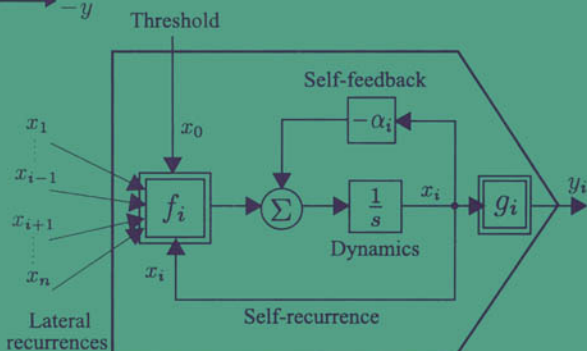
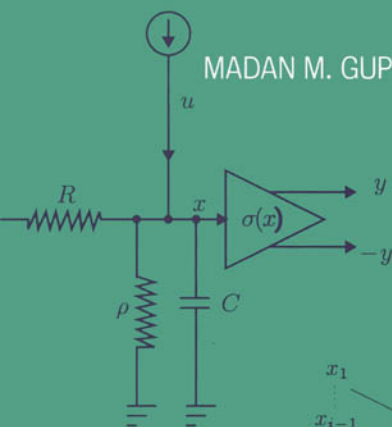


STATIC AND DYNAMIC NEURAL NETWORKS

From Fundamentals to Advanced Theory

MADAN M. GUPTA, LIANG JIN, and NORIYASU HOMMA

Foreword by Lotfi A. Zadeh



*Static and Dynamic
Neural Networks*

This page intentionally left blank

Static and Dynamic Neural Networks

From Fundamentals to Advanced Theory

Madan M. Gupta, Liang Jin, and Noriyasu Homma

Foreword by Lotfi A. Zadeh

 **IEEE**
IEEE PRESS

 **WILEY-
INTERSCIENCE**

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2003 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400, fax 978-750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, e-mail: permreq@wiley.com.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services please contact our Customer Care Department within the U.S. at 877-762-2974, outside the U.S. at 317-572-3993 or fax 317-572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print, however, may not be available in electronic format.

Library of Congress Cataloging-in-Publication Data:

Static and Dynamic Neural Networks: From Fundamentals to Advanced Theory—
Madan M. Gupta, Liang Jin, and Noriyasu Homma

ISBN 0-471-21948-7

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ॐ भूर्भुवः स्वः ।
तत्स वितुर्व रेण्यम ॥
भर्गो देवस्य धीमहि ।
धियो यो नः प्रचोदयात् ॥
॥ ॐ शान्ति शान्ति शान्तिः ॥

OM BHURBHUVAH SVAH !
TATSAVITUR VARENYAM !!
BHARGO DEVASYA DHIMAH !
DHIYO YO NAH PRACHODAYATH !!
OM SHANTI ! SHANTI !! SHANTIHI !!!

(yajur-36-3, Rig Veda 3-62-10)

*We meditate upon the Adorable Brilliance of that Divine Creator.
Who is the Giver of life, Remover of all sufferings, and Bestower of bliss.
We pray to Him to enlighten our minds and make our thoughts clear,
And inspire truth in our perception, process of thinking, and the way of our life.
Om Peace! Peace!! Peace!!!*

全能の神への祈り
神は生命を与え 苦しみを取り除き そして至福を授ける
神よ 我々の心に真実の光を照らし
知覚 思考 人生すべてを真理へと導きたまえ
そして 泰平の安らぎを

We dedicate this book to

*Professor Lotfi A. Zadeh
(The father of fuzzy logic and soft computing)*

and

*Dr. Peter N. Nikiforuk
(Dean Emeritus, College of Engineering),
who jointly inspired the work reported in these pages;*

and, also to

*The research colleagues and students in this global village,
who have made countless contributions to the developing fields of
neural networks, soft computing and intelligent systems,
and, have inspired the authors to learn, explore and thrive in these areas.*

Also, to

*Suman Gupta, Shan Song, and Hideko Homma,
who have created a synergism in our homes
for quenching our thirst for learning more and more.*

*Madan M. Gupta
Liang Jin
Noriyasu Homma*

Contents

<i>Foreword: Lotfi A. Zadeh</i>	<i>xix</i>
<i>Preface</i>	<i>xxiii</i>
<i>Acknowledgments</i>	<i>xxvii</i>

PART I FOUNDATIONS OF NEURAL NETWORKS

1 Neural Systems: An Introduction	3
1.1 <i>Basics of Neuronal Morphology</i>	4
1.2 <i>The Neuron</i>	8
1.3 <i>Neurocomputational Systems: Some Perspectives</i>	9
1.4 <i>Neuronal Learning</i>	12
1.5 <i>Theory of Neuronal Approximations</i>	13
1.6 <i>Fuzzy Neural Systems</i>	14
1.7 <i>Applications of Neural Networks: Present and Future</i>	15
1.7.1 <i>Neurovision Systems</i>	15
1.7.2 <i>Neurocontrol Systems</i>	16
1.7.3 <i>Neural Hardware Implementations</i>	16
1.7.4 <i>Some Future Perspectives</i>	17
1.8 <i>An Overview of the Book</i>	17
2 Biological Foundations of Neuronal Morphology	21
2.1 <i>Morphology of Biological Neurons</i>	22
2.1.1 <i>Basic Neuronal Structure</i>	22

2.1.2	<i>Neural Electrical Signals</i>	25
2.2	<i>Neural Information Processing</i>	27
2.2.1	<i>Neural Mathematical Operations</i>	28
2.2.2	<i>Sensorimotor Feedback Structure</i>	30
2.2.3	<i>Dynamic Characteristics</i>	31
2.3	<i>Human Memory Systems</i>	32
2.3.1	<i>Types of Human Memory</i>	32
2.3.2	<i>Features of Short-Term and Long-Term Memories</i>	34
2.3.3	<i>Content-Addressable and Associative Memory</i>	35
2.4	<i>Human Learning and Adaptation</i>	36
2.4.1	<i>Types of Human Learning</i>	36
2.4.2	<i>Supervised and Unsupervised Learning Mechanisms</i>	38
2.5	<i>Concluding Remarks</i>	38
2.6	<i>Some Biological Keywords</i>	39
	<i>Problems</i>	40
3	<i>Neural Units: Concepts, Models, and Learning</i>	43
3.1	<i>Neurons and Threshold Logic: Some Basic Concepts</i>	44
3.1.1	<i>Some Basic Binary Logical Operations</i>	45
3.1.2	<i>Neural Models for Threshold Logics</i>	47
3.2	<i>Neural Threshold Logic Synthesis</i>	51
3.2.1	<i>Realization of Switching Function</i>	51
3.3	<i>Adaptation and Learning for Neural Threshold Elements</i>	62
3.3.1	<i>Concept of Parameter Adaptation</i>	62
3.3.2	<i>The Perceptron Rule of Adaptation</i>	65
3.3.3	<i>Mays Rule of Adaptation</i>	68
3.4	<i>Adaptive Linear Element (Adaline)</i>	70
3.4.1	<i>α-LMS (Least Mean Square) Algorithm</i>	71
3.4.2	<i>Mean Square Error Method</i>	75
3.5	<i>Adaline with Sigmoidal Functions</i>	80
3.5.1	<i>Nonlinear Sigmoidal Functions</i>	80
3.5.2	<i>Backpropagation for the Sigmoid Adaline</i>	82
3.6	<i>Networks with Multiple Neurons</i>	84

3.6.1	<i>A Simple Network with Three Neurons</i>	85
3.6.2	<i>Error Backpropagation Learning</i>	88
3.7	<i>Concluding Remarks</i>	94
	<i>Problems</i>	95

PART II STATIC NEURAL NETWORKS

4	Multilayered Feedforward Neural Networks (MFNNs) and Backpropagation Learning Algorithms	105
4.1	<i>Two-Layered Neural Networks</i>	107
4.1.1	<i>Structure and Operation Equations</i>	107
4.1.2	<i>Generalized Delta Rule</i>	112
4.1.3	<i>Network with Linear Output Units</i>	118
4.2	<i>Example 4.1: XOR Neural Network</i>	121
4.2.1	<i>Network Model</i>	121
4.2.2	<i>Simulation Results</i>	123
4.2.3	<i>Geometric Explanation</i>	127
4.3	<i>Backpropagation (BP) Algorithms for MFNN</i>	129
4.3.1	<i>General Neural Structure for MFNNs</i>	130
4.3.2	<i>Extension of the Generalized Delta Rule to General MFNN Structures</i>	135
4.4	<i>Deriving BP Algorithm Using Variational Principle</i>	140
4.4.1	<i>Optimality Conditions</i>	140
4.4.2	<i>Weight Updating</i>	142
4.4.3	<i>Transforming the Parameter Space</i>	143
4.5	<i>Momentum BP Algorithm</i>	144
4.5.1	<i>Modified Increment Formulation</i>	144
4.5.2	<i>Effect of Momentum Term</i>	146
4.6	<i>A Summary of BP Learning Algorithm</i>	149
4.6.1	<i>Updating Procedure</i>	149
4.6.2	<i>Signal Propagation in MFNN Architecture</i>	151
4.7	<i>Some Issues in BP Learning Algorithm</i>	155
4.7.1	<i>Initial Values of Weights and Learning Rate</i>	155
4.7.2	<i>Number of Hidden Layers and Neurons</i>	158
4.7.3	<i>Local Minimum Problem</i>	162

4.8	<i>Concluding Remarks</i>	163
	<i>Problems</i>	164
5	Advanced Methods for Learning and Adaptation in MFNNs	171
5.1	<i>Different Error Measure Criteria</i>	172
5.1.1	<i>Error Distributions and L_p Norms</i>	173
5.1.2	<i>The Case of Generic L_p Norm</i>	175
5.2	<i>Complexities in Regularization</i>	177
5.2.1	<i>Weight Decay Approach</i>	179
5.2.2	<i>Weight Elimination Approach</i>	180
5.2.3	<i>Chauvin's Penalty Approach</i>	181
5.3	<i>Network Pruning through Sensitivity Calculations</i>	183
5.3.1	<i>First-Order Pruning Procedures</i>	183
5.3.2	<i>Second-Order Pruning Procedures</i>	186
5.4	<i>Evaluation of the Hessian Matrix</i>	191
5.4.1	<i>Diagonal Second-Order Derivatives</i>	192
5.4.2	<i>General Second-Order Derivative Formulations</i>	196
5.5	<i>Second-Order Optimization Learning Algorithms</i>	198
5.5.1	<i>Quasi-Newton Methods</i>	199
5.5.2	<i>Conjugate Gradient (CG) Methods for Learning</i>	200
5.6	<i>Linearized Recursive Estimation Learning Algorithms</i>	202
5.6.1	<i>Linearized Least Squares Learning (LLSL)</i>	202
5.6.2	<i>Decomposed Extended Kalman Filter (DEKF) Learning</i>	204
5.7	<i>Tapped Delay Line Neural Networks (TDLNNs)</i>	208
5.8	<i>Applications of TDLNNs for Adaptive Control Systems</i>	211
5.9	<i>Concluding Remarks</i>	215
	<i>Problems</i>	215
6	Radial Basis Function Neural Networks	223
6.1	<i>Radial Basis Function Networks (RBFNs)</i>	224
6.1.1	<i>Basic Radial Basis Function Network Models</i>	224
6.1.2	<i>RBFNs and Interpolation Problem</i>	227
6.1.3	<i>Solving Overdetermined Equations</i>	232

6.2	<i>Gaussian Radial Basis Function Neural Networks</i>	235
6.2.1	<i>Gaussian RBF Network Model</i>	235
6.2.2	<i>Gaussian RBF Networks as Universal Approximator</i>	239
6.3	<i>Learning Algorithms for Gaussian RBF Neural Networks</i>	242
6.3.1	<i>K-Means Clustering-Based Learning Procedures in Gaussian RBF Neural Network</i>	242
6.3.2	<i>Supervised (Gradient Descent) Parameter Learning in Gaussian Networks</i>	245
6.4	<i>Concluding Remarks</i>	246
	<i>Problems</i>	247
7	Function Approximation Using Feedforward Neural Networks	253
7.1	<i>Stone–Weierstrass Theorem and its Feedforward Networks</i>	254
7.1.1	<i>Basic Definitions</i>	255
7.1.2	<i>Stone–Weierstrass Theorem and Approximation</i>	256
7.1.3	<i>Implications for Neural Networks</i>	258
7.2	<i>Trigonometric Function Neural Networks</i>	260
7.3	<i>MFNNs as Universal Approximators</i>	266
7.3.1	<i>Sketch Proof for Two-Layered Networks</i>	267
7.3.2	<i>Approximation Using General MFNNs</i>	271
7.4	<i>Kolmogorov’s Theorem and Feedforward Networks</i>	274
7.5	<i>Higher-Order Neural Networks (HONNs)</i>	279
7.6	<i>Modified Polynomial Neural Networks</i>	287
7.6.1	<i>Sigma–Pi Neural Networks (S-PNNs)</i>	287
7.6.2	<i>Ridge Polynomial Neural Networks (RPNNs)</i>	288
7.7	<i>Concluding Remarks</i>	291
	<i>Problems</i>	292

PART III DYNAMIC NEURAL NETWORKS

8	Dynamic Neural Units (DNUs): Nonlinear Models and Dynamics	297
8.1	<i>Models of Dynamic Neural Units (DNUs)</i>	298
	8.1.1 <i>A Generalized DNU Model</i>	298
	8.1.2 <i>Some Typical DNU Structures</i>	301
8.2	<i>Models and Circuits of Isolated DNUs</i>	307
	8.2.1 <i>An Isolated DNU</i>	307
	8.2.2 <i>DNU Models: Some Extensions and Their Properties</i>	308
8.3	<i>Neuron with Excitatory and Inhibitory Dynamics</i>	317
	8.3.1 <i>A General Model</i>	317
	8.3.2 <i>Positive–Negative (PN) Neural Structure</i>	320
	8.3.3 <i>Further Extension to the PN Neural Model</i>	322
8.4	<i>Neuron with Multiple Nonlinear Feedback</i>	324
8.5	<i>Dynamic Temporal Behavior of DNN</i>	327
8.6	<i>Nonlinear Analysis for DNUs</i>	331
	8.6.1 <i>Equilibrium Points of a DNU</i>	331
	8.6.2 <i>Stability of the DNU</i>	333
	8.6.3 <i>Pitchfork Bifurcation in the DNU</i>	334
8.7	<i>Concluding Remarks</i>	338
	<i>Problems</i>	339
9	Continuous-Time Dynamic Neural Networks	345
9.1	<i>Dynamic Neural Network Structures: An Introduction</i>	346
9.2	<i>Hopfield Dynamic Neural Network (DNN) and Its Implementation</i>	351
	9.2.1 <i>State Space Model of the Hopfield DNN</i>	351
	9.2.2 <i>Output Variable Model of the Hopfield DNN</i>	354
	9.2.3 <i>State Stability of Hopfield DNN</i>	357
	9.2.4 <i>A General Form of Hopfield DNN</i>	361
9.3	<i>Hopfield Dynamic Neural Networks (DNNs) as Gradient-like Systems</i>	363
9.4	<i>Modifications of Hopfield Dynamic Neural Networks</i>	369
	9.4.1 <i>Hopfield Dynamic Neural Networks with Triangular Weighting Matrix</i>	369

9.4.2	<i>Hopfield Dynamic Neural Network with Infinite Gain (Hard Threshold Switch)</i>	372
9.4.3	<i>Some Restrictions on the Internal Neural States of the Hopfield DNN</i>	373
9.4.4	<i>Dynamic Neural Network with Saturation (DNN-S)</i>	374
9.4.5	<i>Dynamic Neural Network with Integrators</i>	378
9.5	<i>Other DNN Models</i>	380
9.5.1	<i>The Pineda Model of Dynamic Neural Networks</i>	380
9.5.2	<i>Cohen–Grossberg Model of Dynamic Neural Network</i>	382
9.6	<i>Conditions for Equilibrium Points in DNN</i>	384
9.6.1	<i>Conditions for Equilibrium Points of DNN-1</i>	384
9.6.2	<i>Conditions for Equilibrium Points of DNN-2</i>	386
9.7	<i>Concluding Remarks</i>	387
	<i>Problems</i>	387
10	<i>Learning and Adaptation in Dynamic Neural Networks</i>	393
10.1	<i>Some Observation on Dynamic Neural Filter Behaviors</i>	395
10.2	<i>Temporal Learning Process I: Dynamic Backpropagation (DBP)</i>	398
10.2.1	<i>Dynamic Backpropagation for CT-DNU</i>	399
10.2.2	<i>Dynamic Backpropagation for DT-DNU</i>	403
10.2.3	<i>Comparison between Continuous and Discrete-Time Dynamic Backpropagation Approaches</i>	407
10.3	<i>Temporal Learning Process II: Dynamic Forward Propagation (DFP)</i>	411
10.3.1	<i>Continuous-Time Dynamic Forward Propagation (CT-DFP)</i>	411
10.3.2	<i>Discrete-Time Dynamic Forward Propagation (DT-DFP)</i>	414
10.4	<i>Dynamic Backpropagation (DBP) for Continuous-Time Dynamic Neural Networks (CT-DNNs)</i>	421
10.4.1	<i>General Representation of Network Models</i>	421
10.4.2	<i>DBP Learning Algorithms</i>	424

10.5	<i>Concluding Remarks</i>	431
	<i>Problems</i>	432
11	Stability of Continuous-Time Dynamic Neural Networks	435
11.1	<i>Local Asymptotic Stability</i>	436
11.1.1	<i>Lyapunov's First Method</i>	437
11.1.2	<i>Determination of Eigenvalue Position</i>	440
11.1.3	<i>Local Asymptotic Stability Conditions</i>	443
11.2	<i>Global Asymptotic Stability of Dynamic Neural Network</i>	444
11.2.1	<i>Lyapunov Function Method</i>	444
11.2.2	<i>Diagonal Lyapunov Function for DNNs</i>	445
11.2.3	<i>DNNs with Synapse-Dependent Functions</i>	448
11.2.4	<i>Some Examples</i>	450
11.3	<i>Local Exponential Stability of DNNs</i>	452
11.3.1	<i>Lyapunov Function Method for Exponential Stability</i>	452
11.3.2	<i>Local Exponential Stability Conditions for DNNs</i>	453
11.4	<i>Global Exponential Stability of DNNs</i>	461
11.5	<i>Concluding Remarks</i>	464
	<i>Problems</i>	464
12	Discrete-Time Dynamic Neural Networks and Their Stability	469
12.1	<i>General Class of Discrete-Time Dynamic Neural Networks (DT-DNNs)</i>	470
12.2	<i>Lyapunov Stability of Discrete-Time Nonlinear Systems</i>	474
12.2.1	<i>Lyapunov's Second Method of Stability</i>	474
12.2.2	<i>Lyapunov's First Method</i>	475
12.3	<i>Stability Conditions for Discrete-Time DNNs</i>	478
12.3.1	<i>Global State Convergence for Symmetric Weight Matrix</i>	479
12.3.2	<i>Norm Stability Conditions</i>	481
12.3.3	<i>Diagonal Lyapunov Function Method</i>	481
12.3.4	<i>Examples</i>	486

12.4	<i>More General Results on Globally Asymptotic Stability</i>	488
12.4.1	<i>Main Stability Results</i>	490
12.4.2	<i>Examples</i>	496
12.5	<i>Concluding Remarks</i>	500
	<i>Problems</i>	500

PART IV SOME ADVANCED TOPICS IN NEURAL NETWORKS

13	Binary Neural Networks	509
13.1	<i>Discrete-Time Two-State Systems</i>	510
13.1.1	<i>Basic Definitions</i>	510
13.1.2	<i>Lyapunov Function Method</i>	519
13.2	<i>Asynchronous Operating Hopfield Neural Network</i>	521
13.2.1	<i>State Operating Equations</i>	521
13.2.2	<i>State Convergence of Hopfield Neural Network with Zero-Diagonal Elements</i>	524
13.2.3	<i>State Convergence of Dynamic Neural Network with Nonnegative Diagonal Elements</i>	530
13.2.4	<i>Estimation of Transient Time</i>	534
13.3	<i>An Alternative Version of the Asynchronous Binary Neural Network</i>	539
13.3.1	<i>Binary State Updating</i>	539
13.3.2	<i>Formulations for Transient Time in Asynchronous Mode</i>	543
13.4	<i>Neural Network in Synchronous Mode of Operation</i>	547
13.4.1	<i>Neural Network with Symmetric Weight Matrix</i>	547
13.4.2	<i>Neural Network with Skew-Symmetric Weight Matrix</i>	556
13.4.3	<i>Estimation of Transient Time</i>	560
13.5	<i>Block Sequential Operation of the Hopfield Neural Network</i>	561
13.5.1	<i>State Updating with Ordered Partition</i>	561
13.5.2	<i>Guaranteed Convergence Results for Block Sequential Operation</i>	564

13.6	<i>Concluding Remarks</i>	571
	<i>Problems</i>	572
14	Feedback Binary Associative Memories	579
14.1	<i>Hebb's Neural Learning Mechanisms</i>	580
14.1.1	<i>Basis of Hebb's Learning Rule</i>	580
14.1.2	<i>Hebb's Learning Formulations</i>	582
14.1.3	<i>Convergence Considerations</i>	584
14.2	<i>Information Retrieval Process</i>	591
14.2.1	<i>The Hamming Distance (HD)</i>	591
14.2.2	<i>Self-Recall of Stored Patterns</i>	592
14.2.3	<i>Attractivity in Synchronous Mode</i>	597
14.3	<i>Nonorthogonal Fundamental Memories</i>	608
14.3.1	<i>Convergence for Nonorthogonal Patterns</i>	608
14.3.2	<i>Storage of Nonorthogonal Patterns</i>	613
14.4	<i>Other Learning Algorithms for Associative Memory</i>	618
14.4.1	<i>The Projection Learning Rule</i>	618
14.4.2	<i>A Generalized Learning Rule</i>	620
14.5	<i>Information Capacity of Binary Hopfield Neural Network</i>	624
14.6	<i>Concluding Remarks</i>	626
	<i>Problems</i>	627
15	Fuzzy Sets and Fuzzy Neural Networks	633
15.1	<i>Fuzzy Sets and Systems: An Overview</i>	636
15.1.1	<i>Some Preliminaries</i>	636
15.1.2	<i>Fuzzy Membership Functions (FMFs)</i>	639
15.1.3	<i>Fuzzy Systems</i>	641
15.2	<i>Building Fuzzy Neurons (FNs) Using Fuzzy Arithmetic and Fuzzy Logic Operations</i>	644
15.2.1	<i>Definition of Fuzzy Neurons</i>	645
15.2.2	<i>Utilization of T and S Operators</i>	647
15.3	<i>Learning and Adaptation for Fuzzy Neurons (FNs)</i>	652
15.3.1	<i>Updating Formulation</i>	652
15.3.2	<i>Calculations of Partial Derivatives</i>	654
15.4	<i>Regular Fuzzy Neural Networks (RFNNs)</i>	655

15.4.1	<i>Regular Fuzzy Neural Network (RFNN) Structures</i>	656
15.4.2	<i>Fuzzy Backpropagation (FBP) Learning</i>	657
15.4.3	<i>Some Limitations of Regular Fuzzy Neural Networks (RFNNs)</i>	658
15.5	<i>Hybrid Fuzzy Neural Networks (HFNNs)</i>	662
15.5.1	<i>Difference-Measure-Based Two-Layered HFNNs</i>	662
15.5.2	<i>Fuzzy Neurons and Hybrid Fuzzy Neural Networks (HFNNs)</i>	665
15.5.3	<i>Derivation of Backpropagation Algorithm for Hybrid Fuzzy Neural Networks</i>	667
15.5.4	<i>Summary of Fuzzy Backpropagation (FBP) Algorithm</i>	670
15.6	<i>Fuzzy Basis Function Networks (FBFNs)</i>	671
15.6.1	<i>Gaussian Networks versus Fuzzy Systems</i>	672
15.6.2	<i>Fuzzy Basis Function Networks (FBFNs) Are Universal Approximators</i>	677
15.7	<i>Concluding Remarks</i>	679
	<i>Problems</i>	680
	References and Bibliography	687
	Appendix A Current Bibliographic Sources on Neural Networks	711
	Index	715

This page intentionally left blank

Foreword

It is very hard to write a book that qualifies to be viewed as a significant addition to the voluminous literature on neural network theory and its applications. Drs. Gupta, Jin, and Homma have succeeded in accomplishing this feat. They have authored a treatise that is superlative in all respects and links neural network theory to fuzzy set theory and fuzzy logic.

Although my work has not been in the mainstream of neural network theory and its applications, I have always been a close observer, going back to the pioneering papers of McCulloch and Pitts, and the work of Frank Rosenblatt. I had the privilege of knowing these major figures and was fascinated by the originality of their ideas and their sense of purpose and mission. The coup de grace of Minsky and Papert was an unfortunate event that braked the advancement of neural network theory for a number of years preceding publication of the path-breaking paper by Hopfield. It is this paper and the rediscovery of Paul Werbos' backpropagation algorithm by Rumelhart et al. that led to the ballistic ascent of neural-network-related research that we observe today.

The power of neural network theory derives in large measure from the fact that we possess the machinery for performing large volumes of computation at high speed, with high reliability and low cost. Without this machinery, neural network theory would be of academic interest. The stress on computational aspects of neural network theory is one of the many great strengths of "static and dynamic neural networks" (SDNNs). A particularly important contribu-

tion of SDNN is its coverage of the theory of dynamic neural networks and its applications.

Traditionally, science has been aimed at a better understanding of the world we live in, centering on mathematics and the natural sciences. But as we move further into the age of machine intelligence and automated reasoning, a major aim of science is becoming that of automation of tasks performed by humans, including speech understanding, decisionmaking, and pattern recognition and control.

To solve some of the complex problems that arise in these realms, we have to marshal all the resources that are at our disposal. It is this need that motivated the genesis of soft computing — a coalition of methodologies that are both complementary and synergistic — and that collectively provide a foundation for computational intelligence. Neural network theory is one of the principal members of the soft computing coalition — a coalition that includes, in addition, fuzzy logic, evolutionary computing, probabilistic computing, chaotic computing, and parts of machine learning theory. Within this coalition, the principal contribution of neural network theory is the machinery for learning, adaptation, and modeling of both static and dynamical systems.

One of the important contributions of SDNN is the chapter on fuzzy sets and fuzzy neural systems (Chapter 15), in which the authors present a compact exposition of fuzzy set theory and an insightful discussion of neurofuzzy systems and their applications. An important point that is stressed is that backpropagation is a gradient-based technique that applies to both neural and fuzzy systems. The same applies to the widely used methods employing radial basis functions.

Another important issue that is addressed is that of universal approximation. It is well known that both neural networks and fuzzy rule-based systems can serve as universal approximators. However, what is not widely recognized is that a nonlinear system, S , can be arbitrarily closely approximated by a neural network, N , or a fuzzy system, F , only if S is known, rather than merely given as a black box. The fact that S must be known rules out the possibility of asserting that N or F approximates to S to within a specified error, based on a finite number of exemplars drawn from the input and output functions.

An important aspect of the complementarity of neural network and fuzzy set theories relates to the fact that, in most applications, the point of departure in the construction of a fuzzy system for performing a specified task is the knowledge of how a human performs that task. This is not a necessity in the case of a neural network. On the other hand, it is difficult to construct a neural network with a capability to reason through the use of rules of inference, since such rules are a part of the machinery of fuzzy logic but not of neural network theory.

SDNN contains much that is hard to find in the existing literature. The quality of exposition is high and the coverage is thorough and up-to-date. The authors and the publisher, John Wiley and Sons, have produced a treatise that addresses, with high authority and high level of expertise, a wide variety of issues, problems, and techniques that relate in a basic way to the conception, design, and utilization of intelligent systems. They deserve our applause.

University of California, Berkeley

Lotfi A. Zadeh

This page intentionally left blank

Preface

With the evolution of our complex technological society and the introduction of new notions and innovative theoretical tools in the field of intelligent systems, the field of neural networks is undergoing an enormous evolution. These evolving and innovative theoretical tools are centered around the theory of *soft computing*, a theory that embodies the theory from the fields of *neural networks*, *fuzzy logic*, *evolutionary computing*, *probabilistic computing*, and *genetic algorithms*. These tools of soft computing are providing some intelligence and robustness in the complex and uncertain systems similar to those seen in natural biological species.

Intelligence — the ability to learn, understand, and adapt — is the creation of nature, and it plays a key role in human actions and in the actions of many other biological species. Humans possess some robust attributes of learning and adaptation, and that's what makes them so intelligent. We humans react through the process of learning and adaptation on the information received through a widely distributed network of sensors and control mechanisms in our bodies. The *faculty of cognition* — which is found in our carbon-based computer, the brain — acquires information about the environment through various natural sensory mechanisms such as vision, hearing, touch, taste, and smell. Then the process of cognition, through its intricate neural networks — *the cognitive computing* — integrates this information and provides ap-

propriate actions. The cognitive process then advances further toward some attributes such as learning, recollection, reasoning, and control.

The process of cognition takes place through a perplexing biological process — *the neural computing* — and this is the process of computation that makes a human an intelligent animal. (More or less all animals possess intelligence at various levels, but *humans fall into the category of the most intelligent species.*)

Human actions in this advancing technological world have been inspired by many intriguing phenomena occurring in the nature. We have been inspired to fly by birds, and then we have created flying machines that can fly almost in synchrony with the sun.

We are learning from the carbon-based cognitive computer — the brain — and now trying to induce the process of cognition and intelligence into robotic machines. One of our aims is to construct an autonomous robotic vehicle that can think and operate in uncertain and unstructured driving conditions. Robots in manufacturing, mining, agriculture, space and ocean exploration, and health sciences are just a few examples of challenging applications where humanistic attributes such as *cognition* and *intelligence* can play an important role. Also, in the fields of decisionmaking, such as health sciences, management, economics, politics, law, and administration, some of the mathematical tools evolving around the notion of neural networks, fuzzy logic, and, in general, soft computing may contribute to the strength of the decisionmaking field. We envision robots evolving into electromechanical systems — perhaps having some attributes of human cognition.

The human cognitive faculty — the carbon-based computer — has a vast network of processing cells called *neural networks*, and this science of neural networks has inspired many researchers in biological as well as nonbiological fields. This inspiration has generated keen interest among engineers, computer scientists, and mathematicians for developing some basic mathematical models of neurons, and to use the collective actions of these neural models to find the solutions to many practical problems. The concepts evolved in this realm have generated a new field of *neural networks*.

The idea for this textbook on neural networks was conceived during the classroom teachings and research discussions in the laboratory as well as at international scientific meetings. We are pleased to see that our several years of work is finally appearing in the form of this book. This book, of course, has gone through several phases of writings and rewritings over the last several years.

The contents of this book, entitled *Static and Dynamic Neural Networks: From Fundamentals to Advanced Theory*, follows a logical style providing

the readers the basic concepts and then leading them to some advanced theory in the field of neural networks.

The mathematical models of a basic neuron, the elementary components used in the design of a neural network, are a fascinating blend of heuristic concepts and mathematical rigor. It has become a subject of large interdisciplinary areas of teaching and research, and these mathematical concepts have been successfully applied in finding some robust solutions for problems evolving in the many fields of science and technology. Our own studies have been in the fields of *neurocontrol systems*, *neurovision systems*, *robotic systems*, *neural chaotic systems*, *pattern recognition*, and *signal and image processing*.

In fact, since the early 1980s the field of neural networks has undergone the phases of exponential growth, generating many new theoretical concepts. At the same time, these theoretical tools have been applied successfully to the solution of many applied problems.

Over the years, through their teaching and research in this exponentially evolving field of neural networks, the authors have collected a large volume of ideas. Some of their works have appeared in the form of research publications, and this present volume represents only a small subset of this large set of ideas and studies.

The material in this volume is arranged in a pedagogical style, which, we do hope, will serve both the students and researchers in this evolving field of neural networks.

In designing the present book we strove to present a pedagogically sound volume that would be useful as a main text for graduate students, as well as provide some new directions to academic and industrial researchers. We cover some important topics in neural networks from very basic to advanced material with appropriate examples, problems, and reference material.

In order to keep the book to a manageable size, we have been selective in our coverage. Our first priority was to cover the central concepts of each topic in enough detail to make the material clear and coherent. Each chapter has been written so that it is relatively self-contained. The topics selected for this book were based on our experience in teaching and research.

This book contains 15 chapters, which are classified into the following four parts:

- Part I: Foundations of Neural Networks
 (Chapters 1–3)
- Part II: Static Neural Networks
 (Chapters 4–7)

Part III: Dynamic Neural Networks
(Chapters 8–12)

Part IV: Some Advanced Topics in Neural Networks
(Chapters 13–15)

Part I provides the basic material, but from Parts II, III, and IV, instructors may choose material to suit their class needs. Part IV deals with some advanced topics on neural networks involving *fuzzy sets* and *fuzzy neural networks* as well, which have become very important topics in terms of both the theory and applications.

Also, we append this book with two appendixes:

Appendix A: Current Bibliographic Sources on Neural Networks

Appendix B: Classified List of Bibliography on Neural Networks
([ftp://ftp.wiley.com/public/sci_tech_med/
neural_networks/](ftp://ftp.wiley.com/public/sci_tech_med/neural_networks/))

Appendix A provides various sources from which a student or researcher can find the current work in the field. Appendix B gives an extensive list of references (over 1500) classified into various categories on the ftp site:

ftp://ftp.wiley.com/public/sci_tech_med/neural_networks/
that will provide the readers with the information on reference material from its inception (early 1940s) to recent works.

This book is written for graduate students and academic and industrial researchers working in this developing field of neural networks and intelligent systems. It provides some comprehensive views of the field, as well as its accomplishments and future potentials and perspectives.

We do hope that this book will provide new challenges to its readers, that it will generate curiosity for learning more in the field, and that it will arouse a desire to seek new theoretical tools and applications. We will consider our efforts successful if the study of neural networks through this book raises the level of curiosity and thirst of its readers.

*University of Saskatchewan
GlobespanVirata, Inc.
Tohoku University*

*Madan M. Gupta
Liang Jin
Noriyasu Homma*

Acknowledgments

The authors would like to express their appreciation and gratitude to many research colleagues and students from this international community who have inspired our thinking and, thereby, our research in these emerging field of fuzzy logic and neural networks. Indeed, we are pleased to see that the fruits of our teaching and research are finally appearing in the form of this textbook.

We wish to acknowledge the very constructive and positive feedback that we have received from the reviewers on the raw manuscript for this book. Their comments were very helpful in improving the contents of the book. Several of our students provided some very constructive feedback on the contents and organization of the book. We are grateful to Sanjeeva Kumar Redlapalli and Mubashshar Ahmed for helping us in the reorganization of the bibliography and in some proofreading of the text. We also acknowledge the great assistance of our graduate and undergraduate students at Tohoku University — Masao Sakai, Taiji Sugiyama, Misao Yano, and Yosuke Koyanaka — for helping us in making the diagrams and typing some of the manuscript.

Also the authors would like to thank John Wiley & Sons Inc. and its staff for providing valuable professional support during the various phases of the preparation of this book. Specifically we would like to acknowledge the following persons for their professional support: Philip Meyler (Former Editor), George Telecki (Associate Publisher), Val Moliere (Editor for the Wiley Interscience Division), Andrew Prince (Senior Managing Editor), Rosalyn

Farkas (Production Manager), Mike Rutkowski (Graphic Designer), Kirsten Rohstedt (Editorial Assistant), and many more who have helped us make this book possible.

Finally, we are very grateful to the University of Saskatchewan and our research colleagues and students in the College of Engineering for creating a warm teaching and intellectual research atmosphere for the nourishment of this book and many similar research projects and research publications over the years. Our gratitude is also extended to the staff of the Engineering Computer Centre and the Peter N. Nikiforuk Teaching and Learning Centre, in particular to Ian MacPhedren, Bruce Coates, Randy Hickson, and Mark Tomtene, for their continuous assistance that we received during the preparation of this manuscript.

We also acknowledge the very constructive help of our research assistant, Elizabeth Nikiforuk, who took on the challenging task of organizing and assembling the manuscript during the many phases of its preparation over the last several years.

*University of Saskatchewan
GlobespanVirata, Inc.
Tohoku University*

*Madan M. Gupta
Liang Jin
Noriyasu Homma*

December, 2002

Part I

***FOUNDATIONS OF
NEURAL NETWORKS***

Chapter 1. Neural Systems: An Introduction

Chapter 2. Biological Foundations of Neuronal Morphology

Chapter 3. Neural Units: Concepts, Models, and Learning