Eyal Kolman and Michael Margaliot

Knowledge-Based Neurocomputing: A Fuzzy Logic Approach

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Prof. Janusz Kacprzyk
Systems Research Institute
Polish Academy of Sciences
ul. Newelska 6
01-447 Warsaw
Poland
E-mail: kacprzyk@ibspan.waw.pl

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Authors

Eyal Kolman
School of Electrical Engineering
Tel Aviv University
69978 Tel Aviv
Israel
E-mail: eyal@eng.tau.ac.il

Michael Margaliot, Ph.D.
School of Electrical Engineering
Tel Aviv University
69978 Tel Aviv
Israel
E-mail: michaelm@eng.tau.ac.il

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To my parents and my wife. All that I am, I owe to you – E.K.

To three generations of women: Hannah, Miri, and Hila – M.M.

I have set before you life and death,
the blessing and the curse.
So choose life in order that you may live,
you and your descendants. (Deuteronomy 30:19)

Preface

Artificial neural networks (ANNs) serve as powerful computational tools in a diversity of applications including: classification, pattern recognition, function approximation, and the modeling of biological neural networks. Equipped with procedures for learning from examples, ANNs can solve problems for which no algorithmic solution is known.

A major shortcoming of ANNs, however, is that the knowledge learned by the network is represented in an exceedingly opaque form, namely, as a list of numerical coefficients. This *black-box* character of ANNs hinders the possibility of more widespread acceptance of them, and makes them less suitable for medical and safety-critical applications.

A very different form of knowledge representation is provided by *fuzzy rule-bases* (FRBs). These include a collection of If-Then rules, stated in *natural language*. Thus, the knowledge is represented in a form that humans can understand, verify, and refine. In many cases, FRBs are derived based on questioning a human expert about the functioning of a given system. Transforming this information into a complete and consistent set of rules, and determining suitable parameter values, is a nontrivial challenge.

It is natural to seek a synergy between the plasticity and learning abilities of ANNs and the transparency of FRBs. Indeed, considerable research attention has been devoted to the development of various neuro-fuzzy models, but this synergy is a target yet to be accomplished.

In this monograph, we introduce a novel FRB, referred to as the *Fuzzy All-permutations Rule-Base* (FARB). We show that inferring the FARB, using standard tools from fuzzy logic theory, yields an input-output relationship that is *mathematically equivalent* to that of an ANN. Conversely, every standard ANN has an equivalent FARB. We provide the explicit bidirectional transformation between the ANN and the corresponding FARB.

The FARB–ANN equivalence integrates the merits of symbolic FRBs and subsymbolic ANNs. We demonstrate this by using it to design a new approach for knowledge-based neurocomputing using the FARB. First, by generating the equivalent FARB for a given (trained) ANN, we immediately obtain a symbolic representation of the knowledge learned by the network. This provides a novel and simple method for knowledge extraction from trained ANNs.

The interpretability of the FARB might be hampered by the existence of a large number of rules or complicated ones. In order to overcome this, we also present a systematic procedure for rule reduction and simplification. We demonstrate the usefulness of this approach by applying it to extract knowledge from ANNs trained to solve: the Iris classification problem, the LED display recognition problem, and a formal language recognition problem.

Second, stating initial knowledge in some problem domain as a FARB immediately yields an equivalent ANN. This provides a novel approach for knowledge-based design of ANNs. We demonstrate this by designing recurrent ANNs that solve formal language recognition problems including: the AB language, the balanced parentheses language, and the 0^n1^n language. Note that these languages are context-free, but not regular, so standard methods for designing RNNs are not applicable in these cases.

Some of the results described in this work appeared in [89, 88, 90, 91]. We are grateful to several anonymous reviewers of these papers for providing us with useful and constructive comments.

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Tel Aviv, Israel
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Eyal Kolman
Michael Margaliot

Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
COG	Center Of Gravity
DFA	Discrete Finite-state Automaton
DOF	Degree Of Firing
FARB	Fuzzy All-permutations Rule-Base
FFA	Fuzzy Finite-state Automaton
FL	Fuzzy Logic
FRB	Fuzzy Rule-Base
IFF	If and only if
IO	Input-Output
KBD	Knowledge-Based Design
KBN	Knowledge-Based Neurocomputing
KE	Knowledge Extraction
LED	Light Emitting Diode
MF	Membership Function
MLP	Multi-Layer Perceptron
MOM	Mean Of Maxima
RBFN	Radial Basis Function Network
RNN	Recurrent Neural Network
SVM	Support Vectors Machine

Symbols

$\mathbf{x}$	column vector
$\mathbf{x}^T$	transpose of vector $\mathbf{x}$
x_i	ith element of the vector $\mathbf{x}$
$\|\|\mathbf{x}\|\|$	Euclidean norm of the vector $\mathbf{x}$
$[j:k]$	set of integers $\{j, j+1, \ldots, k\}$
$\mathbb{R}^n$	space of n-dimensional real-valued numbers
$\mu_{term}(\cdot)$	membership function for the fuzzy set *term*
i-or	interactive-or operator (see p. 8)
$\sigma(\cdot)$	logistic function (see p. 8)
$\sigma_L(\cdot)$	piecewise linear logistic function (see p. 18)
$h^{-1}(\cdot)$	inverse of the function $h(\cdot)$
&	logical and operator
L_4	language generated by Tomita‘s 4th grammar
$t^k(\mathbf{x})$	truth value of Rule k for input $\mathbf{x}$
$Prob(A)$	probability of event A
$E\{x\}$	expected value of the random variable x

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