Correspondence

Forty-five years of fuzzy sets and fuzzy logic—A tribute to Professor Lotfi A. Zadeh (the father of fuzzy logic)

1. Fuzzy sets and fuzzy logic: an introduction

Mathematics is the mother of all sciences. Over the centuries, mathematicians and scientists have introduced many new notions and have developed some novel theories; some of these theories finding applications in our everyday life. The theory of fuzzy sets and fuzzy logic is one of such mathematical theory.

Fuzzy logic is a new mathematical tool introduced in 1965, forty-five years ago, by Lotfi A. Zadeh (University of California, Berkeley) when he published his first celebrated paper opening the new field of Fuzzy Sets & Fuzzy Logic. In this paper, he introduced a novel type of information and uncertainty that arises from human thinking, reasoning and cognition, and thereby the information associated in our human language. Through this paper, he provided a mathematical formulation of the qualitative type of uncertainty; something which is inherent in our everyday decision making processes, and thus laid the new foundation of the theory of fuzzy sets. He showed the path which leads to some beautiful gardens full of immortal and ever increasing fragrance. Though we learned the basic notion of cognition and perception in our schools, we were very ignorant regarding this type of cognitive uncertainty and its pervasiveness surrounding our environment. Indeed, to some extent, this type of uncertainty and information was disdained by scientists and mathematicians in the past.

Now, the notion of ‘fuzzy-ism’ has just entered the fifth decade of its existence, and is spreading in research institutions, industries and the applied world. Also its doctrines are having a profound impact on the development of theories in decision-making in various applied fields. For example, fuzzy set theory has been applied to the solution of a wide range of practical problems, such as fuzzy logic controllers for industrial processes, fuzzy logic in medical decision making, and more recently, fuzzy logic in a court of law, just to name a few. In many applications, a conventional quantitative type of mathematics has been replaced by, or united with, fuzzy (qualitative) mathematics. At the same time, researchers have introduced several new mathematical concepts in fuzzy theory; for example, the notion of Soft-Computing (SC), and Computing With Words (CW or CWW), which have been applied to a wide variety of humanistic types of processes.

The theories of deterministic systems and stochastic processes have been an integral part of my graduate studies, teaching and research. In fact, I was, and still am a member of the school of determinism and stochasticism. It was in the summer of 1968 that I first had the privilege of listening to Professor Lotfi A. Zadeh, exponent, founder and father of ‘Fuzzy-ism’, at a Symposium on Adaptivity and Sensitivity held under the auspices of the International Federation of Automatic Control (IFAC) in Dubrovnik, Yugoslavia.

His lucid exposition on Fuzzy Set Theory, the theory which deals with information and uncertainty arising from human thinking, reasoning, cognition and perception, and thereby of human language, aroused my interest in this new class of mathematics dealing with qualitative information arising from humanistic types of processes. Since then, I have also become a student of the School of Fuzzy-ism.

Since then, during my studies, I soon realized that the ‘lack of uncertainty’ or the excess of ‘precision and certainty’ in our engineering design, decision and control problems are providing us with unrealizable solutions. Certainty (precision) has become an absolute standard in both our teaching and research, and far too often it is introduced into our scientific work; also without thought or feeling. This is an attribute which does not exist in our cognition, perception, reasoning and thinking. A baby of one week starts recognizing his mother by smiling at her, but the cognition, perception and recognition of his mother and his environment do not take place in a precise sense. The same imprecision or uncertainty plays an important role in his thinking, reasoning and decision making throughout his life.

In our scientific decision and control studies, we have realized that the notion of ‘precision’ is rapidly leading us towards unrealizable goals, but we are still continuing to move along that path. Of course, we know that any ‘precise’ design will be doomed to failure. Under the shroud of ‘precision’ we have become impotent, and thus have to some extent, lost scientific creativity.
In December, 1980 at the International Congress on Applied Systems Research and Cybernetics Acapulco, Mexico, I have had the privilege of being one of the presenters. I was the first president of NAFIPS and had the privilege of having Dr. King Sun Fu, professor at the Purdue University, West Lafayette, Indiana, as the first president and I served as the NAFIPS secretary. Again, Lotfi played a major role in the establishment of this flourishing NAFIPS.

2. Two classes of uncertainty

One can classify uncertainties into various classes, but for the purpose of our discussion here, we classify these uncertainties mainly into two broad categories: the statistical type and the cognitive type.

The statistical type of uncertainty deals with information or phenomena that arise from the random behaviour of physical systems. The pervasiveness of this type of uncertainty can be witnessed in the random vibrations of a machine, the randomness of a message, random fluctuations of electrons in a magnetic field, diffusion of gases in a thermal field, random electrical activities of cardiac muscles, uncertain fluctuations in weather patterns and turbulent blood flow through a damaged cardiac valve. This type of uncertainty has been studied for centuries, and we have a very rich statistical theory to have a mathematical characterization of such random phenomena. The calculus of mean and variance is very rich in this respect and is being used very widely. Thus the statistical theory of uncertainty provides some quantitative measure (precision) to randomness in physical systems, and this type of theory has been used very widely in the design of systems and for generating algorithms for decision making processes.

The cognitive type of uncertainty, unlike the statistical type of uncertainty, is the uncertainty that arises from our human thinking, reasoning, cognition and perception processes and thereby is associated with our human language and thus is inherently very subjective in nature. This type of cognitive or subjective uncertainty has either been neglected or taken very lightly. The cognition and perception of the physical environment through our natural sensors (vision, hearing, smell, touch and taste) and the perception of pain and other similar biological events through our nervous system and neural networks deserve special attention. The ‘perception phenomena’ associated with our natural sensors are very subjective, in the sense that expressions of these phenomena through our human language are time, space and circumstance dependent. Thus these types of process are full of ‘uncertainties’ and cannot be characterized by conventional statistical theory. We can feel pain: “my back is very painful”, but this pain can neither be measured nor characterized using the statistical theory. Similarly, we express our perception linguistically, ‘this red flower is just beautiful and is full of pleasing fragrance’. This corresponds to the ‘perception’ of the beauty of the flower through our sensors (vision and smell in this case), where ‘red’ and ‘beautiful’ describe the visual perception in a fuzzy way, whereas ‘pleasing fragrance’ is the expression for the perception of smell. Again, we cannot characterize these linguistic expressions of our perceptions, using the strength of quantitative mathematics or statistical theory.

In this context, let us consider another example. For a three-year-old child, ‘A’, a book weighing about two kilograms is very heavy to carry, even for a short distance, but the same book for a ten-year-old, ‘B’, again for a short distance, is not very heavy. But this book becomes too heavy for ‘B’ to carry for a longer distance, say about a kilometer.

Let us consider one more example in which we illustrate that the characterization of uncertainty is time dependent. Consider an example of weather in Saskatoon; most familiar to us. In the month of January, a temperature of 5 °C in Saskatoon is characterized as very warm, but this 5 °C is classified as cold in the month of June. Also for someone from a tropical climate, say India, this temperature gives the feeling of very cold in the month of June. Thus we can say that most of the perception based ‘feelings’ do not have any quantitative value in the absolute sense. The expressions of these feelings are very subjective and time and space dependent.

Cognitive uncertainty and its cognate, cognitive information, involve activities of neural networks. To non-scientists, it may seem strange that such familiar ‘notions’ have recently become the focus of intense research. But it is the ‘ignorance’ of these subjective notions and their possible technological applications in man-made intelligent systems, and not ‘familiarity’ with them, which has forced scientists to conduct intensive research in this field.

The development of the human cognitive process and the perception of his environment start taking shape with the development of imaginative power in a baby’s brain. A baby in the cradle can recognize a human face long before it is conscious of any visual physical attributes of a human or its environment.

In spite of the richness of conventional mathematical methods, they are very often thought to be dry and cold. One reason lies in their inability to describe the beauty of snow capped mountains, blue lakes, the rising sun, the full moon, or the richness of the fragrance of a spring flower or the melody of a sitar. No doubt, one can estimate the volume of snow or the height of a mountain or the frequencies of vibrating musical strings, but the conventional mathematical methods cannot be used to convey, logically, the subjective feelings and emotions associated with our perception.

The study of such formless uncertainties provides us with a scientific challenge. Scientists have now started to think of giving morphology to this amorphous uncertainty. In the past, mathematicians disdained this challenge and increasingly chose to flee from natural mention by devising theories unrelated to human perception, cognition, feelings and emotions.

No one saw the beauty of Fuzzy Sets before Professor Lotfi Zadeh, and it was he who showed the perspective of consolidating this beauty into an organized field, with rich theories and promising applications.

3. The principle of incompatibility

The stimulus for advances in fuzzy set theory may be summarized by a principle that Zadeh calls the ‘principle of incompatibility’, which may be stated as follows:

‘The closer one looks at a ‘real world’ problem, the fuzzier becomes its solution. Stated informally, the essence of this principle is that as the complexity of a system increases, our ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached, beyond which precision and significance (or relevance) become almost mutually exclusive characteristics.’

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Advances in science and technology have made our modern society very complex. Thus, our decision processes have become increasingly fuzzy and it has become difficult to analyze them. The human brain and its cognitive facility possess some special characteristics that enable it to learn and reason in a vague and fuzzy environment. It has the ability to arrive at decisions based on imprecise and qualitative data, in contrast to formal mathematics and formal Boolean (binary) logic, which demand precise and quantitative data. Modern computers possess high capacity but they lack human ability. Undoubtedly, in many areas of cognition, human intelligence far exceeds the computer 'intelligence' of today, and the development of fuzzy concepts is indeed a step forward toward the development of tools capable of handling humanistic types of problem.

We do have sufficient mathematical tools and computer-based techniques for analyzing and solving problems embodied in deterministic and uncertain (probabilistic) environments. Here, uncertainty may arise from the probabilistic behaviour of certain physical phenomena in mechanistic types of system. (Mechanistic types of system are those which, in the main, are governed by the laws of mechanics, electromagnetism, and thermodynamics.) We know the important role that uncertainty associated with vagueness arising from our cognition plays in a human decision-making process, but we did not know until 1965 how the vagueness arising from human subjectivity (which is inherent in our thought processes) can be modeled mathematically or analyzed.

In 1965, Professor Zadeh laid the foundation of 'fuzzy-ism' by introducing what he called 'fuzzy sets'. In fact, fuzzy set theory is a body of concepts and techniques that lay a form of mathematical precision to human thought processes, which in many ways are imprecise, vague and ambiguous by the standards of classical mathematics. Today, these fuzzy concepts are gaining a growing acceptability among engineers, scientists, mathematicians, linguists, lawyers and philosophers.

Professor Zadeh coined the term fuzzy sets. Fuzzy sets deal with sets of objects or phenomena that are vague and do not have sharp boundaries. The calculus of fuzzy sets is a very promising tool for dealing with cognitive uncertainty. Indeed, applications of these fuzzy sets, which once were thought to be dull and dry, can be found in much scientific and scholarly work. It is true that Boole introduced the beautiful notion of binary sets that are so pervasive in our digital world, but this beauty is naked and without any adornment. Boolean logic is unable to model the human cognition and thinking process. This is the very reason that no-one today is indifferent to the logic of fuzzy sets. In fact, many view their first encounter with fuzzy logic as a totally new and exciting experience in their scientific life.

From a purely mathematical viewpoint, the evolution of the theory is very exciting but complex. Many scientific theories start by borrowing notions from already developed areas of mathematics but in this case, Professor Zadeh introduced the basic notion of 'vagueness' having no sharp morphology, but which is so common in our human thought processes.

Indeed, Professor Zadeh laid the foundation of fuzzy mathematics on a very robust rock. It now serves the needs of many existing scientific disciplines, but equally important is that many new disciplines, such as the study of fuzzy neural networks, have begun arising from these fuzzy mathematics. Thus this type of mathematics has united several, both old and new, noble, narrow streams of scientific discipline into one, while at the same time instilling life into several other streams that have been dormant during the past.

Since 1965, when the notion of fuzzy mathematics was first introduced, many studies have been undertaken on this topic. These studies have brought many intellectual and scientific revelations. Presently, researchers are engaged in several scientific studies using fuzzy logic. Some of the striking applications of fuzzy set theory are found in the area of feedback control (fuzzy logic controller for cement kiln processes, and control of subway trains, etc.), knowledge-based systems, operations research, management sciences and fuzzy logic in a court of law. New fuzzy logic hardware and software have been developed, which promise to have many applications to building intelligent robots and knowledge-based systems for industrial applications. Fuzzy neural networks are an exciting area of research, which again promises to put some intelligence into industrial control problems and robotic systems. The newly developing technology of optoelectronics and molecular electronics computing will make it possible to expand the use of fuzzy set theory in the development of new applications, both private and industrial.

Over the last forty-five years, since the notion of fuzzy logic was first introduced in 1965, the father of fuzzy logic, our friend and mentor, Lotfi A. Zadeh, has witnessed many innovative theoretical fuzzy tools along with many of its applications, in the field of control systems, robotic systems, medical diagnoses and courts of law. Also from infancy to adulthood of the field, there has been a steady exponential growth in the number of research journals, paper publications and books, both authored and edited. In 1973, I was invited to hold a workshop on this newly developing field of fuzzy logic at the IFAC Symposium on Systems Sensitivity and Adaptivity held at The Hague, the Netherlands, and then in 1975, at the IFAC Congress held at MIT, Boston, USA. There was a time when the Institute of Electrical and Electronics Engineers (IEEE) refused to publish any papers containing the word 'fuzzy', but about two and a half decades ago, the same institute established a new journal entitled; IEEE Transactions on Fuzzy Sets and Systems. Also, in 1978, I was invited by the then Chairman, Professor King-Sun Fu, of the IEEE Control and Decision Conference, to hold a special symposium on fuzzy sets and systems in New Orleans. Now in the year 2010, the field of fuzzy logic is in its adulthood, and indeed we are pleased to see its growth with the introduction of many innovative theoretical notions and applications.

Now we can see that the innovative mathematical tool of fuzzy mathematics has become an integral part of our research. Over the last forty-five years, this new mathematical logic, unlike Boolean (binary) logic, has revolutionized logical thinking and computing methods for the analysis and management of cognitive uncertainty. More recently, these logical tools have been used to introduce virtual intelligence into household appliances, entertainment tools, automobiles, trains, and aircraft and space industries. This fuzzy mathematics has been extensively explored for the development of a new class of expert systems for their potential applications to fields, such as medical diagnosis, control of complex processes, manufacturing, art, architecture, music composition, mining, space exploration, commerce, management science, stock market evaluation and fuzzy logic in a court of law. In general, fuzzy mathematics has proven to be very useful in the creation of a new class of intelligence: virtual intelligence for solving problems where human intelligence is intimately needed.

4. Fuzzy logic and neural networks at the intelligent systems research laboratory, University of Saskatchewan

I was, and still am, a member of the school of 'determinism' and 'stochasticism'. The new notion of fuzzy-ism was introduced
to me in the very early stages of its inception. It was in the summer of 1968 that I had an opportunity to listen to Professor Zadeh, the father of ‘Fuzzy-ism’, at the IFAC Symposium on Adaptivity and Sensitivity held at Dubrovnik, Yugoslavia (former). There I heard Zadeh’s lucid exposition of his fuzzy notions, and was very much impressed by his break with traditional modes of thinking. These fuzzy concepts were just three years old at that time, and it was very difficult to assign any certainty to the growth and acceptability of ‘fuzzy mathematics’ in mathematical and technological circles.

In 1968, to me, fuzzy logic was just a mathematical curiosity. This curiosity led me to explore the field at much greater depths. Now, over the last four and a half decades I have witnessed various phases in its development, from heavy criticism by notable scientists and mathematicians to the emergence of successful industrial applications. Dr. Zadeh introduced us to the notion of graded membership, the notion that is so pervasive in human cognitive processes. This logic which captures the vagueness of our thought processes has revolutionized the field of logic by introducing many new soft mathematical tools. Oriental philosophy is very ambiguous (imprecise, vague) and for this reason, countries, such as India, China, Korea and Japan, have had no problem in understanding and employing the mathematical notion of graded membership. Japan was the first country to introduce virtual intelligence in inanimate systems, such as cameras, washing machines, vacuum cleaners, trains, cars and industrial control processes. After great scepticism for over two decades, only recently, organizations and companies, such as NASA, General Motors, General Electric, Motorola, DuPont and Kodak, have shown that fuzzy technology will introduce multi-billion dollar opportunities in North America alone. However, the question remains: Will North Americans be able to compete in the field of virtual intelligence in inanimate systems, the cutting edge of new technology?

I continued having a casual interest in the field by occasionally reading the literature, but without much excitement. It was in 1972 that I came across some very interesting and convincing papers which reawakened my interest in the field.

I was invited to organize a special Round-Table Discussion session on ‘Estimation and Control in a Fuzzy Environment’ at the Third IFAC Symposium on Identification and Parameter Estimation held at The Hague in June 1973. Panel members of international repute were invited to present their views on this newly developing subject of fuzzy uncertainty followed by a long discussion. Although most of the work presented there was theoretical in nature, the discussion helped to remove some misconceptions, and opened challenging opportunities for further theoretical developments and applied research in the field. This discussion inspired the interest of many more researchers including me. In particular, it was found that there was a great deal of interest in Japan, and that Japanese researchers were significantly contributing both theory and applications to this newly developing field.

Following this, a very successful US/Japan seminar on ‘Fuzzy Set Theory’ was held at the University of California, Berkeley, in July 1974. The seminar was marked by many interesting applications of fuzzy set theory to cognitive and decision processes. The important papers have appeared in a volume edited by Zadeh, Fu, Tanaka and Shimura.

Following the success of the discussion session at The Hague, I was invited to organize and chair the Second IFAC Round-Table Discussion session on ‘Fuzzy Automata and Decision Processes’ held at MIT during the Sixth Triennial World IFAC Congress, Boston/Cambridge, August 24–30, 1975. A panel of researchers from various international institutions were invited to present their work. The presentation had an integrated and balanced mixture of theory and applications. A detailed report appears in the IFAC proceedings, as well as in Automatica.

Fuzzy logic and neural networks, until a few years ago, were two distinct disciplines, but over the last decade or so, they have made tremendous progress in parallel, and now they are on the verge of converging onto a new field: neural-fuzzy systems. This synergy has the potential of producing robust sensors and systems embedded with virtual intelligence. The innovative fields of neural-fuzzy systems, fuzzy chaos, and genetic algorithms have the capability of capturing certain human cognitive aspects and neural phenomena.

At the Intelligent Systems Laboratory, University of Saskatchewan, Canada, we are continuously facing new technological challenges, and unwrapping the complexities and mysteries of a natural and industrial society through the mathematics of fuzzy logic, fuzzy neural networks, genetic algorithms and chaos theory. We are exploring possibilities of creating virtual intelligence in animate systems. New computing systems will be based on virtual cognitive machines for solving real-world perception, reasoning and decision-making problems.

The theory of fuzzy logic was introduced to me in the very early stages of its inception by its creator, Professor Lotfi A. Zadeh, during the International Federation of Automatic Control (IFAC) conference on System Sensitivity and Adaptivity, held in Dubrovnik, Yugoslavia, August 26–31, 1968. At that time, to me, it was purely a mathematical curiosity.

Ever since my association with the field of fuzzy logic and neural systems, our Intelligent Systems Research Laboratory (ISRL), has contributed substantially to these remarkable fields. Our academic research has appeared at numerous international conferences (IFAC, SPIE, AS ME, NAFIP, IPSA, ACC, etc.), and in archival journals, books and encyclopedias. We have aided the field in its development through the publications of books (two authored and eighteen edited) and the organization of international conferences, symposia and workshops, the foundation of international associations (IFSA) and national organizations (NAFIP, etc.) around the world, and the establishment of international journals devoted to fuzzy sets, fuzzy logic, neural-fuzzy systems and fuzzy chaos. In Canada, a new society was established in June 1993 during the IRIS conference in Ottawa: the Canadian Society for Fuzzy Information and Neural Systems (CANS-FINS).

Some of the work of this laboratory is appearing extensively in the Japanese marketplace, resulting in fuzzy logic and fuzzy computing, and in the Japanese translation of two textbooks.

5. Father of fuzzy logic (Lotfi A. Zadeh) and Intelligent Systems Research Laboratory, University of Saskatchewan: some intimate associations

In the earlier years of my graduate work (M.S. and Ph.D.), I had the opportunity to study some of the work of Lotfi A. Zadeh, like the frequency response of time varying systems, z-transform for the solution of discrete systems and the state space approach for feedback control systems. (z-transform for the solution of discrete linear dynamic systems (just like the Laplace transform for the solution of linear continuous systems) was introduced in early 1950’s by Lotfi A. Zadeh, where ‘z’ is the first letter in the name of Zadeh.) However, it was in August 1968, when I had the honor and privilege of a first meeting with Lotfi along with his gracious wife, Fay, at the IFAC Symposium held in Dubrovnik, former Yugoslavia.
We spend a week together in Dubrovnik, where he fuzzified my deterministic and stochastic thoughts. Since then, I have had the opportunity to meet with him and interact with his 'fuzzy thought processes' at many international conferences and symposia. During these meetings, his presentations and discussions on fuzzy logic have always inspired me, and I strongly feel that this is the very reason the members of my research group at the Intelligent Systems Research Laboratory were able to get involved so heavily in the growing field of fuzzy-neural systems, with its applications to control, vision, robotics, medical diagnosis and the field of law. This work has appeared in conference proceedings, books and research journals (http://www.usask.ca/Madan.Gupta).

I am pleased to mention that over the last twenty-five years, 1985–2010, Lotfi has visited our university five times. During these visits, he has always inspired my research group at the Intelligent Systems Research Laboratory, and others at the university and local industries. (We had the honor of having Lotfi visit our university in 1984, 1988, 1995, 1998, and May 2006. The formal name of my research group used to be 'Systems and Adaptive Research Laboratory' which on the advice of Lotfi Zadeh during his first visit in 1984 to U of S was changed to more appropriate name as 'Intelligent Systems Research Laboratory'.)

It was in early 2005, when I nominated Professor Lotfi Zadeh to the University of Saskatchewan for awarding an Honorary Doctor of Science degree for his founding of, and seminal contributions to, the field of fuzzy logic. After going through the regular process at the university, finally, the awarding of this honorary DS degree was approved in the fall of 2005. I was privileged to make an informal announcement for the award of this honor to Lotfi, our friend and mentor, at the celebration of the fortieth anniversary of fuzzy logic, held at the University of California, Berkeley, in October 2005.

It was in May, 2006, when President Peter Mac-Kinnon invited Professor Lotfi A. Zadeh for the awarding of the honorary DS degree at the convocation of the University of Saskatchewan. During his opening remarks, the president remarked:

‘In fact, Professor Zadeh is honoring our university by accepting this honorary D.Sc. degree’

(Mrs. Fay Zadeh, wife of Lotfi, was supposed to be at this convocation ceremony, but unfortunately due to an air booking mistake made by her travel agent, she could not come to Saskatoon. We missed her!)

Professor Zadeh has, over the past five decades, been awarded many honorary degrees and awards from various universities and organizations. This additional award of a D.S. degree from the University of Saskatchewan is, in fact, a sign of honor for our university from this distinguished professor.

6. Conclusions

Neural-Fuzzy logic is now gaining wider acceptance among academics and industry. I have extensively neural-fuzzified my own academic research and industrial development work. Presently, at the Intelligent Systems Research Laboratory (ISRL), we are heavily involved in research in the following fields: neuro-vision systems, neuro-control systems, neuro-fuzzy systems, cognitive processes, Virtual Intelligence (VI), and Virtual Cognitive Systems (VCS), genetic algorithms, and chaos theory.

The scientific success and technological progress of fuzzy neural networks should be attributed to the flexibility and softness reflected in the notion of graded membership, as well as the missionary zest and great energy of our mentor Professor Lotfi A. Zadeh, the father of fuzzy logic. The field will witness another exponential growth in the decades to come. Neural-fuzzy technology is also on its way to becoming a multi-billion dollar industry in North America and around the world.

References


Madan M. Gupta is Professor (Emeritus), and holds the Distinguished Chair, at the College of Engineering, and is Director of the Intelligent Systems Research Laboratory at the University of Saskatchewan. Dr. Gupta’s current research interests are in the areas of Neuro-Vision Systems, Neuro-Control Systems, Integration of Fuzzy-Neural Systems, Neuronal Morphology of Biological Vision Systems, Intelligent and Cognitive Robotic Systems, Cognitive Information, New Paradigms in Information Processing, Chaos in Neural Systems, and Fuzzy-Neural Logic in Law. He is also developing some new architecture of Computational Neural Networks and Computational Fuzzy Neural Networks for application to Advanced Robotics, Aerospace, Medical, Industrial, Business Systems and Law. His interests also lie in: Signal and Image Processing with Applications to Medical Systems. Dr Gupta is a Fellow of IEEE, IFSA and SPIE.

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