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Konstantina Chrysafiadi

Fuzzy Logic-Based Software Systems

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Series Editors' Foreword

Fuzzy Logic is one of the most popular and most widely applied mathematical theories. Indeed, it was first proposed over a century ago by Łukasiewicz and Tarski [1, 2] who presented it as infinite-valued logic and called it "Multivalued Logic." The term "fuzzy" was much later introduced by the late Professor Lotfi A. Zadeh of the University of California at Berkeley in his seminal 1965 paper [3]. Since then, Fuzzy Logic has been an area of basic research and occasional controversy, but, above all, broad and particularly successful applications.

The popularity of Fuzzy Logic stems from its ability to successfully model imprecision, vagueness and uncertainty that are present in essentially all scientific and technological regimes. This characteristic feature of Fuzzy Logic resembles human representation of subjective knowledge, mimics human reasoning processes, and provides a very powerful tool to "compute" with linguistic terms.

Despite its long history, Fuzzy Logic remains an area of very active research worldwide and new applications keep on continuously emerging. Indeed, **Artificial Intelligence-empowered Software Systems** are constantly being developed and Fuzzy Logic is quite often their underlying empowering technology. As series editors of the *LEARNING AND ANALYTICS IN INTELLIGENT SYSTEMS SERIES* of Springer and to verse the scientific community in the most recent relevant developments, we are particularly happy to present the monograph at hand, by Dr. Konstantina Chrysafiadi, which is devoted to **Fuzzy Logic-based Software Systems**.

More specifically, Dr. Chrysafiadi first presents the general structure of Fuzzy Logic-based Software Systems, which consists of three basic modules, namely: (i) the Fuzzifier, (ii) the Inference Engine and (iii) the Defuzzifier. In these software systems, the Fuzzifier converts crisp numerical data into fuzzy sets. In turn, the Inference Engine produces fuzzy outputs via use of linguistic information and application of fuzzy rules over the fuzzy sets returned by the Fuzzifier. Finally, the Defuzzifier, converts the fuzzy values returned by the Inference Engine into crisp values at the system output.

Next, Dr. Chrysafiadi discusses the significant role Fuzzy Logic can play in Artificial Intelligence-empowered Software Systems, improving their efficiency and effectiveness. In this context, she presents methodologies of Artificial Intelligence which are combined with Fuzzy Logic. Finally, the book also outlines several Fuzzy Logic-based Software Systems in various disciplines, including Medicine, Education, Decision Making and Recommendation, Natural Language Processing, Automotive Engineering and Industry, Heating, Ventilation and Air-conditioning, Navigation, Scheduling, Network Traffic Management and Security.

This monograph fills in a gap in the available literature, as it verses its readers in streamline aspects and applications of Fuzzy Logic-based Software Systems. Overall, the book is very well written. It starts from introductory ideas and concepts and leads its readers to the most recent and most advanced research results in this area. Thus, the book is a valuable guide for the expert in the field of Fuzzy Logic who wishes to embed Fuzzy Logic components in Software Systems. At the same time, the book also appeals to the newcomer who wishes to learn about Fuzzy Logic and its ability to empower Software Systems. Finally, the book will certainly attract the interest of readers from other areas as well who wish to get versed in this significant scientific discipline.

As series editors, we welcome this monograph to the *LEARNING AND ANALYTICS IN INTELLIGENT SYSTEMS SERIES* of Springer and present it to the research communities worldwide. We congratulate the author for her great work, in confidence that her monograph will help its readers not only understand, but also apply the proposed Fuzzy Logic-based methodologies in various Software Systems in many and diverse scientific areas. Finally, we encourage the author to continue her research work in this important area and keep the scientific communities appropriately updated of her research results.

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Preface

Humans several times in their everyday lives deal with situations in which data is vague, subjective and uncertain. Such data can be the security of a system, the performance of a machine, the productivity of an employee, the speed of a car, the knowledge level of a student, etc. In many circumstances, there are problems whose answer is not 'Yes' or 'No', but it can be an intermediate value, which indicates that it is partially true or false. It can be 'possibly yes', 'maybe', 'possible no', 'little', 'very much', 'less', etc. For example, in the question "is the water hot?", the answer can be 'no', or 'very little' or 'little', or 'quite' or 'very much', or 'yes'. Furthermore, there are phenomena and data that cannot be defined with certainty and accuracy. For example, a student can be 'novice', 'moderate', good', 'very good' or 'expert', concerning her/his knowledge level; the way that a vehicle moves concerning its velocity can be characterized as 'very slow' or 'slow' or 'normal' or 'fast' or 'very fast'; a person can be characterized as 'baby' or 'child' or 'young' or 'middle-aged' or 'old' according to her/his age. Therefore, Binary Logic, according to which a variable or data takes two values, the absolute true (1) and the absolute false (0), cannot be used to describe data that confront with vagueness, uncertainty and subjectivity. Such data can be described with fuzzy logic, according to which a variable or data takes all the intermediate values between 0 and 1 representing a variety of strengths of true. The main differences between Binary Logic (or Crisp Logic) and Fuzzy Logic are depicted in Table 1.

Fuzzy logic has been studied by Lukasiewicz and Tarski as infinite valued logic since 1920 [1]. However, Lotfi A. Zadeh of the University of California at Berkeley

Table 1 The main differences between Binary and Fuzzy Logic

Characteristic	Binary Logic	Fuzzy Logic
Values	0 or 1	Any value from 0 up to 1
Sets' limits	Distinct	Indistinct
Belonging degree	Absolute yes or absolute no	Absolute or partially yes or no
Mathematicalization	Boolean algebra	Fuzzy math, sets and computing with words

is considered the 'father' of fuzzy logic. He introduced the idea of fuzzy logic in 1965 as a methodology for computing with words [2]. He noticed that there are data which cannot be valued as 0 or 1 to be stored and managed by computers. Therefore, he proposed using fuzzy sets and membership functions [3], which assigned to data values which vary from 0 to 1. In such a way, he succeeded in introducing a reasoning method that imitates the human way of thinking and decision making. So, he proposed new issues, theories and operations for the calculus of logic, in order to manage effectively the data that are characterized by uncertainty, imprecision and vagueness. He proved that fuzzy logic is a generalization of the binary (Boolean) logic. As he notes in his study [2] on page 339 "the notion of a fuzzy set provides a convenient point of departure for the construction of a conceptual framework which parallels in many respects the framework used in the case of ordinary sets, but is more general than the latter and, potentially, may prove to have a much wider scope of applicability, particularly in the fields of pattern classification and information processing. Essentially, such a framework provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria of class membership rather than the presence of random variables."

The first reactions of the scientific community towards fuzzy logic were negative. Scientists believed that 'vagueness' was contrary to the basic scientific principles. Furthermore, they supported that the theory of probabilities was able to solve adequately any problem that fuzzy logic can deal with. However, later the scientific community understood the importance, novelty and contribution of fuzzy logic. Therefore, the first published work of Lotfi Zadeh on fuzzy sets [2] had 63,612 citations up to 4 August 2023, according to the Scopus scientific peer-reviewed published studies database. Since then, fuzzy logic has been studied by several researchers and used in control systems and complex systems that have to take a decision and give an output based on vague and inaccurate data. For complex systems, Zadeh stated that "as the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics" [4]. As a consequence, the term "Fuzzy Inference System" was derived. A Fuzzy Inference System is any system that uses fuzzy logic and rules to reason and/or take a decision. It consists of four modules (Fig 1): (i) fuzzification: it converts input data into fuzzy sets; (ii) fuzzy rules base: a set of IF-THEN rules with linguistic variables and values; (iii) the inference engine: it decides which rules to activate for the input values, and then, execute and combine them to 'calculate' the result; (iv) defuzzification: it converts the fuzzy value of the result into a crisp value.

The term "Fuzzy Inference System" includes Fuzzy Logic-based software systems, which concern any automated program, process or application that uses Fuzzy Logic to perform reasoning and/or decision making. Fuzzy logic-based software systems are used in medicine, education, natural language processing, automotive engineering, business processes, consumer electronics (like air-conditioning, dishwashers and heating), decision making and recommendation, control systems, etc. For example, in an automotive system, fuzzy logic is used for speed and traffic control; in dishwashers, fuzzy logic is used to determine the washing strategy and

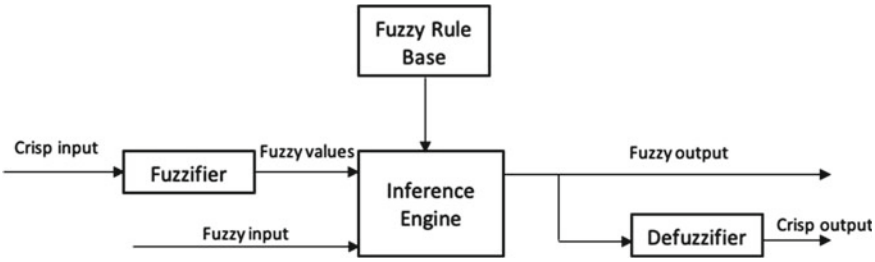

Fig. 1 The architecture of a Fuzzy Inference System

Table 2 Statistics concerning published studies on fuzzy logic

Keyword	Published research document results	Period
Fuzzy logic	102,262	From 1953 up to August 2023
	25,969	Last 5 years-from 2019 to August 2023
Fuzzy inference system	21,141	From 1989 up to August 2023
	7,908	Last 5 years-from 2019 to August 2023
Fuzzy systems	61,693	From 1969 up to August 2023
	13,543	Last 5 years-from 2019 to August 2023

the power needed, according to which the dishes load and the food scraps on them; in medicine, fuzzy logic is used for automatic and computer-aided diagnoses; in natural language processing, fuzzy logic is used to determine semantic relations between words.

In recent years, the increased interest in Artificial Intelligence has led researchers to work actively with fuzzy logic. According to the Scopus scientific peer-reviewed published studies database, there is an increased scientific interest in Fuzzy Logic (Table 2). 26.70% of the total published research manuscripts concerning Fuzzy Logic have been published in the last 5 years. Similarly, 39.43% of the overall published scientific research papers, which concerns Fuzzy Inference Systems, have been published in the last five years. The corresponding percentage for the published research studies on fuzzy systems is 25.21%. The reasons for the increased interest in fuzzy logic and systems are the following.

1. Fuzzy logic manages effectively vague and imprecise data.
2. The mathematics of fuzzy logic is simple.
3. Fuzzy logic and rules are understandable.

4. Fuzzy logic is flexible.
5. Fuzzy logic imitates the human way of thinking and reasoning.
6. Fuzzy logic can be combined with other AI techniques.

The main body of this work is organized into the following five chapters. In Chap. 1, an introduction to fuzzy logic, fuzzy sets, fuzzy operators, membership functions, fuzzy rules and fuzzy inference systems is presented. In Chap. 2, the role of fuzzy logic in artificial intelligence and its use in smart applications are described. In Chap. 3, several fuzzy logic-based software systems in the discipline of medicine, education, decision making and recommendation, natural language processing, automotive engineering and industry, heating, ventilation and air-conditioning, navigation, scheduling, network traffic and security are presented. In Chap. 4, a comparative discussion about the use of fuzzy logic in smart applications and systems of a variety of fields is presented. Finally, in Chap. 5, conclusions are drawn and discussed.

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Contents

Abbreviations

AHRS	Attitude-Heading Reference System
AI	Artificial Intelligence
ANFIS	Adaptive Neuro Fuzzy Inference System
CPU	Central Processing Unit
CT	Computed Tomography
FAHP	Fuzzy Analytic Hierarchy Process
FCE	Fuzzy Comprehensive Evaluation
FCM	Fuzzy Cognitive Map
FIS	Fuzzy Inference System
FSVM	Fuzzy Support Vector
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HFLTS	Hesitant Fuzzy Linguistic Term Set
HVAC	Heating, Ventilation and Air Conditioning
INS	Inertial Navigation System
IPFCM	Intuitionist Possibilistic Fuzzy Clustering
IT2FLS	Interval Type-II Fuzzy Logic System
LLSM	Logarithmic Least Square Method
MANET	Mobile Adhoc NETwork
MCDM	Multi-Criteria Decision-Making Method
MRA	Magnetic Resonance Angiography
MRI	Magnetic Resonance Image
NLP	Natural Language Processing
QoS	Quality of Service
RFID	Radio Frequency Identification
SINS	Strap-Down Inertial Navigation System
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
URL	Uniform Resource Locator

USBL	Ultra-Short Baseline
VANET	Vehicular Ad hoc NETwork
6LoWPAN	IPv6 over Low-power Wireless Personal Area Networks

Chapter 1
Fuzzy Logic

Abstract Fuzzy logic was introduced by Lotfi A. Zadeh in 1965 as a methodology for computing with words and since then it is used extensively. It is a generalization of the Binary (Boolean) logic, which can manage effectively data that deal with uncertainty, vagueness and subjectivity. In this chapter basic concepts of fuzzy logic, fuzzy sets and membership functions are presented. Also, the structure and operation of a Fuzzy Inference System (FIS) and the different types of FIS are described.

1.1 Introduction

Fuzzy logic is a generalization of the Binary (Boolean) logic, which can manage effectively data that deal with uncertainty, vagueness and subjectivity. It was introduced by Lotfi A. Zadeh in 1965 as a methodology for computing with words [1]. According to fuzzy logic an element can belong to a set in a degree between 0 (not at all) and 1 (absolutely). When, according to the Binary (Boolean) logic, an element can belong absolutely to a set or does not belong to the set. There are no intermediate states. This difference is illustrated in Fig. 1.1.

In other words, a logical sentence can be true or false according to the Binary (Boolean) logic. For example, "the dolphin is a mammal" is true, 'the dog flies" is false, "2 + 3 = 5" is true, "3 * 8 = 10" is false. However, according to Fuzzy Logic a logical sentence can be true in a degree of truth. For example, "a man 15 years old is young" is 100% true (truth value = 1), "when the temperature is 26 °C, then it is warm" is 70% true (truth value = 0.7), "when the car's speed is 65 km/h, then it goes fast" is 50% true (truth value = 0.5), "the sky is green" is 0% true" (truth value = 0). Fuzzy logic uses linguistic values to describe data, situations and conditions.

1.1.1 Fuzzy Sets and Basic Concepts

A fuzzy set is a set of objects, each one of which were characterized by a function that associates to each object a real number in the interval [0, 1], which indicates the degree

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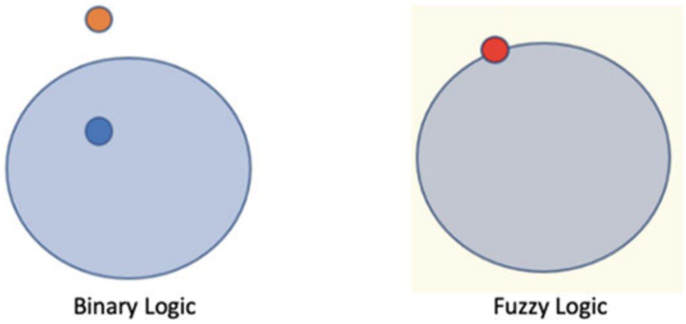

Fig. 1.1 Binary logic versus fuzzy logic

in which the object belongs to the set. This function is called "membership function" and its value is called "membership value" or "membership degree". Therefore, fuzzy set A is called a set of ordered pairs (x, μ_A(x)), where x Î X (a space of objects) and μ_A(x) Î [0,1]. μ_A is the membership function of A and μ_A(x) is the membership value of x to A. If μ_A(x) equals to 0, then it means that x does not belong to A. While, if μ_A(x) equals to 1, then it means that x belongs fully to A. If $0 < \mu_A(x) < 1$, then it means that x belongs partially to A. Some examples of fuzzy sets are the following:

- Warm = {(5, 0), (10, 0), (15, 0.25), (20, 0.5), (25, 0.75), (30, 1)}
- Young-aged = {(1,0), (5, 0.21), (10, 0.47), (15, 0.74), (20, 1), (25, 1), (30, 0.8), (35, 0.6), (40, 0.4), (45, 0.2), (50, 0)}
- Good_Knowledge_level = {(0,0), (20, 0), (50, 0), (60, 0), (65, 0.25), (70, 0.5), (75, 0.75), (80, 1), (85, 0.5), (90, 0), (100, 0)}
- Fast = {(0, 0), (20, 0), (40, 0), (60, 0.25), (80, 0.5), (100, 0.75), (120, 1), (140, 1), (160, 1), (180, 1)}.

In Fig. 1.2 the graphical representation of the above fuzzy sets is depicted.

A membership function calculates the membership degree of each fuzzy set's object to the fuzzy set. As input, it takes all the possible values of the set's members and as output it gives a value between 0 and 1. In its graphical representation, the horizontal axis (axis X) concerns the possible members of the set and the vertical axis (axis Y) has values from 0 to 1. The most common used types of membership functions are the following:

- Triangular membership function

This is one of the most common used membership functions in fuzzy systems. It is called triangular because in the graphical representation, it designs a triangle. It is defined by three parameters a, b and c. a is the first object (with lower value) that belongs to the fuzzy set, b is the object whose membership value is 1 (the value that corresponds to the top of the designed triangle), and c is the last object (with higher value) that belongs to the fuzzy set (Fig. 1.3). A triangular membership function is

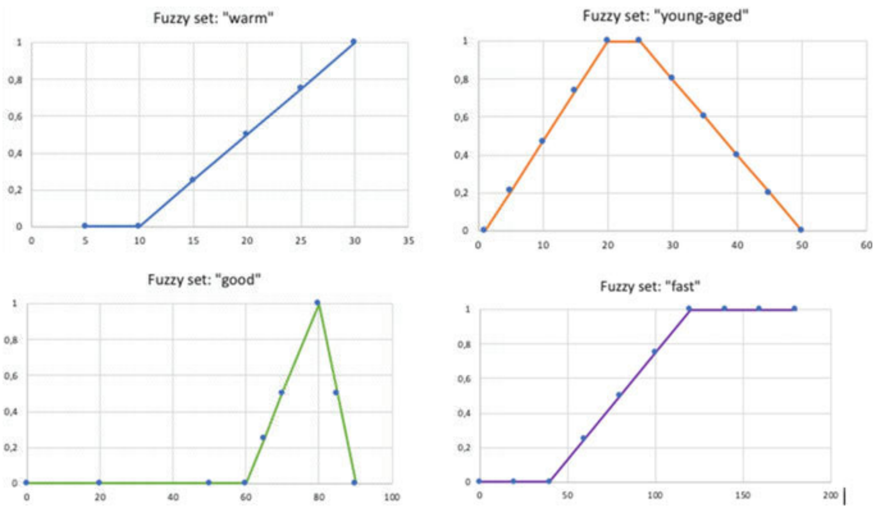

Fig. 1.2 Examples of fuzzy sets

defined as follows:

$$\mu_{\mathrm{A}}(x) = \begin{cases} 0, if\ x \leq a\ or\ x \geq c \\ \frac{x-a}{b-a}, if\ a \leq x \leq b \\ \frac{c-x}{c-b}, if\ b \leq x \leq c \end{cases}$$

An example of triangular fuzzy sets is the phases of a 24 h day. We define the following fuzzy sets: {morning, noon, afternoon, evening, midnight}. The set of input values is [0, 24]. The membership functions of the above fuzzy sets and their graphical representation are depicted in Figs. 1.4 and 1.5.

- Trapezoidal membership function

This is another most common used membership functions in fuzzy systems. It is called trapezoidal because in the graphical representation, it designs a trapezoid. It is defined by four parameters a, b, c and d. a is the first object (with lower value—the

Fig. 1.3 Triangular membership function