Some Thoughts about Appealing Directions for the Future of Fuzzy Theory and Technologies along the Path Traced by Lotfi Zadeh

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Extended Abstract

> Alas, it is always dangerous to prophesy, particularly, as the Danish proverb says, about the future.
>
> *Proceedings of the Meeting of the Royal Statistical Society* [1]

The quoted text is an interesting instance of a fuzzy object: it is currently known in slightly diversified forms, each rather different from the quoted one, which corresponds to the first known appearance in English of this adage[1]. Indeed, most of the times we are used to reading or hearing variations of the sentence "it is difficult to make predictions, particularly about the future". The fuzziness here also extends to the source of the aphorism, which over the years has been attributed, among others, to Mark Twain, Niels Bohr, and even Nostradamus. This induces *a fortiori* further uncertainty of about half a century on the time of introduction of this saying. Actually, the first written evidence of what we could call an academic proverb is found in the autobiography of a Danish politician (published in 1948, by the way, in Danish). Summing up, what we have here is a rather definite concept (a humorous, yet effective warning about the assertion of forecasts) exhibiting several forms of imprecision: in its statement, in its authorship and in its temporal origin. Having this warning in mind, the challenging idea of shaping the future of fuzzy logic and fuzzy sets fields one year after Lotfi Zadeh passed away looks like a venturesome and hazardous task. On the one hand, almost any scholar investigating the broad umbrella of soft computing knows the papers originating the rich veins of fuzzy

[1] according to https://quoteinvestigator.com/2013/10/20/no-predict/, where the subject of tracing the various incarnations of this quote is covered in depth.

sets and fuzzy logic [22, 26]; however, the fact of having extended the basic brick of mathematical architecture (namely, the concept of set, along with the immediate application bringing to the definition of *fuzzy numbers* [8]) allowed Zadeh to publish more than forty years ago quite a number of seminal papers concerning the "fuzzification" of several key fields in mathematics and informatics. The following list shows some interesting example of such fields[2], without any pretence of exhaustiveness:

- the notion of *fuzzy languages* [12], introduced as fuzzy sets defined over the universe of strings induced by a finite alphabet;
- the extension of probability theory characterized by expressing the probabilities of events in terms of the above mentioned fuzzy numbers, giving thus rise to *fuzzy probabilities* [25];
- the concept of *fuzzy random variable*, which over the years has been studied under various interpretations, intended for instance as random variables whose specifications are fuzzy random numbers [11], or identified with random fuzzy sets [17];
- the field of *fuzzy control* [24], which has been widely applied in the industrial domains, also in its *neurofuzzy* variant [16] devoted to the integration of neural and fuzzy technologies;
- the reformulation of algorithms to the fuzzy domain [23, 18], for instance through the use of rules based on fuzzy conditional statements.

Since they have been introduced, some of these promising research lines have had less fortune than the widely known ones: for instance, the papers authored by Zadeh and focusing on fuzzy probabilities and on fuzzy random variables have been cited, respectively, two and one order of magnitude fewer times than its paper originating the rich vein of fuzzy sets. Thus for sure there are relatively unexplored fields of the fuzzy universe which are worth studying and whose investigation could even bring to serendipitous research results. This could also help to strengthen the mathematical foundations of fuzzy systems and to establish a tighter connection with other techniques such as deep learning, which recently experienced a tremendous expansion also in terms of industrial applications. Within this thread, big data and security emerge as two critical issues, as briefly explained below.

Big data The amount of data to be processed in modern applications is more and more characterized by inputs not even fitting the hard disk of a computer. The only option in such cases consists in considering distributed storage systems (see [6, 19] for two of the mainly used technologies). Moreover, in several interesting situations data is organized in *streams* requiring each item to be either processed on the fly, or forgotten forever. Although some efforts to adapt mainstream fuzzy procedures to such a massive scale already exist in the literature

[2] it is also worth mentioning the contribution of Zadeh in the rise of other specific frameworks dealing with uncertainty, such as those of possibility theory [9] and granular computing [3–5].

(see for instance [14] for an extension of the fuzzy C-means algorithm exploiting the map-reduce distributed computational framework [7]), a lot of work still needs to be done; this process will inevitably bring to new views of the fuzzy world when the available techniques are inherently difficult to scale up with the dimension of processed data (such as when standard optimization techniques are involved, as in [15]). Moreover, several approaches and algorithms born expressly to deal with big data problems might represent interesting grounds for fuzzy techniques as well (just to state an example, [13] and [20] deal with a fuzzy declination of the collaborative filtering procedure at the basis of several modern recommendation systems).

Security The transition from research domain to industrial and real-world applications brings up the need of ensuring robustness of the proposed methods against unauthorized access. Again, other soft computing realms might inspire new categories of malicious attacks, as well as suggest defensive techniques. An example is constituted by the attacks expressly designed in order to fool deep neural networks on the basis of adversarial examples [10, 21]. Analogously, the maturity of fuzzy systems for the business market requires the design and development of specific digital rights management techniques against the unauthorized use of illegal copies of a sold fuzzy artifact; here, once again, the neural networks world might suggest interesting candidate solutions, for instance referring to watermarking techniques [2]. More generally, the security field is highly unexplored as far as fuzzy techniques are concerned.

Summing up, Lotfi Zadeh has unveiled a world which for sure is far from being fully explored and understood. Instead, his work laid the foundations for a thorough management of uncertainty in several fields of mathematics and informatics yet to be completed in its theoretical form.

Moreover, it is worth pointing out that one of the key factors which led to the success of the vast umbrella of fuzzy technologies is related to their early implementation in industrial and electronic devices. In order to keep the pace up in this domain, a big challenge is envisaged in terms of applications, with specific reference to big data and stream processing, as well as of providing a secured access to artifacts based on fuzzy technologies.

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