NEURAL NETWORKS AND FUZZY SYSTEMS

A DYNAMICAL SYSTEMS APPROACH TO MACHINE INTELLIGENCE

Bart Kosko University of Southern California





This edition may be sold only in those countries to which it is consigned by Prentice-Hall International. It is not to be re-exported and it is not for sale in the U.S.A., Mexico, or Canada.



© 1992 by **PRENTICE-HALL, INC.**A Division of Simon & Schuster
Englewood Cliffs, N.J. 07632

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

IBM is a registered trademark of International Business Machines Corporation.

Printed in the United States of America

10 9 8 7 6 5 4 3

IZBN 0-73-675334-7

Prentice-Hall International (UK) Limited, London
Prentice-Hall of Australia Pty. Limited, Sydney
Prentice-Hall Canada Inc., Toronto
Prentice-Hall Hispanoamericana, S.A., Mexico
Prentice-Hall of India Private Limited, New Delhi
Prentice-Hall of Japan, Inc., Tokyo
Simon & Schuster Asia Pte. Ltd., Singapore
Editora Prentice-Hall do Brasil, Ltda., Rio de Janeiro
Prentice-Hall, Inc., Englewood Cliffs, New Jersey

CONTENTS

	FOREWORD by Lotfi A. Zadeh	xvii
	FOREWORD by James A. Anderson	xix
	PREFACE	xxv
1	NEURAL NETWORKS AND FUZZY SYSTEMS	1
	Neural and Fuzzy Machine Intelligence 2	
	Neural Pre-Attentive and Attentive Processing, 2	
	Fuzziness as Multivalence 3	
	Bivalent Paradoxes as Fuzzy Midpoints, 4 Fuzziness in the Twentieth Century, 5	

Sets as Points in Cubes, 7 Subsethood and Probability, 9 2

The Dynamical-Systems Approach to Machine Intelligence: The Brain as a Dynamical System 12 Neural and Fuzzy Systems as Function Estimators, 13 Neural Networks as Trainable Dynamical Systems, 14 Fuzzy Systems and Applications, 18 Intelligent Behavior as Adaptive Model-Free Estimation 19 Generalization and Creativity, 20 Learning as Change, 22 Symbols vs. Numbers: Rules vs. Principles, 24 Expert-System Knowledge as Rule Trees, 24 Symbolic vs. Numeric Processing, 25 Fuzzy Systems as Structured Numerical Estimators, 26 Generating Fuzzy Rules with Product-Space Clustering, 28 Fuzzy Systems as Parallel Associators, 29 Fuzzy Systems as Principle-Based Systems, 32 References 34 Problems 36 **Neural Network Theory** NEURONAL DYNAMICS I: ACTIVATIONS AND SIGNALS 39 Neurons as Functions 39 Signal Monotonicity 40 Signal and Activation Velocities, 41 Biological Activations and Signals 41 Competitive Neuronal Signals, 43 Neuron Fields 44 Neuronal Dynamical Systems Neuronal State Spaces, 45 Signal State Spaces as Hypercubes, 46 Neuronal Activations as Short-Term Memory, 47 Common Signal Functions 48 Pulse-Coded Signal Functions 50

Velocity-Difference Property of Pulse-Coded Signals, 51

References 52 Problems 53

ce:

19

NEURONAL DYNAMICS II: ACTIVATION MODELS

Neuronal Dynamical Systems

Additive Neuronal Dynamics 56

Passive Membrane Decay, 56 Membrane Time Constants, 57 Membrane Resting Potentials, 57 Additive External Input, 58

Additive Neuronal Feedback 59

Synaptic Connection Matrices, 59
Bidirectional and Unidirectional Connection Topologies,

Additive Activation Models 61

Additive Bivalent Models 63

Bivalent Additive BAM, 63 Bidirectional Stability, 68 Lyapunov Functions, 69 Bivalent BAM Theorem, 73

BAM Connection Matrices 79

Optimal Linear Associative Memory Matrices, 81 Autoassociative OLAM Filtering, 83 BAM Correlation Encoding Example, 85 Memory Capacity: Dimensionality Limits Capacity, 91 The Hopfield Model, 92

Additive Dynamics and the Noise-Saturation Dilemma 94

Grossberg's Saturation Theorem, 95

General Neuronal Activations: Cohen-Grossberg and Multiplicative Models 99

References 103

Problems 106

Software Problems 108

Part I: Discrete Additive Bidirectional Associative Memory (BAM), 108 Part II, 109

38

NALS 39

4 SYNAPTIC DYNAMICS I: UNSUPERVISED LEARNING

111

Learning as Encoding, Change, and Quantization 111

Supervised and Unsupervised Learning in Neural Networks, 113

Four Unsupervised Learning Laws 115

Four Deterministic Unsupervised Learning Laws, 116 Brownian Motion and White Noise, 118

Probability Spaces and Random Processes 119

Measurability and Sigma-Algebras, 119
Probability Measures and Density Functions, 122
Gaussian White Noise as a Brownian Pseudoderivative
Process, 127

Stochastic Unsupervised Learning and Stochastic Equilibrium 131

Stochastic Equilibrium, 133

Signal Hebbian Learning 138

Recency Effects and Forgetting, 138 Asymptotic Correlation Encoding, 138 Hebbian Correlation Decoding, 140

Competitive Learning 145

Competition as Indication, 146 Competition as Correlation Detection, 147 Asymptotic Centroid Estimation, 148 Competitive Covariance Estimation, 149

Differential Hebbian Learning 152

Fuzzy Cognitive Maps, 152 Adaptive Causal Inference, 158 Klopf's Drive Reinforcement Model, 159 Concomitant Variation as Statistical Covariance, 161 Pulse-Coded Differential Hebbian Learning, 163

Differential Competitive Learning 166

Differential Competitive Learning as Delta Modulation, 168

References 170

Problems 173

CO	LIT	TO
1,1	I V	13

χi

		-	
-	-	-	

C	oftware	Problems	175
_	ULLWAIC	1100101113	1 / - /

Part I: Competitive Learning, 175

Part II: Differential Competitive Learning, 176

5 SYNAPTIC DYNAMICS II: SUPERVISED LEARNING

179

Supervised Function Estimation 180

Supervised Learning as Operant Conditioning 181

Supervised Learning as Stochastic Pattern Learning with Known Class Memberships 183

Supervised Learning as Stochastic Approximation 185

The Perceptron: Learn Only If Misclassify, 187
The LMS Algorithm: Linear Stochastic Approximation, 190

The Backpropagation Algorithm 196

History of the Backpropagation Algorithm, 196 Feedforward Sigmoidal Representation Theorems, 199 Multilayer Feedforward Network Architectures, 201 Backpropagation Algorithm and Derivation, 203 Backpropagation as Stochastic Approximation, 210 Robust Backpropagation, 211 Other Supervised Learning Algorithms, 212

References 213

Problems 215

Software Problems 218

Part I: Exclusive-OR (XOR), 218 Part II: Sine Function, 219

Part III: Training Set versus Test Set, 220

6 ARCHITECTURES AND EQUILIBRIA

221

Neural Networks as Stochastic Gradient Systems 221

Global Equilibria: Convergence and Stability 223

Synaptic Convergence to Centroids: AVQ Algorithms 225

Competitive AVQ Stochastic Differential Equations, 225 Competitive AVQ Algorithms, 227 Unsupervised Competitive Learning (UCL), 227 Supervised Competitive Learning (SCL), 228 Differential Competitive Learning (DCL), 228 Stochastic Equilibrium and Convergence, 228

Global Stability of Feedback Neural Networks 232

ABAMs and the Stability-Convergence Dilemma, 233
Stability-Convergence Dilemma, 235
The ABAM Theorem, 236
Higher-Order ABAMs, 239
Adaptive Resonance ABAMs, 240
Differential Hebbian ABAMS, 241

Structural Stability of Unsupervised Learning 242

Random Adaptive Bidirectional Associative Memories 243

Noise-Saturation Dilemma and the RABAM Noise-Suppression Theorem, 247 RABAM Noise-Suppression Theorem, 248 RABAM Annealing, 253

References 255

Problems 257

Software Problems 258

Part I: Random Adaptive Bidirectional Associative Memory (RABAM), 258 Part II: Binary Adaptive Resonance Theory (ART-1), 259

Part 2 Adaptive Fuzzy Systems

262

7 FUZZINESS VERSUS PROBABILITY

263

Fuzzy Sets and Systems 263

Fuzziness in a Probabilistic World 264

Randomness vs. Ambiguity: Whether vs. How Much 265

The Universe as a Fuzzy Set 268

The Geometry of Fuzzy Sets: Sets as Points 269

Paradox at the Midpoint, 273 Counting with Fuzzy Sets, 274

The Fuzzy Entropy Theorem 275

The Subsethood Theorem 278

Bayesian Polemics, 289

339

CONTENTS The Entropy-Subsethood Theorem 293 References 294 Problems 296 **FUZZY ASSOCIATIVE MEMORIES** 299 Fuzzy Systems as Between-Cube Mappings 299 Fuzzy and Neural Function Estimators 302 Neural vs. Fuzzy Representation of Structured Knowledge, FAMs as Mappings, 306 Fuzzy Vector-Matrix Multiplication: Max-Min Composition, 307 Fuzzy Hebb FAMs 308 The Bidirectional FAM Theorem for Correlation-Minimum Encoding, 310 Correlation-Product Encoding, 311 Superimposing FAM Rules, 313 Recalled Outputs and "Defuzzification", 314 FAM System Architecture, 316 Binary Input-Output FAMs: Inverted-Pendulum Example, Multiantecedent FAM Rules: Decompositional Inference, Adaptive Decompositional Inference, 326 Adaptive FAMs: Product-Space Clustering in FAM Cells Adaptive FAM-Rule Generation, 328 Adaptive BIOFAM Clustering, 329 Adaptive BIOFAM Example: Inverted Pendulum, 333 References 335 Problems 336 Software Problems 337 COMPARISON OF FUZZY AND NEURAL TRUCK

263

262

243

265

BACKER-UPPER CONTROL SYSTEMS

Fuzzy and Neural Control Systems 339

Backing up a Truck 340

Fuzzy Truck Backer-Upper System, 340

Neural Truck Backer-Upper System, 345 Comparison of Fuzzy and Neural Systems, 346 Sensitivity Analysis, 347 Adaptive Fuzzy Truck Backer-Upper, 348 Fuzzy Truck-and-Trailer Controller, 352 BP Truck-and-Trailer Control Systems, 356 AFAM Truck-and-Trailer Control Systems, 356 Conclusion, 360

References 361

10 FUZZY IMAGE TRANSFORM CODING

363

Transform Image Coding with Adaptive Fuzzy Systems 363

Adaptive Cosine Transform Coding of Images, 365

Adaptive FAM systems for Transform Coding 366

Selection of Quantizing Fuzzy-Set Values, 367 Product-Space Clustering to Estimate FAM Rules, 368 Differential Competitive Learning, 370 Simulation, 373 Conclusion, 374

References 377

Problems 378

11 COMPARISON OF FUZZY AND KALMAN-FILTER TARGET-TRACKING CONTROL SYSTEMS

379

Fuzzy and Math-Model Controllers 379

Real-Time Target Tracking 381

Fuzzy Controller 382

Fuzzy-Centroid Computation, 386 Fuzzy-Controller Implementation, 390

Kalman-Filter Controller 392

Fuzzy and Kalman-Filter Control Surfaces, 394

Simulation Results 396

Sensitivity Analysis, 399 Adaptive FAM (AFAM), 402

Conclusion 406

References 406

\sim	N ITI	=NT9	`
1.1	31/31 1 B	-171 1 3	•

CONTENTS

χV

APPENDIX: NEURAL AND FUZZY SOFTWARE INSTRUCTIONS

407

Neural Network Software Instructions: Using the OWL Demonstration Programs (IBM-PC/AT) 408

General, 408 ART, 409 BAM, 411 BKP, 413 CL, 414 RABAM, 416

Fuzzy-Associative-Memory Software Instructions 418

Fuzzy Truck Backer-Upper Control System, 418 Fuzzy Target-Tracking Demonstration, 419 Adaptive Fuzzy Control of Inverted Pendulum, 421

INDEX 425

379

363

363