntactic forms:

A1: $\forall x\ \forall y[\epsilon xy \equiv \exists z(\epsilon zx) \wedge \forall v\ \forall w(\epsilon vx \wedge \epsilon wx \rightarrow \epsilon vw) \wedge \forall u(\epsilon ux \rightarrow \epsilon uy)]$

A2: $\forall x\ \forall y[\epsilon xy \rightarrow (\epsilon x\mathrm{N}y)']$

D1: $\forall x\ \forall y\ \forall z(\epsilon x\mathrm{A}yz \equiv \epsilon xy \vee \epsilon xz)$

D2: $\forall x\ \forall y\ \forall z(\epsilon x\mathrm{K}yz \equiv \epsilon xy \wedge \epsilon xz)$

A3: $\forall x\ \forall y\ \forall z[(\epsilon x\mathrm{NA}yz \equiv \epsilon x\mathrm{N}y \wedge \epsilon x\mathrm{N}z) \wedge (\epsilon x\mathrm{NK}yz \equiv \epsilon x\mathrm{N}y \vee \epsilon x\mathrm{N}z) \wedge (\epsilon x\mathrm{NN}y \equiv \epsilon xy)]$

A1 is an axiom of ontology and D1, D2 are definitions of conjunction and alternation. It should be noted that the functors $\{\wedge, \vee, \rightarrow, '\}$ belong to a different semantic category from that of the functors {A, K, N}—the former are "expression-generating" while the latter are "name-generating".

Kubiński's semantic definition of vague terms involves the concept of a *fringe*. The fringe of a term "a" is the set of all objects which are denoted neither by "a" nor by "non-a". A term is vague if and only if its fringe is non-empty. The following are the semantical axioms for the system.

Let U be a set of individuals and Z a set with the following two properties:

(1) $a_1, s_3 \ldots$ belong to Z;

(2) if x and y belong to Z then so do Axy, Kxy and Nx.

Let f be a function whose domain is Z and whose range is subsets of U. Then:

(a) $f\mathrm{A}xy = fx \cup fy$
(b) $f\mathrm{K}xy = fx \cap fy$
(c) $f\mathrm{NN}x = fx$
(d) $f\mathrm{NA}xy = f\mathrm{N}x \cap f\mathrm{N}y$
(e) $f\mathrm{NK}xy = f\mathrm{N}x \cup f\mathrm{N}y$
(f) $fx \cup f\mathrm{N}x = \varnothing$

Z is called the "name space" and the elements of the set fx are called the designates of the name x. The set Bx is the *fringe* of the name "x" (where x is a member of the name space Z) if and only if Bx is equal to the set difference, U-(fx+fNx). The name "x" belonging to Z is *vague* (nieostre—not sharp, not crisp) if and only if the fringe Bx is not empty, and it is *crisp* (ostre—sharp) otherwise.

Kubiński (1960) introduces some new primitive functors into his system, with the intuitive meanings: x is undoubtedly y; x is rather y than z; x is rather y than non-y; x is y and z to the same degree. Neustupný (1966) outlines the application of this system to questions of linguistic vagueness.

Kubiński's work is important as a formalisation of vagueness within the framework of Lesniewski's ontology, and it is interesting to compare it with similar attempts within the framework of set theory. Whereas Black (1937, 1963) approaches vagueness from the point of view of pragmatics and Kubiński through syntax and *extensional* semantics, Materna (1972) chooses an *intensional* approach, modifying Tichý's (1969) explication in terms of Turing machines. He also gives an intensional definition of "fringe" that satisfies the axioms of Kubiński. Other papers relevant to Kubiński's work are Przełecki (1958) who discusses the connections between meaningfulness and vagueness of theoretical terms and Wojcicki (1966) who applies model theory to the analysis of *empirical meaningfulness* (significance) and investigates some of its properties.

That vagueness is an important issue in linguistics has been shown by the *Prague Linguistic Circle* (Vachek, 1966*a*) whose writings since the late twenties have consistently emphasized the role of vagueness in language (Skalička, 1935) under the heading of the relation of *centre and periphery*. It has been proposed that vagueness might be an important *language universal*, and an impressive volume of evidence for this has been built up by analysis of actual language at phonological, grammatical, and other levels [see Daneš (1966) for a survey and references]. Neustupný succinctly reviewed and summarized the problem of vagueness in a lecture given to the linguistic association in Prague in 1964 (Neustupný, 1966), adumbrating the similarities and distinctions between the work of the Circle and the philosophical and logical theories of vagueness of Black, Quine and Kubiński. He also outlined the implications of this issue for the structure of logical theories of language and mathematical linguistics.

Basic methodological issues concerning the dynamics of language raised by Mathesius (1911) that influenced the whole development of the views of the Prague Linguistic

Circle strikingly resemble many of the methodological problems raised by contemporary system theory. Thus it is not surprising that the approach of the Circle is particularly attractive in terms of the "linguistic" approach to systems advanced by Zadeh:

(a) they regard language as a *semantic system*, where the *linguistic sign* and *communication* are two fundamental concepts;
(b) their approach is based on *functional* structuralism concerned with problems of (synchronic) structural stability as well as with the dynamics of temporal (diachronic) changes and evolution in language;
(c) prominence has been given to methodological problems of the segmentation of language and to the identification of units of language at various levels of the *structural hierarchy*.

The combination of structuralism with a "functional" point of view means that language is evaluated not only with respect to the linguistic system as a whole but also with respect to the ultimate function it fulfils in the larger setting of extra-linguistic reality.

Prague linguists distinguished and analysed separately vagueness appearing on several different functional levels, e.g. in a phonological system or on the structural grammar level (Vachek, 1964*a*; Daneš & Vachek, 1964; etc.). For example, in terms of grammar, ". . . one is faced with a phenomenon strikingly parallel to the one noted above in the discussion on phonological problems in language . . . one meets here again what might be termed the 'fuzzy points' of the system . . ." (Daneš & Vachek, 1964). Vachek (1964*a*, *b*) points out that, "research in generative grammar has failed to cope with the problem of the 'fuzzy points' of the system of language, the problem of paramount importance for dynamics of the synchrony of language". Vachek (1964*b*) is criticized by Chomsky & Halle (1965) but Vachek (1966*a*) replies to this criticism, "N. Chomsky's and M. Halle's reaction to this paper misses exactly this most important point of 'fuzzy points', and so in no way invalidates our arguments".

Travaux Linguistiques de Prague devotes its second volume (1966) to a series of articles concerned with *problems of centre and periphery*. The date of the editorial, June 1965, indicates that the collection went to the printers that year and hence could not have contained any reflections on Zadeh's pioneering paper. This issue contains a list of terms by which vagueness is referenced by various linguists, Nestupný's (1966) paper, and an exposition of the concepts of vagueness of the Prague Circle in terms of Kubiński's logic.

In conclusion, it is illuminating to compare the views of the Prague Linguistic Circle, a group of linguists primarily concerned with the structural stability of language, with those of the eminent control theorist, Aizerman (1975), on the need for a new approach to handle problems of stability in control engineering:

"unsolved problems . . . of structural stability, absolute stability, etc. In such areas we do not have answers . . . a mathematics which should be based on a different system of axioms, a different set of rules of inference, and above all, a different concept of precision" (Aizerman, 1975);

"A final remark should justify the fact that the above arguments do not attempt to formalize the present theses. It will have been noted that the theses are, for the great part, concerned with problems of diachronistic, though strictly structural, character. And it is commonly admitted that mathematical science has not yet developed a formal apparatus capable of expressing what is happening within a changing structure. There can be no doubt, however, that one day such apparatus will be available. Perhaps one of the justifications of these modest lines may be to urge the necessity of working out such apparatus" (Vachek, 1966*a*).

2.3. PARADOXES

In the same way that much of our understanding of human behaviour comes from study of its pathology, so do the *paradoxes* of formal reasoning act to clarify its structure and mould the form of associated research. Patterns of reasoning that lead to contradictory or counter-intuitive results indicate a flaw in the logic, its application, or in our interpretation of it. Russell's discovery of a paradox in Frege's *Foundations of Arithmetic* (Van Heijenoort, 1967) may be seen as the prime source of the major research on axiomatic set theory. The paradox takes many forms (Kleene, 1952; Martin, 1970; Chiara, 1973; Post, 1973; Parsons, 1974), and Hughes & Brecht (1976) is a particularly useful source book of interesting variants.

Many attempts to circumvent Russell's paradox involve legislating to remove the constructs leading to problems (e.g. of a set being a member of itself) but some non-standard analyses regard it as a logical problem arising from the law of the excluded middle (LEM) and change the logic to a 3-valued one that does not give rise to the paradox (Shaw-Kwei, 1954; Skolem, 1960; Skyrms, 1970). Varela (1975, 1976*a*, *b*) has put forward a very interesting approach extending G. S. Brown's (1969) *calculus of indications* to allow the paradoxical self-referential concepts (Smullyan, 1957) but use them in a way similar to Asenjo's (1966) *calculus of antimonies* to generate new truth values. He argues that living organisms use self-reference and it is inappropriate to attempt to avoid it, yet in order to avoid certain unwanted consequences the self-referential loops should be separate in the calculus—hence the third value assignment. This introduction of new truth values is a general procedure that can be used to staticize certain aspects of a dynamical system giving a new MVL. It is a homomorphism on the fine structure of the consequence-closure system and the main danger comes from this being inadequately known (e.g. in human and animal behaviour) so that the MVL generated is misleading.

Pinkava (1965, 1976*b*) analyses some paradoxes listed in Kleene (1952) and shows that, in general:

(a) self-reference is relevant only to a certain type of paradox;
(b) when it is relevant it is only the *necessary*, not a sufficient, condition, i.e. there may exist self-referential systems without paradoxes.

Further he shows that a paradox can be generated in a self-referential system if, for example, the following additional conditions are satisfied:

(1) the problem is representable by a certain form of propositional function;
(2) non-logical constants appearing in this representation have to come from a certain *critical* subset of all constants.

Pinkava's approach makes it possible to view the interaction of paradoxes and self-reference as a problem of stability in Tarski's general calculus of systems (Tarski, 1956, pp. 30–37, 60–109, 342–383). The approach is constructive allowing paradoxes with specified structures to be generated. Sadovskiĭ (1974) has analysed various General Systems theories and come to the conclusion that such paradoxes appear in the foundations of the subject and require urgent attention. Mackie's (1973) book on *Truth, Probability and Paradox* is particularly interesting in bringing these three topics together.

The analysis of Russell's paradox in fuzzy logic takes a similar route to that of Varela (Hendry, 1972; Gaines, 1976*g*) and resolves it by allocating a new truth-value to the paradoxical case. This can be extended to allow the continuum of truth values in fuzzy logic to be generated from the higher-order "paradoxical" expressions of an axiomatic system (Gaines, 1976*g*).

Another class of paradoxes that has been widely studied in terms of fuzzy reasoning are those concerned with the application of conventional logic to vague predicates. The problems that arise were noted by Greek philosophers and go under the names of *sorites* (the heap that remains one even if an item is removed), *falakros* (the bald man that remains one even if he grows one more hair), and so on (Cargile, 1969; Weiss, 1973, 1976). Because they are concerned with vagueness as such, these paradoxes provide a good test of systems of fuzzy reasoning and their avoidance has been studied by Goguen (1969*b*), Lake (1974*b*), Gaines (1976*g*), and others. Weiss (1973, 1976) gives an interesting alternative analysis of these paradoxes, as does Sandford (1975*b*).

2.4. MANY-VALUED LOGICS

Although Zadeh (1965*a*) proposes a theory of fuzzy *sets*, set theory is itself dependent on the underlying logic and his proposal may be viewed as using an MVL as an alternative to the 2-valued classical logical calculus. In later papers Zadeh (1975*b*) suggests that this MVL is in fact the infinite-valued logic, $Ł_1$, first studied by Łukasiewicz (Borkowski, 1970; Borkowski & Slupecki, 1958; Rescher, 1969). The literature on MVLs is very extensive (Rescher, 1969; Wolf, 1975) but their development has been somewhat erratic. The introduction of more than two truth values leads to philosophical problems of interpretation (Zinovev, 1963; Haack, 1974), for example in Tarski's theory of truth (Tarski, 1956; Blackburn, 1975; Evans & McDowell, 1976; McKay & Merrill, 1976), and, whilst 3-valued logics have been given reasonable interpretations (e.g. Putnam, 1957; Segerberg, 1967; Borkowski, 1970; Evenden, 1974), the problem of doing so for infinite values has never been satisfactorily resolved. Hence much of the literature is concerned with uninterpreted MVLs used for technical purposes such as demonstrating the independence of logical axioms. Dana Scott's (1976) paper, "Does many-valued logic have any use?", and the ensuing discussion by Smiley and Cleave (Körner, 1976*b*) is particularly interesting for its remarks on the important work of Giles (see section 2.7), Körner, and Hájek (section 2.2).

Zadeh's application of fuzzy system theory to imprecise reasoning does seem to provide a reasonable interpretation of logics such as $Ł_1$, and recently Bellman & Zadeh (1976), Maydole (1975) and Gaines (1976*g*) have argued strongly for there being a reasonable theory of truth in terms of infinite-valued MVLs. Even at a fundamental level this should not be unexpected since Tarski's theory is based on a general theory of consequence that does not require the 0–1 valuation.

Rescher's (1969) book is the best overall introduction to MVLs, being reasonably non-technical, covering the most interesting cases and having an excellent review of the literature. Ackermann's (1967) short book is more concerned with the axiomatic form of $Ł_1$ and enables the logic to be compared with the classical propositional calculus (PC). He points out the absence of a key deduction theorem from $Ł_1$ which makes Fitch-stely (Hackstaff, 1966) *natural deduction* impossible, and hence the patterns of reasoning in $Ł_1$ markedly different from those of PC. Rosser & Turquette's (1952) book is another useful reference, although concerned primarily with the axiomatization of finite-valued

MVLs, and the older review papers by Frink (1938) and Salomaa (1959) are still worth reading. Epstein, Frieder & Horn (1974) is a recent note on applications of MVLs in computer science, and Kitahashi (1975) surveys Japanese work. Pinkava (1975), Kohout (1974) and Kohout & Pinkava (1976) give a very useful construction for arbitrary complete families of MVLs.

It is not possible here to do more than highlight a few papers with significant results related to $Ł_1$, such as those of Wajsberg (1967), Rosser & Turquette (1945), Rose (1950, 1951*a*, *b*, 1952, 1953, 1958) Rose & Rosser (1958), C. C. Chang (1958*a*, 1959), Meredith (1958), Rosser (1960), Jobe (1962), Schock (1964*a*, *b*, 1965), Turquette (1963), Marek & Traczyk (1969), Georgescu & Vraciu (1970), Georgescu (1971*a*–*d*) and Grigolia (1975). Dummett (1959) links MVLs with the intuitionistic propositional calculus (IPC) and proves a key tautology of truth-functional MVLs. Morgan (1976*a*) provides a very interesting interpretation of many-valued intuitionistic logics. Dienes (1949) has an interesting discussion of MVL implication, as do Webb (1936), and Salomaa (1959)—Turquette (1954), Prior (1955*a*), and Schuh (1973) compare it with *strict implication* in modal logic and Woodruff (1974) gives a translation of $Ł_3$ into S5. Segerberg (1967) is one of a series of papers going back to antiquity which discusses many-valued *modal* logics, a topic also deeply studied by Łukasiewicz (Borkowski, 1970; Borkowski & Slupecki, 1958), although Dugundji (1940) has shown that no finite-valued MVL can be characteristic of the Lewis–Langford modal logics.

The most important area of development for $Ł_1$, however, is to extend it to a predicate calculus with quantifiers. Rescher (1969) discusses the introduction of quantifiers in MVLs and Mostowski (1957), Borkowski (1958) and Rescher (1964) give some interesting possibilities. Studies of axiomatic predicate calculi built on $Ł_1$ include: McNaughton (1951), Mostowski (1961), Scarpellini (1962), Hay (1963), Belluce & Chang (1963), and Belluce (1964). Scott's (1974) Tarski Symposium paper is particularly worth reading, and Maydole's (1972) thesis contains a wealth of material. The series of papers in German by Klaua and its continuation by Gottwald is also a major contribution. In the context of fuzzy logics, Goguen (1967) introduces fuzzy quantities and Giles (1975, 1976*b*, *c*) and Gaines (1976*g*) both consider quantified forms of $Ł_1$.

Papers giving special semantics for MVLs, such as Kripke-style *possible worlds* (Snyder, 1971; Lewis, 1973), are also of interest, such as those of Bertolini (1971), and Urquhart (1973), and related studies of other logics (Nagai, 1973; Ohnishi & Matsumoto, 1957). The problems of making deductions in a non-standard logic give computer-based theorem-proving systems special significance and, apart from the general literature (Chang & Lee, 1973), papers by Ehrenfeucht & Orlowska (1967) and Orlowska (1967, 1973) that consider MVLs are particularly worth studying. The recent special issue of the *IEEE Transactions on Computers* (**C–25**, August 1976) on *automated theorem proving* is a useful source, and Morgan's (1976*b*) paper in it on *non-classical logics* is particularly relevant. It should be noted that many theorem provers for classical predicate calculi rely on LEM and need radical change for MVLs.

2.5. OTHER NON-STANDARD LOGICS

Those attempting to break out of the framework of classical formal reasoning can gain much by studying the motivations and attempts of others to do so, for example, with *intuitionistic logics*, *strict implication*, *relevance logics*, and general *modal logics*. In addition there is also a variety of technical links between these topics and fuzzy system theory.

Kneale & Kneale (1962) is a scholarly but readable general history. Prior's (1962) textbook is an excellent introduction using Polish notation (which is essential to many key references), whilst Hughes & Creswell (1968) has an excellent introduction to classical propositional and predicate calculi in *Principia* notation as well as its survey of the Lewis–Langford modal systems. Mostowski's (1966) survey of *thirty years of foundational studies* gives a feel both for the intuitionistic propositional calculus and for the task of developing non-standard systems, and Prior's (1967) book on tense logics has some historical background again giving a feel for the problems involved. His many other books and papers are an excellent introduction to both the techniques and the motivations behind many logical developments (e.g. Prior, 1953, 1954, 1955*a*, *b*, 1957, 1962, 1967, 1971). The same can be said for Rescher's (1968) collection and for Von Wright's (1957) collection. Tharp (1975) gives some motivation for, and constraints upon, non-standard approaches. McCall (1967) is an excellent introduction to the key work in Polish logic between the wars, and Łukasiewicz's collected works (Borkowski, 1970) are clearly mandatory reading!

As well as the use of numeric quantifiers in MVLs mentioned in the previous section, there have also been developed models of the linguistic usage of vague numeric terms such as *some*, *any*, *almost all*, etc. (Altham, 1971; Adams, 1974). Such "modalities" are included amongst the very extensive list discussed in White's (1975) book on *modal thinking*, and Creswell (1973) develops a reasonably full model of language within a modal framework. Snyder (1971) is a very clear introduction to modal logic, its history, technicalities and proof techniques. Lewis (1973) shows how the model-theoretic, possible worlds, semantics of Kripke and Hintikka allows a formal model to be established of the *counterfactual conditional*, and hence of much practical reasoning. A contrasting approach to modal logics, based on the *intension* of predicates rather than their extensions (Carnap, 1947), is taken by Gallin (1975). Schotch (1975) discusses *fuzzy modal logics*, a topic worthy of much further study.

The studies of *strict implication* (Barcan, 1946; Marcus, 1953; Hacking, 1963; Lemmon, Meredith, Meredith, Prior & Thomas, 1969) motivating the development of the modal logics of possibility and necessity are of particular interest because they are in turn motivated by practical problems of reasoning about causality. Indeed all studies of implication that attempt to place upon it constraints corresponding to *reasonableness* in human reasoning are very interesting in the context of imprecise reasoning. For example Goddard & Routley (1973) have investigated contraints of *significance and content*, and have much incidental material on MVLs also. Anderson & Belnap's (1975) book on *entailment* has a fascinating presentation and wide-ranging reviews of attempts to impose relevance and necessity on logical implication so that it more closely models entailment in reasoning. The notion of *relevance* (Belnap, 1960; Anderson & Belnap, 1962, 1975) is important in any logical system and its introduction in $Ł_1$ could well follow the lines they suggest for more classical logic.

2.6. FOUNDATIONS OF SET THEORY

Zadeh's proposal of $Ł_1$ as a logic on which to found a set theory was based on informal pragmatic arguments applying to engineering applications. There has been a parallel, and apparently independent, development of the same structure based on purely formal arguments concerned with removing the paradoxes from naïve set theory already discussed. This is reviewed in Gaines (1976*g*) and involves a sequence of papers commencing with Shirai (1937), but coming to full fruition with Shaw-Kwei (1954), Skolem (1957, 1960), C. C. Chang (1963*a*, *b*, 1965) and Fenstad (1964). The initial avoidance of the paradoxes of Russell and of Curry (1942) (a variant not involving negation) involved 3-valued logics (Prior, 1955*b*) but higher order paradoxes were found that forced infinite-valued logics. The current state-of-the-art is best summarized by Maydole (1972, 1975) who has developed a technique for generating paradoxes that eliminates the standard predicate calculus, intuitionistic and modal (strict implication) variants, etc., leaving only a few infinite-valued MVLs as possible paradox-free foundations.

There have also been various developments within the framework of fuzzy set theory: Goguen (1974*b*) gives a Lawvere-style axiomatization of the category of fuzzy sets based on his thesis (1968); Lake (1974*a*) suggests a von Neumann style axiomatization that encompasses both Zadeh's fuzzy sets and Rado's multisets; Netto (1970) develops a theory in which fuzzy classes are taken as primitives using the first-order predicate calculus with equality; Chapin (1971) announced a ZF-like axiomatization of fuzzy set theory and has now developed it in some detail (Chapin, 1974, 1975). The models involve a set-valued membership function as a primitive and contain classical ZF set theory, Zadeh's fuzzy set theory, and various generalizations of them. Chapin also notes that Zadeh's fuzzy set theory is not contained in J. G. Brown's (1969) lattice-theoretic generalization.

Another important series of papers on MVL foundations for set theory are those of Klaua (1965, 1966*a*, *b*, 1967*a*, *b*, 1968, 1969*a*, *b*, 1970, 1972, 1973) in which he develops variants based upon both Łukasiewicz finite-, and infinite-valued, logics, and uses them a foundation for MVL-based mathematics. Klaua's set theory is developed cumulatively as a theory of types, which suggests that the prime motivation was not the parodoxes of the axiom of comprehension (although he quotes Skolem's work). His principal connectives are:

$$\sim_w s = 1 - s,$$

$$s \wedge_w t = \min\{s,t\}, \qquad s \vee_w t = \max\{s,t\},$$

$$s \rightarrow_w t = \min\{1, 1-(s-t)\}, \qquad s \leftrightarrow_w t = 1 - |s-t|,$$

$$s \wedge^w t = \max\{0, s+t-1\}, \qquad s \vee^w t = \min\{1, s+t\}.$$

Klaua's work has been continued by some of his former students, notably Gottwald (1969, 1971*a*, *b*, 1973, 1974, 1975*a*, *b*, 1976*a–c*) who in his *Habilitationschrift* (1975*a*) investigates in great detail the features of various finite variants. He finds that direct, many-valued analogies may be found for the following axioms: (i) empty set; (ii) pairing; (iii) union; (iv) power-set; (v) substitution; (vi) choice; (vii) infinity. The axiom of extension is valid only in a weaker form. The possibility of a many-valued analogy of the classical axiom of choice that suggests the existence of a choice-set is still open. An example is given which shows that a many-valued analogy of the axiom of choice (in this formulation) does not hold in constructive sets.

A rather different motivation for a deviant set theory arises in the context of the Popper–Carnap "controversy" discussed earlier. Both Popper and Carnap aim at quantifying the process of precisiation and its evaluation by introducing various measures upon it, and both their approaches seem completely plausible and self-consistent. Indeed, in recent years, Carnap (1963) has gone so far as to say that there is no mutual incompatibility in their views and that Popper exaggerates the difference. Yet recent developments have indicated that there may be a fundamental source of conflict between the approaches in the underlying logic and set theory. For example, Hájek & Harmancová (1973) show that one of Carnap's measures of subjective probability is not viable in terms of classical set theory but it exists if the weaker structure of *semisets* is used instead (Vopěnka & Hájek, 1972; Hájek, 1967, 1973*a*).

Similarly, Popper's development of a verisimilitude measure (in terms of knowledge or a theory being only partially true and having some falsity content) is based (Popper, 1972*a*, pp. 330–335) on Tarski's metalogical theory of consequence (Tarski, 1956, pp. 30–37, 60–109). However, Miller (1974) and Tichý (1974) show independently that Popper's definition of verisimilitude is empty if the Tarski calculus of systems is restricted to classical logic. Miller and Tichý both infer that Popper's intuition is wrong and that they should find a new definition, perhaps less general. Hence, Popper abandons his most general definition (but not his intuitive views) and all three start a new search for a less general but better definition (disagreeing as to what it should be) (Popper, 1976*a*, Tichý, 1976). It is interesting to note that Popper, as a philosopher, would probably reject any non-classical logic as a foundation for reasoning, but nevertheless his general theory of verisimilitude is closely connected with fuzzy system theory (Kohout, 1976*c*). Rather than search for a new definition, it may be better to assume that Popper's original approach was correct and that it is classical logic that is at variance with a real-world epistemology where imprecision and vagueness, as Popper (1976*b*) has noted himself, cannot be avoided (or perhaps *should* not be avoided).

Jaskowski (1969) (who, independently of Gentzen, developed the first system of natural deduction in classical logic) analyses the role of contradiction in logical inference in the process of precisiation of theories, and discusses the limitations of classical logic. He surveys the suitability of various non-standard logics for inference from contradictory data, and develops a new system for this purpose.

It appears that metalogical and epistemological studies into the structure of fuzzy systems will become of increasing importance, and we have included in the bibliography a selection of key papers for this purpose. On the algebraic side are Birkhoff (1948), C. C. Chang (1958*b*), Halmos (1962), Epstein & Horn (1974, 1975*a*, *b*), Rasiowa (1974), Rasiowa & Sikorski (1970) and L. Rieger (1967). The approach based on residuated lattices (L. Rieger, 1949*a*, *b*; Blyth & Janowitz, 1972; Epstein & Horn, 1975*a*, *b*) links algebra to topology. And on the topological side are Čech (1966, 1968), Lemmon (1966*a*, *b*), McKinsey (1941, 1945), McKinsey & Tarski (1944, 1948), Pospíšil (1937, 1939*a*, *b*, 1941*a*–*d*), Rasiowa & Sikorski (1970), Stone (1937–38), Tarski (1956), Rieger (1949*a*), and Takeuti & Zaring (1973). Some more general non-standard systems necessitate the use of generalized topologies, e.g. Tarski's (1956, pp. 60–109) calculus of consequence is based on an MIU-topology, and the basic work here is Čech's 1937 paper which has recently become available in English translation (Čech, 1968). Kohout (1975) surveys the work triggered off by this paper. Hempel (1937) is particularly interesting in a fuzzy systems context because of its use of order relations to define a topology. Study of ordered algebraic structures leads naturally to *semirings* (Aczel, 1948; Arbib, 1970) which play a key role in fuzzy automata (Gaines & Kohout, 1975*a*, *b*) where important links between semirings and fuzzy languages are Schutzenberger (1962), Wechler & Dimitrov (1974), and Negoit & Ralescu (1975*a*). All of these concepts integrate together under the auspices of *category theory* (Bunge, 1966; Banaschewska & Bruns, 1967; Banaschewska, 1968; Goguen 1968, 1969*a*, Arbib & Manes, 1974, 1975*a*, *b*; Manes, 1976)—see particularly Goguen's (1974*b*) work on categories of fuzzy concepts, MacLane's (1971, p. 94) note of adjoint properties in Boolean algebras, and the related developments of connections between category theory and logic (Lawvere, 1972; Lawvere, Maurer & Wraith, 1975).

2.7. PROBABILITY THEORY

Many of the early writers on fuzzy system theory emphasized that although it used truth values in the interval [0, 1] it was in no way related to probability theory. However, probability theory has many aspects (Hamblin, 1959; Rubin, 1969; Stalnakre, 1970; Stalnaker & Thomason, 1970; Wolniewicz, 1970; Hart, 1972, T. L. Fine, 1973; Hacking, 1975*a*, *b*; L. J. Cohen, 1975; Pollock, 1975; Mathie & Rathie, 1975), and the lack of correspondence with any one of them was probably exaggerated because an obvious initial reaction from any audience to a [0, 1] system of vagueness was, "oh, this is some form of probability theory". In fact, although there are clearly significant differences, there are also both formal and practical links between fuzzy system theory and probability theory (Gaines, 1976*c*, *d*, *h*). Because it is not truth-functional, the treatment of probability theory as a *logical calculus* (probability logic, PL) has never been fully developed although, for example, both Łukasiewicz (Borkowski, 1970, pp. 16–63) and Popper (1972*b*) have proposed such calculi [some notes on early developments will be found in Rescher (1969, pp. 187–188)]. Popper's theory was developed in the late thirties and since that time he has repeatedly emphasized that the Boolean model is only one of the many possible. More recently an interesting *non-Boolean* model of probability has been proposed by Novák (1968).

Carnap's (1950) studies of the logical foundations of probability in the context of confirmation theory (Bar-Hillel, 1964; Foster & Martin, 1966; Swinburne, 1973) have also triggered off several studies of probability systems over logical languages (Gaiffman, 1964; Adams, 1966; Scott & Krauss, 1966; Fenstad, 1967). There are also important links between probability theory and modal logic (Rescher, 1963; Danielson, 1967; Miura, 1972).

Giles (1974*a*–*c*, 1975, 1976*a*–*c*) in a series of papers has given a very attractive exposition of a formal calculus that encompasses both probability logic and $Ł_1$, and gives an interesting interpretation of it in terms of a *dialogue model*—his initial area of application was quantum physics. Gaines (1976*c*, *d*, *h*) has given a construction for a non-truth-functional *basic probability logic* whose connectives are the same for PL and $Ł_1$, and which reduces to PL when LEM is added but to $Ł_1$ when strong truth-functionality is required. This logic again has an interesting interpretation in terms of the responses of a population and serves to link fuzzy logics with both frequentist, and subjective, approaches to probability. It is interesting to compare the analyses of Giles and Gaines with the related studies of Watanabe (1969, 1975) (again initiated in quantum physics), and the purely algebraic expositions of Epstein & Horn (1974, 1975*a*, *b*).

Watanabe (1975) emphasizes that under some circumstances both probabilistic and fuzzy approaches may be inadequate, e.g. when there is a strong interaction between observer and observed. DeLuca & Termini (1971) have stressed that in this situation the valuation-lattice is non-distributive, and there are also quantum-mechanical situations where non-commutativity is essential so that various lattice-like structures are of interest but with weaker properties. Jordan (1952) and Kotas (1963) give some background and corresponding algebraic structures are developed in Jordan (1962), Gerhardts (1965, 1969), and Beran (1974). Prugovecki's (1973, 1974, 1975, 1976*a*, *b*) is important in combining probabilistic and fuzzy structures in the context of quantum mechanics. Zadeh (1968*b*) and Loginov (1966) suggest other combinations, and the work on fuzzy measures of R. E. Smith (1970) and Sugeno (1972*a*, *b*, 1973, 1974, 1975*a–d*) establishes other important relationships in the context of non-additive measure theory.

Studies of human decision-making have tended to assume a probabilistic norm, probably based on a Bayesian approach. Re-analysis of such experiments as those of Edwards, Phillips, Hayes & Goodman (1968) in terms of fuzzy reasoning might provide some new insights into the results obtained since these indicate a poorer performance by humans than the Bayesian model would predict. Indeed there is much to be gained by closer liaison between work on human decision-making and *subjective probability* (Smith, 1961, 1965; Edwards, 1962; Good, 1962; Von Wright, 1962; Villegas, 1964; Aczel & Pfanzagl, 1966; Shuford, Albert & Massengill, 1966; Winkler & Murphy, 1968; Menges, 1970, 1974; Savage, 1971; Winkler, 1974; Shuford & Brown, 1975; Hogarth, 1975; Vickers, 1975), and work on fuzzy reasoning. In this context Pearl's (1975*e*) recent analysis of subjective probability, and related papers on modelling and approximation (Pearl, 1974, 1975*a–e*, 1976*a*, *b*; Leal & Pearl, 1976) are particularly interesting.

Whereas studies of subjective probability are largely concerned with isolated decisions, there have also been developed complete logics of human decision-making, preference, belief, etc. Some of these are within a framework of probability theory (Hintikka & Suppes, 1970; Grofman & Hyman, 1973), but others are based on systems of modal logic (Rescher, 1967, Von Wright, 1957, 1963*a*, *b*, 1972). There are direct relationships between modal and probability logics already mentioned, and it would seem worthwhile to examine the comparable relationships with fuzzy logics for decision-making.

The studies of both logical probability/confirmation, and subjective probability/information, converge naturally in the analysis of *inductive reasoning* (De Finetti, 1972; Levi, 1967; Kyburg, 1970), and the literature discussing the relationship between inductive and deductive logics (Dilman, 1973; Dummett, 1973; Haack, 1976) or attempting to vindicate induction (Stove, 1973; Katz, 1962) is also relevant in a fuzzy context. There are important practical studies that link inductive reasoning to variable-valued logics (Michalski, 1974, 1975; Chilausky, Jacobsen & Michalski, 1976; Larsen, 1976) and a far-reaching series of studies previously discussed initiated by Hájek in Czechoslovakia that link it to MVLs including fuzzy logics. The GUHA schemes of Hájek find practical realization in algorithms such as those of Klir (1975, 1976; Klir & Uttenhove, 1976*a*, *b*) and Gaines (1975*b*, 1976*e*, *f*) for determination of system structure from behaviour, and these also serve to provide other links between various aspects of probability theory and fuzzy system theory.

There are now also a range of applications studies contrasting probabilistic and fuzzy systems: Baas & Kwakernaak (1975) re-analyse using fuzzy reasoning the problems analysed by Kahne (1975) on a probabilistic basis; Gaines (1975*a*) re-analyses the fuzzy control strategies of Mamdani & Assilian (1975) using a probability logic; Shortliffe & Buchanan's (1975) critique of Bayesian methods in medical inference is particularly interesting, although it only mentions fuzzy reasoning in passing—Shortliffe's book (1976) contains a wealth of theoretical material and practical results on inductive reasoning with inexact data.

2.8. FUZZIFICATION OF MATHEMATICAL SYSTEMS

If one takes the viewpoint that fuzzy sets are an alternative to classical sets then it is possible to consider the *fuzzification* (Goguen, 1967) of a wide variety of mathematical structures by taking the underlying sets to be fuzzy. This has been done for many specific structures, e.g. logics (Lee & Chang, 1971; Gaines, 1976*d*; Pinkava, 1976*a*); relations (Goguen, 1967; Dijkman & Lowen, 1976); functions (Goguen, 1967; Davio & Thayse, 1973); graphs (Longo, 1975; Rosenfeld, 1975); groups (Rosenfeld, 1971); automata (Nasu & Honda, 1968; Santos, 1968*a*, *b*, 1969*a*, *b*, 1972*a*, *b*, 1975*a*, *b*; Santos & Wee, 1968; Mizumoto, Toyoda & Tanaka, 1969; Mizumoto & Tanaka, 1976; Bertoni, 1973); grammars (Mizumoto, 1971; Mizumoto, Toyoda & Tanaka, 1971, 1972*a*, *b*, *d*, 1973*a*, *b*; DePalma & Yau, 1975; Santos, 1975*c*); languages (Lee & Zadeh, 1969, 1970; Mizumoto, Toyoda & Tanaka, 1970; Santos, 1974; Thomason & Marinos, 1974; Honda & Nasu, 1975; Rajasethupady & Lakshmivarahan, 1974; Lashmivarahan & Rajasethupady, 1974); algorithms (Zadeh, 1968*a*; Santos, 1970); programs (C. L. Chang, 1975; Santos, 1975*d*, *e*): and so on.

In his 1967 paper, Goguen uses a category-theoretic approach to fuzzification which may be seen as encompassing all these specific structures, and Goguen (1974*b*) gives a Lawvere-style axiomatization of the category of fuzzy sets and hence, with specific extensions, of all such fuzzified structures. This approach is developed extensively and tutorially by Negoiţă & Ralescu (1975*a*) in their book, and is a key element in the important papers by Sols and Meseguer on fuzzified algebraic and topological systems (Sols, 1975*a*–*c*; Meseguer & Sols, 1974, 1975*a*, *b*) and by Arbib & Manes (1974, 1975*a*, *b*) on fuzzy antomata. For those concerned with the theory of fuzzified structures, categories are important tools in avoiding duplication of the same results in a differing terminology and in transferring mathematical techniques from one area to another.

The structures obtained by fuzzification are not uniquely defined, being generally uninteresting unless some link is hypothesized between the fuzzy set operations and the other structural operations—this generally comes down to specifying what interaction rules for classical sets are to be preserved with fuzzy sets, and then determining what happens to other rules. This variety of possible approaches means that, for example, the *fuzzy topologies* of one author are not necessarily those of another.

Zadeh's original motivation in introducing fuzzy sets was systems theoretical and one would expect fuzzy topologies over these sets to have a key role paralleling that of crisp topologies in conventional system theory. As one would expect, the "deep" results in this area have been obtained by those, such as Goguen, Sols and Meseguer, cited above, using the category-theoretic approach. There are also key works in the "non-fuzzy" literature on *generalized topologies* and *topologies without points* which are directly applicable to fuzzified topologies.

The majority of other papers on fuzzy topologies seem to stem from C. L. Chang's (1968) definition of a fuzzy topology as a family of open sets that preserves this property under arbitrary unions and finite intersections. Further development of the properties of such topologies appears in Hutton (1974, 1975), Hutton & Reilly (1974), Lowen (1974*a*, *b*, 1975, 1976*a*–*d*), M. D. Weiss (1975), Wong (1973, 1974*a*, *b*, 1975, 1976), Warren (1974*b*, *c*), Ganter, Steinlage & Warren (1975), and Meseguer & Sols (1975*b*). Other results on fuzzy topologies appear also in papers on the optimization of dynamical systems (Nazaroff, 1973; Warren, 1974*a*).

In these papers, a closed set is defined as the complement of an open set (using Zadeh's $1-x$ complementation). However, since the lattice of all subsets of a fuzzy set is not complemented, this leads to a relationship between open and closed sets which is different from that of a standard crisp topology. Not all authors seem to realize the implications of this difference which creates a demand for increased mathematical rigour if one is to obtain meaningful and correct results. On the other hand, some authors who do fully realize the difference, seem to "infer" from it that fuzzy topologies defined on closed sets are of little significance (Goguen, 1974*a*; Negoiţă & Ralescu, 1975*a*).

The results of Michálek (1975) indicate that fuzzy topologies defined on families of closed sets are at least as important as those based on open set definition. He defines a topological structure in which the closed sets are fuzzified. This corresponds to fuzzification of a Fréchet topological space (ABU-topology†), generalized Fréchet convergence space (AB-topology) and Čech closure space (IM-topology), which includes the former cases as special instances. This approach leads to some interesting results which are expressible in the terms of probability theory (probabilistic Menger topological spaces—see Kramosil & Michálek, 1975) but which, it appears, have not been studied or proved in the probability context. Kramosil & Michálek (1975) define a fuzzy metric space by fuzzifying the metric and prove a theorem on the equivalence of their fuzzy topology to some stochastic metric topological spaces.

The lattice of fuzzy subsets is distributive (Negoiţă & Ralescu 1975*a*, p. 15) and hence fuzzy topologies are closely related to a generalization of crisp topologies that has been surveyed and studied by Koutský (1947, 1952) who examined many general mappings on an arbitrary lattice as closure operators of topologies "*without points*" (Meseguer & Sols, 1975*b*). Papers concerning such generalized topologies contain important results for fuzzy topologies (Foradori, 1933; Terasaka, 1937; Nakamura, 1941; Monteiro & Ribeiro, 1942; Chittenden, 1941; Koutský, 1947, 1952; Beran, 1974; Sikorski, 1964; D. Papert Strauss, 1968; Dowker & Papert, 1966; etc.). The set of fuzzy subsets may also be described as a Morgan algebra, so that papers on Morgan and quasi-Boolean algebras are also relevant to fuzzy topologies (Moisil, 1935; Kalman, 1958; Henkin, 1963; State, 1971; Petrescu, 1971; Maronna, 1964; Bialnicki-Birula, 1957; Rasiowa, 1974).

Certain categories of generalized topologies which have been studied in great depth by Čech and his school (1966, 1968) admit not only generalized crisp topologies but also fuzzy and other lattice topologies as their realizations. The wealth of results contained in these works remains yet to be fully explored in the context of fuzzy topologies. Goguen (1974*a*) defines a class of fuzzy topologies based on the open set approach. In categorical terms, he investigates one of the possible duals to the category of IM-topologies and proves a Tychonov theorem. This theorem in its classical version plays an important role in meta-mathematics of mathematical proofs (Łos & Ryll-Nardzewski, 1951). It would be interesting to examine the role of Goguen's version of the theorem in the meta-mathematics of fuzzy systems. It is also interesting to compare Goguen's results with Sikorski's on σ-additive closure algebras (for the list of references see Sikorski, 1964).

The previous discussion illustrates well the need to delimit carefully what part of a mathematical structure is to be fuzzified. For example, the distinction between the fuzzification of objects (or a family of subsets of objects) and the fuzzification of morphisms is a key one. The majority of modern algebraic techniques and theories are modelled on, or are extensions of, the theory of equivalence telations and congruences [as exemplified by the work of Dubreil & Dubreil-Jacotin (1937), or Ore (1942)]. Yet

† Each letter designates an axiom according to the Čech-Koutský classification of generalized topologies and topologies without points, e.g. that defined by the Kuratowski closure axioms is designated as an AIOU-topology. For a list of the axioms see Kohout (1975), pp. 26–27.

in order to make the distinction between the fuzzification of morphisms and objects, it is often necessary to work with the objects directly.

A similar distinction appears in the structural theory of automata as exemplified by the remark of Hartmanis & Stearns (1966):

> "The mathematical foundations of this structure theory rest on an algebraization of the concept of 'information' in a machine and supply the algebraic formalism necessary to study problems about the flow of this information in machines as they operate. The formal techniques and results are very closely related to modern algebra. Many of its results show considerable similarity with results in universal algebra, and some can be derived directly from such considerations. Nevertheless, the engineering motivation demands that this theory go its own way and raises many problems which require new mathematical techniques to be invented that have no counterpart in the development of algebra."

Analogous remarks can be made for fuzzy systems, but Hartmanis & Stearns' "error" of assuming that their techniques had no counterpart in the development of algebra should not be repeated. The extensive work of Borůvka (1937, 1938, 1939, 1941, 1974) and his school is based on the development of modern algebra through the theory of decompositions in sets. It is probable that any successful attempt at general fuzzification of mathematical systems will also invoke semantic distinctions that are not necessary in the standard textbook approach to algebra and will find a more appropriate basis in Borůvka's approach. Similar remarks apply to the work of Čech and his school, already cited, where finer semantic distinctions are made than are generally necessary for crisp structures. Apart from the material on generalized topologies, the sections of his book on non-topological constructs are also very relevant to fuzzification.

Clearly the key papers on fuzzification cited in this section are based on a full awareness of these distinctions, but there are others in which the results are superficial or incorrect because implicit results on crisp structures have been carried over when they no longer hold and may even be contradictory. When a mathematical structure is fuzzified, *all* the standard assumptions and results about its properties need explicit verification.

Note that the term, *fuzzy*, has also been used in a sense distinct from that of Zadeh in the context of *tolerance spaces* (having a non-transitive neighbourhood relation). However, this work is also of interest in terms of imprecision and we have included some references (Arbib, 1967; Poston, 1971*a*, *b*; Roberts, 1973; DalCin, 1975*a*, *b*).

2.9. SOME APPLICATION AREAS

We cannot detail the wide range of application studies using fuzzy system theory—the papers are in the bibliography with key words indicating the main application areas. In particular, *Pattern recognition* (**PAT**) and *Decision-making* (**DEC**) are two such obvious and extensive application areas that it is best to glance through looking for these keys. However, certain applications are of special interest or importance and we shall briefly outline those not already discussed.

Zadeh has emphasized throughout his work the direct relationship of fuzzy system theory to *human linguistic reasoning* with imprecise concepts. This is probably a very important factor in the wide general interest in this work, a breadth of interest never aroused by the work on formal logic which will probably, in the long term, be seen to provide the formal foundations for Zadeh's development. Whilst the logical progress through, "this (e.g. induction) is formally impossible—however, people do it successfully

—let's copy the behaviour patterns of people", is almost a tautology for engineers, the resultant models of human linguistic behaviour are also potentially of interest to linguists. One of the key early papers on fuzzy reasoning is that by George Lakoff (1973) already referenced, who has contributed to developments in linguistics on a far wider front but continues to emphasize the importance of fuzzy systems theory for linguistics (Parrett, 1974).

The interaction between linguistics and fuzzy systems theory, like that between linguistics and artificial intelligence, is a difficult one to specify—there is much common ground but very different attitudes to the treasures it contains. For the linguist, comprehension of actual language structures is vital, whereas for the system theorist such structures are only a stimulus, a bionic model. A good feel for the motivations and directions of current linguistic research can be gained from the conversations of Parrett (1974). Other useful collections on modern linguistics are Fillmore & Langendoen (1971), and the series of four volumes on *Syntax and Semantics* (Kimball, 1972, 1973, 1975; Cole & Morgan, 1975) which contains articles on such topics as *hedges* (Fraser, 1975; Lysvag, 1975) and *possible and must* (Karttunen, 1972). The study of language as a persuasive medium is clearly central to reasoning and often goes under the term *rhetoric*—a useful recent textbook with many examples is Simons (1976). Lewis' account of *convention* in inter-person communication is particularly important in establishing how precisiation occurs in a community. A particularly interesting non-fuzzy development not using order relationships clearly related to fuzzy logic is Wilks (1975) *preference semantics*. A fascinating example of a linguist actually using fuzzy system theory to analyse actual textual material are Rieger's (1974, 1975, 1976*a*, *b*) studies of 18th-century German student lyric poetry. Reddy (1972) has given a fuzzy sets model of reference and metaphor in English.

Similar considerations to those above apply to the interface between fuzzy system theory and *human psychology*. There are system-theory orientated experiments on what fuzzy functions people use (MacVicar-Whelan, 1974; Kochen & Badre, 1974; Kochen & Dreyfuss-Raimi, 1974; Dreyfuss, Kochen, Robinson & Badre, 1975; Damerau, 1975; Rodder, 1975); psychological experiments on human linguistic usage that throw light on reasoning with imprecise concepts (Sheppard, 1954; Osgood, Suci & Tannenbaum, 1964); and psychological models of human behaviour based on fuzzy systems theory (Hersh, 1976; Hersh & Caramazza, 1975, 1976; Hersh & Spiering, 1976). Hersh & Caramarza (1976) in particular is a key paper on the psychological study of human use of fuzzy logic and hedges. There are also fuzzy system-theoretic studies of cognition and memory (Kokawa, Nakamura & Oda, 1972, 1973, 1974*a*, *b*, 1975*a*, *b*; Slack, 1976*a*, *b*).

Fuzzy system theory has had little impact on the literature of *artificial intelligence* (AI) as yet. Kling (1973*a*, *b*, 1974) and LeFaivre (1974*a*, *b*, 1976) give extensions to the AI programming language, PLANNER, to allow the use of fuzzy logic. R. C. T. Lee (1972) has made a preliminary study of resolution theorem proving for a fuzzified form of predicate calculus (quantified variant standard sequence, *not* quantified Ł1). Winograd (1974) has criticized the role of fuzzy hedges in imprecise reasoning in AI. The only actual operational studies appear to be those of the "Fuzzy Robot Users Group" at UCLA (Goguen, 1976) who have implemented a robot environment similar to Winograd's blocks but allowing fuzzy specifications (Shaket, 1975) and fuzzy hints (Goguen, 1975*b*, 1976).

The *social sciences* provide some particularly attractive applications for fuzzy systems theory, although not as many yet as might be expected given the need for a methodology capable of dealing with inherent imprecision (Menges & Skala, 1974; Gottinger, 1973). Wenstøp (1975*a*, *b*, 1976) provides the most convincing examples of what can be done in his fuzzy linguistic simulation of inter-personal dynamics in organizations. Gale's (1972, 1974*a*, *b*, 1975*a*, *b*) studies of conflict resolution in regional geography are another substantial body of results. Drosselmeyer & Wonneberger (1975) report application in the parochial field, Esogbue (1975) to modelling cancer research appropriation, and Van Velthoven (1974*a*, *b*, 1975*a–c*) to criminal investigation and personnel management. Economic applications have also been reported (Hatten, Whinston & Fu, 1975; Stoica & Scarlat, 1975*a*) and it is interesting to refer back to some of Shackle's (1949, 1961) pioneering studies of economic decision-making.

Biology and medicine now also provide a range of interesting application studies such as Butnariu's (1975) neural models, Malvache's (1975) of visual perception, and Kohout's (1976*c*) of hierarchical movement structures. Adey (1972) reports use of fuzzy clustering for chimpanzee EEG analysis (Larsen, Ruspini, McNew, Walter & Adey, 1972). Albin (1975) has achieved considerable success in ECG diagnosis (Bremermann, 1971) and a variety of comparable applications have been reported (Fujisake, 1971; Kalmanson & Stegall, 1973; Sanchez, 1975; Wechsler, 1975; Woodbury & Clive, 1974). Certainly the direct application of Bayesian techniques to medical diagnosis has proved of limited value, and fuzzy system theory is providing an attractive alternative approach. It is interesting to compare it with other new methodologies such as Atkin's (1974) *q*-analysis, which are also having an impact on automated diagnosis (see the September 1976 special issue of the *International Journal of Man–Machine Studies* on *q*-analysis).

Control engineering provides a good test for fuzzy system theory since it was an area central to Zadeh's interests prior to 1965, and it is generally thought of as a *hard* area, perhaps less appropriate to fuzzification. However, control of complex industrial plant has been one of the key areas of successful application commencing with the work of Mamdani and Assilian (Assilian, 1974; Mamdani, 1974; Mamdani & Assilian, 1975). They were initially comparing learning algorithms for adaptive control of a non-linear, multidimensional plant (a physical steam engine), but found that many learning schemes failed to even begin to converge on a reasonable time scale (running out of steam!). A fuzzy linguistic method was developed to *prime* the learning controller with an initial policy to speed adaption—the verbal statements of engineers were transcribed as fuzzy rules and used under fuzzy logic to form a control policy. The performance of these fuzzy linguistic controllers was so good in their own right, however, that they became central to a range of studies in their own right: Carter & Hague (1976) *sinter plant*; Jensen (1976) and Ostergaard (1976) *heat exchanger*; Kickert (1974, 1975*a–c*); Kickert & Nauta Lemke (1975) *water baths*; King & Mamdani (1975, 1976); Mamdani (1976*a*, *b*); Marks (1975*a*, *b*); Procyk (1974, 1976*a*, *b*); Rutherford (1976) and Rutherford & Bloore (1975) *sinter plant*; Sinha & Wright (1975) *heat exchanger*; and Tong (1976*a–c*). Recently Mamdani has noted that the instructions for manual operation of a lime kiln are essentially fuzzy linguistic rules (Perry & Waddell, 1972), and has shown that fuzzy control policies may be learned automatically by a controller with *fuzzy linguistic adaptive strategies* (Mamdani, 1976*a*, *b*); Mamdani & Baakilini, 1975; Mamdani & Procyk, 1976; Procyk, 1976*b*).

There are many more application areas represented in the bibliography, e.g. Kandel's

TABLE 1

Keywords

FUZ	Mentioning fuzzy system theory	SYS	System theory
MVLOG	Many-valued logic	GAME	Game theory
MLOG	Modal logic	DEC	Decision-making
SWLOG	Switching logic	PAT	Pattern recognition
LOG	General formal logic	PROB	Probability theory
INDUCT	Inductive logic and systems	CON	Control
VAG	Philosophy of vagueness	LMACH	Learning machines and artificial intelligence
TRUTH	Philosophy of truth		
PARA	Analysis of paradoxes	AUT	Automata
CAT	Category theory	LANG	Formal languages
SET	Set theory	LING	Linguistics
TOP	Topology	PSYCH	Psychology
LAT	Lattice theory	SS	Social sciences
SEMR	Semirings	MED	Medical sciences
TOL	Tolerance spaces	BIO	Biological sciences
IMEAS	Inexact measurement	INFR	Information retrieval

work on switching logic, Negoiţa's on information retrieval, Bezdek's on numerical taxonomy, Dunn's on fuzzy clustering, etc. Most of these are also now well represented and cross-referenced in the main literature, and are relatively easy to access. Further development of fuzzy systems theory clearly depends on the growth and strengthening of these, and the many other, applications areas mentioned. Formal logic, philosophy, mathematics and like disciplines, always seem to follow the sources of excitement, and arrive at the party just in time to tidy up. It is in these diverse application areas that the excitement has to be generated and maintained.

TABLE 2

Distribution of additional keywords in papers classified as fuzzy

FUZ	763 (total)	LMACH	22
AUT	65	INFR	18
PAT	55	CAT	15
SS	49	MED	13
LING	49	SYS	11
CON	46	BIO	10
PROB	45	LAT	10
DEC	45	INDUCT	8
MVLOG	38	GAME	7
SWLOG	36	PARA	7
LANG	32	TOL	4
LOG	32	SEMR	3
TOP	29	IMEAS	1
PSYCH	27	TRUTH	1
VAG	24	MLOG	1
SET	23		

3. The bibliography and its classification

The bibliography contains 1164 references in total of which 763 are classified as fuzzy (**FUZ**). Table 1 gives a list and explanation of the 31 keywords used in classifying papers. We aimed at a set comprehensive enough to be useful, but small enough to be remembered in browsing through.

TABLE 3

Distribution of year of publication of papers classified as fuzzy

Year	Number
1965	2
1966	4
1967	4
1968	12
1969	22
1970	25
1971	42
1972	58
1973	88
1974	136
1975	227
1976	143 (incomplete)
Total	763

Table 2 shows the distribution of the keywords over the papers classified as fuzzy, and hence gives some indication of the main interactions with other fields. Table 3 shows the distribution of year of publication over the papers classified as fuzzy, and hence gives some indication of the rate of growth of the literature. Note that the figure for 1976 is not meaningful since (from experience of the 1975 figures a year ago) a very large number of 1976 references have not yet been sent to us.

Comparable tables are not given for the bibliography as a whole since the non-fuzzy references have been very much a personal selection and do not give a comprehensive picture of any specific field.

We are grateful to our colleagues, Wyllis Bandler and Václav Pinkava, for their help and suggestions. Joe Goguen provided 7 pages of detailed critical comment on the annotation that improved it greatly, but probably not enough! As a cautionary note we would like to quote his remark, "*Many of the papers that I really do know the content of are badly misrepresented. I suspect that lots of the ones I don't know are too.*" (Moral—these are quick helpful notes, *not* scholarly evaluations.)

The bibliography started from our own collections and lists of references such as those in Goguen (1974*b*). It had a step function in May 1975 when BRG visited Joe Goguen at UCLA and Lotfi Zadeh at Berkeley and was kindly allowed to ransack their offices and filing systems. It has benefited immensely from free interchange of information with Abe Kandel at Soccorro and Hans Zimmerman at Aachen. Once we realized the immensity of what we were attempting it was probably only the continued support and encouragement of friends and colleagues such as these, and many others all over the world, that sustained our efforts.

In collecting together this bibliography we have become aware as never before that a community of scholarship exists and is united, for all its diverse interests, in a desire to further the

search for truth. Apart from updates and corrections of authors' own work, we have had many helpful letters drawing attention to related work, suggesting references we may have missed, and generally attempting to ensure that the bibliography is as widely useful as possible. We cannot here acknowledge the individual help of all those who have written to us, but we hope that they too will get great satisfaction out of seeing this bibliography published—some part of it is theirs also.

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