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Some reflections on soft computing, granular computing and their roles in the conception, design and utilization of information/intelligent systems

L.A. Zadeh

We are living in a world which is undergoing profound changes brought about by rapid advances in science and technology.

Among such changes, the most visible are those that relate to what is popularly referred to as the information revolution. The artifacts of this revolution are all around us: the e-mail, the world wide web, the cellular phone; the fax; and the desktop computer, among many others.

Linked to the information revolution is another revolution – the intelligent systems revolution. The manifestations of this revolution are not as obvious as those of the information revolution because they involve, for the most part, not new products but higher MIQ (Machine IQ) of existing systems, products and devices. Among the familiar examples are smart appliances, smart cameras, smart robots and smart software for browsing, diagnosis, fraud detection and quality control. The information and intelligent systems revolutions are in a symbiotic relationship. Intelligence requires information and vice-versa. The confluence of intelligent systems and information systems leads to intelligent information systems. In this sense, the union of information systems, intelligent systems and intelligent information systems constitutes what might be referred to as information/intelligent systems, or I/IS for short. In my perception, in coming years, the design, construction and utilization of information/intelligent systems will become the primary focus of science and technology, and I/IS systems will become a dominant presence in our daily lives.

When we take a closer look at information/intelligent systems what we see is the increasingly important role of soft computing (SC) in their conception, design and utilization.

Basically, soft computing is an association of computing methodologies which includes as its principal members fuzzy logic (FL), neurocomputing (NC), evolutionary computing (EC) and probabilistic computing (PC). An essential aspect of soft computing is that its constituent methodologies are, for the most part, complementary and symbiotic rather than competitive and exclusive.

A concomitant of the symbiotic relationship between FL, NC, EC and PC is the growing visibility of information/ intelligent systems which employ the constituent methodologies of soft computing in combination rather than isolation. Currently, the most visible systems of this – hybrid – type are neuro-fuzzy systems. But we are beginning to see systems which are fuzzy-genetic, neuro-genetic and neuro-fuzzy-genetic. I believe that in the future most information/intelligent systems will be of hybrid type [Medsker 1995]. Such systems will have a profound impact on the ways in which information/intelligent systems are conceived, designed, constructed and dealt with.

It is important to have a clear understanding of the unique roles which the methodologies of FL, NC, EC and PC play in soft computing.

In essence, the primary contribution of fuzzy logic is the machinery of granular computing (GrC),** which serves as a basis for the methodology of computing with words (CW). I should like to suggest the use of the label "granular logic" (GL) to describe the subset of fuzzy logic which underlies the machinery of logical inference and granular computing. I will have more to say about granular computing and granular logic at a later point.

The primary contribution of neurocomputing is a machinery for the analysis and design of neural networks, that is, systems which are comprised of a large number of elements (neurons) with weighted interconnections. Such systems are frequently referred to as systems with a connectionist architecture or, more simply, as connectionist systems. The importance of neurocomputing derives in large measure from the fact that NC provides effective algorithms for valuation of weights from data, usually for the purpose of system identification, classification, learning and adaptation.

The primary contribution of evolutionary computing is a machinery for systematic random search. Such search is usually directed at finding an optimum solution to a problem. Genetic algorithms and modes of genetic computing, e.g., genetic programming, may be viewed as special cases of evolutionary computing.

The primary contribution of probabilistic computing is the machinery of probability theory and the subsidiary techniques for decision-making under uncertainty, belief networks, cluster analysis and analysis of strochastic systems.

L.A. Zadeh
Berkeley Initiative in Soft Computing (BISC). Computer Science Division and the Electronics Research Laboratory, Department of EECS, University of California, Berkeley, CA 94720–1776
e-mail: zadeh@cs.berkeley.edu

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What we see is that the principal contributions of FL, NC, EC and PC are largely unique and complementary. Thus, EC can be employed in the design of fuzzy-logic-based systems to improve or optimize their performance. In the reverse direction, the machinery of linguistic variables and fuzzy if-then rules in fuzzy logic can be employed to improve the performance of genetic algorithms and, more particularly, make it possible to use granulated representations of fitness functions in cases where they are not well defined.

A recently initiated restructuring of the foundations of fuzzy logic serves to clarify its role in the conception, design and utilization of information/intelligent systems.

The point of departure for the restructuring is the premise that fuzzy logic has many distinct facets – facets which overlap and have unsharp boundaries. Among these facets there are four that stand out in importance. They are: (i) the logical facet, L: (ii) the set-theoretic facet, S; (iii) the relational face, R: and (iv) the epistemic facet, E.

The logical facet of FL, L, is a logical system or, more accurately, a collection of logical systems which includes as special cases both two-valued and multiple-valued systems. As in any logical system, at the core of the logical facet of FL lies a system of rules of inference. In FL, however, the rules of inference play the role of rules which govern propagation of various types of fuzzy constraints. Concomitantly, a proposition, p, is viewed as a fuzzy constraint on an explicitly or implicitly defined variable. The logical facet of FL plays a pivotal role in the applications of FL to knowledge representation and inference from information which is imprecise, incomplete, uncertain or partially true.

The set-theoretic facet of FL, S, is concerned with classes or sets whose boundaries are not sharply defined. The initial development of FL was focused on this facet. Most of the applications of FL in mathematics have been and continue to be related to the set-theoretic facet. Among the examples of such applications are: fuzzy topology, fuzzy groups, fuzzy differential equations and fuzzy arithmetic.

The relational facet of FL, R, is concerned in the main with representation and manipulation of imprecisely defined functions and relations. It is this facet of FL that plays a pivotal role in its applications to system analysis and control. The three basic concepts that lie at the core of this facet of FL are those of a linguistic variable, fuzzy if-then rule and fuzzy graph.
A problem of central importance in R is that of induction of rules from observed data. In many applications of fuzzy logic, this is accomplished through the use of techniques drawn from neurocomputing and evolutionary computing.

The epistemic facet of FL, E, is linked to its logical facet and is centered on the applications of FL to knowledge representation, information systems, fuzzy databases and the theories of possibility and probability. A particularly important application area for the epistemic facet of FL relates to the conception and design of information/intelligent systems. In essence, the epistemic facet is focused on meaning, knowledge and decision.

At the core of FL lie two basic concepts: (a) fuzziness/fuzzification; and (b) granularity/granulation. Fuzziness is a condition which relates to classes (sets) whose boundaries are unsharply defined, while fuzzification refers to replacing a crisp set with a set whose boundaries are fuzzy. For example, the number 5 is fuzzified when it is transformed into approximately 5.

In a similar spirit, granularity relates to clumpiness of structure while granulation refers to partitioning an object into a collection of granules, with a granule being a clump of objects (points) drawn together by indistinguishability, similarity, proximity or functionality. Granulation may be crisp or fuzzy; dense or sparse; and physical or mental.

Modes of information granulation (IG) in which granules are crisp, i.e., have sharply defined boundaries, play important roles in a wide variety of methods, approaches and techniques. Among them are: interval analysis, quantization, chunking, rough set theory, diakoptics, divide and conquer, Dempster-Shafer theory, machine learning from examples, qualitative process theory, decision trees, semantic networks, analog-to-digital conversion, constraint programming, cluster analysis, image segmentation and many others.

Important though it is, crisp IG has a major blind spot. More specifically, it fails to reflect the fact that in much – perhaps most – of human reasoning and concept formation the granules are fuzzy rather than crisp.

For example, the fuzzy granules of a human head are the nose, ears, forehead, hair, cheeks, etc. Each of the fuzzy granules is associated with a set of fuzzy attributes, e.g., in the case of hair, the fuzzy attributes are color, length, texture, etc. In turn, each of the fuzzy attributes is associated with a set of fuzzy values. For example, in the case of the fuzzy attribute Length(hair), the fuzzy values are long, short, not very long, etc. The fuzziness of granules, their attributes and their values is characteristic of the ways in which human concepts are formed, organized and manipulated. In effect, fuzzy information granulation (fuzzy IG) may be viewed as a human way of employing data compression for reasoning and making rational decisions in an environment of imprecision, uncertainty and partial truth.

In fuzzy logic, the machinery of fuzzy information granulation – based on the concepts of a linguistic variable, fuzzy if-then rule and fuzzy graph – has long played a key role in most of its applications. However, what is emerging now is a much more general theory of information granulation which goes considerably beyond its place in fuzzy logic [Zadeh 1997]. This more general theory leads to two linked methodologies – granular computing (GrC) and computing with words (CW), with CW focused on data sets which have the form of propositions expressed in a natural language. What is important about these methodologies is that they make it possible to conceive and design systems which achieve high MIQ by mimicking the remarkable human ability to perform complex tasks without any measurements and any computations. However, although GrC and CW are intended to deal with imprecision, uncertainty and partial truth, both are well-defined theories built on a mathematical foundation. Another point that should be noted is that granular computing, granular logic and computing with words are not co-extensive. More specifically, in CW the initial and terminal data sets are assumed to be propositions expressed in a natural language, and words are interpreted as labels of granules. In granular computing, the granules may be crisp or fuzzy, while granular logic is the logic which underlies granular computing. In this perspective, rough set theory and interval analysis fall within the scope of granular computing but not within that of computing with words.

A new element in the proposed restructuring relates to linking fuzzy logic to the concept of what might be called "the generalization group," or GG, for short. The elements of GG are various modes of generalization of concepts, constructs, methods and theories. In relation to fuzzy logic, the principal modes are: set-to-fuzzy set generalization (fuzzification); fuzzy-set-to-granulated fuzzy set generalization (fuzzy granulation); and function-to-fuzzy relation generalization. Various modes of generalization can be combined through composition. For example, fuzzy granulation may be viewed as the composition of granulation and fuzzification.

The rules of inference in fuzzy logic are interpreted as rules of constraint propagation. The rules are derived by successive application of fuzzification and fuzzy granulation to what is called the "initial construct." More specifically, the initial construct is taken to be the basic argument assignment/function evaluation rule: $X = a$, $Y = f(X)$, $Y = f(a)$, where a is a singleton and f is a crisp function. The generalization group may be interpreted as a language whose terminal symbols are modes of generalization. Inference rules are linked to the initial construct by derivation chains.

Restructuring of fuzzy logic underscores its close relationship with granular computing (GrC) and computing with words (CW). In combination, the methodologies of soft computing, fuzzy logic, granular computing and computing with words are essential to the conception, design and utilization of information/intelligent systems because such systems reflect the pervasiveness of imprecision, uncertainty and partial truth in the world we live in.

References

1. **Medsker LR** (1995) *Hybrid Intelligent Systems*, Boston: Kluwer Academic Publishers
2. **Zadeh LA** (1997) Toward a theory of fuzzy information granulation and its centrality in human reasoning and fuzzy logic. Fuzzy Sets and Systems **90**, 111–127