

Biophysical Neural Networks

Foundations of Integrative Neuroscience

Biophysical Neural Networks is a compendium of brain modeling methods, techniques, and concepts presented in a self-explanatory and easy-to-understand format. In a clear exposition, this inspirational book demonstrates the biophysical and biochemical processes that underpin the functioning of single neurons in networks. It brings together in one volume a new generation of biologically realistic models for the exploration of brain function that surpass existing neural networks associated with the computer metaphor.

Biophysical Neural Networks examines the interface between theory and experiment at a multi-hierarchical level of neural organization. Each of its fifteen chapters, written by internationally renowned neuroscience experts, contains abundant references, directions for future research, and problems to stimulate further independent research.

Roman Poznanski, Ph.D., is a widely published neuroscientist acclaimed for his innovative approach in modeling methodology. He earned his Ph.D. in neuroscience from Australian National University and is currently engaged in research at the Advanced Research Laboratory of Hitachi, Ltd., in Japan.

“This book is a must for anyone who is serious about modeling realistic neural networks. It will also appeal to an interdisciplinary audience who want to learn more about neuroscience.”

Algis Garliauskas, D.Sc.

*Professor & Neuroinformatics Laboratory Head
Institute of Mathematics & Informatics, Vilnius*

See if you can fit this under the design cover:

- Investigate the new field of analytical neuroscience
- Learn why the brain is intrinsically noncomputational
- Discover how the Darwinian brain model can be made more profitable for engineers
- Challenge yourself with 45 research projects and unsolved problems
- Access more than 500 references

A COMPENDIUM OF BRAIN MODELING METHODS, TECHNIQUES AND CONCEPTS
Biophysical Neural Networks

Foundations of Integrative Neuroscience

TABLE OF CONTENTS

Each chapter begins with a Summary and Introduction.

Chapter 1

Introduction to Integrative Neuroscience

R.R. Poznanski

Hierarchically Driven Functional Organization

Functional Connectivity and Productivity

Computational Functionalism and Reductionism

A Darwinian Neural Ontogeny

Neurodynamics, Self-organization, and Explicit Specification

Are Selectionist Theories Universal Laws?

Quantifying Hierarchical Levels of Functional Organization

Interpretation Based on a Computational Paradigm

An Example of Integrative Neuroscience: Biophysical Neural Networks

Chapter 2

**A Biophysical Perspective on
Neural Information Processing**

K.N. Leibovic

An Appraisal of Neural Modeling

Retinal Rod Length and Optimal Function

The Efficiency of Neural Representation

Dynamic Representations of Functional Operations

Convergence/Divergence in Information Processing Channels

Reliability with Convergence/Divergence

**“The analytical approaches covered
in this book are at the cutting edge
of modeling in neuroscience.”**

Henri Korn

Professor of Cellular Neurobiology

Pasteur Institute, Paris

Chapter 3

**Morphofunctional Roles of Simulated
Neurons in Volume Transmission**

L. da F. Costa, L.G. Rios-Filho, J.S. Tanaka,

E.T.M. Manoel

Neuromorphometric Measures

Complexity

Radiality

Straightness

Radial Distribution

Volume Transmission through Field Interactions

Description of the Concentration Wave Model

Computer Simulations and Results

Orientation and Curvature Estimation

Neuromorphic Modeling of Networks

Computer Simulations and Results

Chapter 4

Biophysical Models of Retinal Horizontal Cells

Y. Hayashida, T. Yagi

Membrane Properties of Isolated Horizontal Cells

Nonlinear Ionic Conductances

Intracellular Ca^{2+} Regulation Mechanisms

Light-Induced Response of Horizontal Cells

Biophysical Model of a Horizontal Cell In Situ

Segmental Cable Model

Computer Simulations

Chapter 5

The Functional Role of *N*-Methyl-D-Aspartate Receptors in the Lateral Amygdala

H.T. Blair, J.E. LeDoux

Introduction

Role of the Amygdala in Fear Conditioning

NMDA Receptors in the Amygdala

Model of a Lateral Amygdala Pyramidal Neuron

Membrane Properties

Excitatory Synaptic Transmission

Inhibitory Synaptic Transmission

Stimulation Intensity

Computer Simulation Results

Recruitment of NMDA Receptors during Early Synaptic Transmission

Z_{Nsyn} Varies with the Location of the Synapse

Is NMDA Transmission Greater at Distal than Proximal Synapses?

NMDA Blockade Prevents Spikes Evoked by Distal but not Proximal Stimulation

Chapter 6

Hebbian Learning in a Network of Biochemical Neurons

M. Okamoto, K. Tanaka

Biochemical Mechanism of Cyclic Enzyme System

Switching Mechanism of Cyclic Enzyme System

Biochemical Neuron as a Mechanism for the Hebb Rule

Signaling Pathways of the Biochemical Neuron

Biochemical Neuron with Multi-Excitatory Input

Biochemical Neuron with Multi-inhibitory Input

Biochemical Neuron with Lateral Inhibition

Hebbian Networks of Biochemical Neurons

Selective Elimination of Synapses

Associative Long-Term Potentiation and Long-Term Depression

Chapter 7

A Physicochemical Basis of Synaptic Transmission in the Myenteric Plexus

R.N. Miftakhov, J. Christensen

Model of a Single Cholinergic Neuron

Signal Propagation Along Axonal Cable

Signal Transmission at a Cholinergic Synapse

Results and Simulations

Model of a Single Adrenergic Neuron

Signal Propagation along Axonal Cable

Signal Transmission at an Adrenergic Synapse

Results and Simulations

Model of Polysynaptic Axonal Network

Signal Propagation in a Chain of Cholinergic Neurons

Neural Circuit of Cholinergic and Adrenergic Neurons

A Planar Neuronal Network of the Auerbach's Plexus

Chapter 8

Dendritic Spike-Like Potentials in a Neural Network

R.R. Poznanski

Theory of Dendritic Networks for Input-Output Relation

Ionic Cable Equation for a Single Neuron

Representation of Non-inactivating Voltage-Dependent

Ionic Currents

Representation of Axo-Dendritic Chemical Synapses

Network Equations without Synaptic Weights

Analysis of a Non-Recurrent Network for Synaptically Connected Neurons

Linearization of Persistent Sodium Current

Electrotonic Potential in Stimulated Neuron

Composite EPSPs in Postsynaptic Neuron

Dendritic Spike-Like Potentials in Response to Composite

EPSPs Input

**“This book covers network models
in the search for a better understanding
of brain function.”**

Gilbert A. Chauvet, M.D., Ph.D.

Professor of Theoretical & Integrative Biology

University of Southern California, Los Angeles

Chapter 9

Mathematical Reduction Techniques for Modeling Biophysical Neural Networks

P.C. Bressloff, S. Coombes

Reduction of the Cell Body

The Space-Clamped Hodgkin-Huxley Equations

Linearized Hodgkin-Huxley Equations

Reduced Hodgkin-Huxley Equations

The Integrate-and-Fire Model

A Canonical Phase Model

Reduction of the Dendritic Tree

Passive Dendritic Cable

Quasi-active, Linearized Dendritic Cable

Cable with Active Spines

Reduction of the Synapse

Kinetics of Chemical Synapses

The Postsynaptic Response

Synaptic Facilitation

Electrical Synapses

Averaging Methods for Network Dynamics

Weak Coupling and Phase-Averaging

Firing Rate Model: Time-Averaging

Firing-Rate Model: Population Averaging

A Unifying Framework

Chapter 10

Nonlinear Dynamics of Small-Scale Biophysical Neural Networks

S. Doi, S. Kumagai

Nonlinear Dynamical Analysis of the Original Hodgkin-Huxley Equations

Simple Dynamics of Gating Variables

FitzHugh's Subsystem Analysis of the Hodgkin-Huxley Equations

Dynamic Current-Voltage Relation of the Squid Giant Axon Membrane

Dimension Reduction of the Hodgkin-Huxley Equations

Bifurcation Analysis

Hodgkin-Huxley Dynamics with Multiple Time Scales

Time Scale Change in the Original Hodgkin-Huxley Equations

Slow-Fast Decomposition Analysis

Generation and Annihilation of Chaotic Dynamics

Extraordinarily Slow Interspike Intervals

Dynamic Behavior of a Small Scale Hodgkin-Huxley-Type Network

Phase Locking of Two Electrically Coupled Neurons

Effects of a Slow Gating Variable

Chapter 11

Comparison between Spike and Rate Models in Networks of Integrate-and-Fire Neurons

F. Chapeau-Blondeau

Network of Integrate-and-Fire Neurons

Modeling Synaptic Transmission

Modeling Spike Dynamics

Input-Output Transfer Function

Modeling Firing-Rate Dynamics

Autonomous Dynamics as a Phase Transition

Conditions of the Numerical Simulation

Results of Simulation

Critical Coupling

Macroscopic Activity at w_c

Critical Exponent

Dispersion Among Neurons

Initial Conditions

Firing Function f_2

Quantitative Interpretation

Recurrent Neural Loop

Constitution of the Neural Loop

Stationary State with Spiking Neurons

Stationary State with Firing-Rate Neurons

Noise-Enhanced Transmission via Stochastic Resonance

The Phenomenon of Stochastic Resonance

Modeling Stochastic Resonance with Spikes or Rates

“Self-organization, selection, and dynamics are all fundamental principles of functional neuroscience. This book covers neural networks inspired by biophysics.”

Aike Guo

*Head, Laboratory for Learning and Memory
Biophysics Institute, Academia Sinica, Beijing*

Chapter 12

Neural Dynamics of Vocal Processing in the Auditory Cortex

Y. Yamaguchi, J. Horikawa, I. Taniguchi

Introduction

Optical Recording of Neural Activity of the Auditory Cortex
Dynamic Activity in the Tonotopic Organization of the Cortex
Lateral Inhibition

Spatio-Temporal Response Patterns to Sounds with Frequency Changes

Spectro-Temporal Response Pattern to a Complex Sound

Mesoscopic Neural Network Model

Neural Oscillators as Population Units of the Network

Lateral Inhibition among Excitatory Populations

A Two Dimensional Network to Represent Spectro-Temporal Neural Activity

Results of Computer Experiments

Reconstruction of the Neural Response Pattern

Synchronization of Propagating Neural Activity

Chapter 13

Characterization of Post-Ontogenic Functional Connectivity

R.J. MacGregor F.G. Ascarrunz, M.A. Kisley

General Theory of Characterization of Functional Connectivity

Gross Connectivity

Coordinated Multi-unit Firing Patterns and Representation of Information

Topographic Considerations

Mechanics of Neuron Firing

Capacities

General Theory of Proportional Scaling

General Unrestricted Scaling

Uniformly Proportional Scaling

Scaling of Discrete Junctions

General Theory of Partial Representation

Topography

Pattern-modules

Partial Representation with all Senders Retained

Truncation

Chapter 14

Chaotic Dynamics of Field Potentials Simulated by a Neural Mass Network

V.I. Sbitnev, N.B. Ampilova

Nervous Tissue Organization

Extracellular Field Potentials of Neural Aggregates

The Balance Equation

2D Coupled Map Lattice as a Model of Field-Like Active Medium

Chapter 15

Advanced Numerical Methods for Modeling Dendrites

K.A. Lindsay, J.M. Ogden, J.R. Rosenberg

The Cable Model of a Dendritic Tree

Connectivity and Boundary Conditions
Specification of the Membrane Currents
Illustrative Example

Mathematical Preliminaries

Sparse Matrices
Time Integration
Solving Systems of Linear Equations
Direct Method
Iterative Method

Generalized Compartmental Models

The General Compartmental Model
Traditional Compartmental Model
Discrete Internodal Input
Uniformly Tapering Dendrites
Specimen Example
Summary

Method of Finite Differences

Finite Differences
Gradient Boundary Conditions
Another Way to Analyze Gradient Boundary Conditions
The Finite Difference Equations
The Effect of Large-Scale Synaptic Activity on Spike Train Output
Specimen Example
Summary

Finite Element Methods

Triangular Basis Functions
Least Squares Fitting
Cable Equation
Integrals of Products of Basis Functions
Finite Element Equations
Specimen Example
Summary

The Spectral Method

Overview of the Spectral Approach
Mathematical Preliminaries
Collocation Algorithm
Spectral Algorithm

**An essential text for all integrative
researchers in neuroscience,
including**

- **Research & Clinical Neurologists**
- **Neurophysiologists**
- **Neurobiologists**
- **Cognitive Psychologists**
- **Biophysicists**
- **Neuropharmacologists**
- **Biomedical Engineers**
- **Biomathematicians**