

Contents

1 Prologue	1
References	5
2 Introduction: From Biological Experiments to Mathematical Models	7
2.1 Morphology and Electrophysiology of Biological Neurons and Synapses	9
2.1.1 Electrical Properties of the Cell Membrane	9
2.1.2 Action Potentials and the Hodgkin–Huxley Neuron Model	13
2.1.3 Synapses	20
2.1.4 Spatial Structure of Neurons	25
2.2 Abstract Models	33
2.2.1 Neurons	33
2.2.2 Synapses	43
References	56
3 Artificial Brains: Simulation and Emulation of Neural Networks	59
3.1 Simulation of Neural Networks	61
3.2 The Spikey Chip	61
3.2.1 The Neuromorphic Chip	62
3.2.2 System Environment	64
3.2.3 Configurability	65
3.2.4 Calibration	67
3.3 Wafer-Scale Integration	68
3.3.1 HICANN Building Block	70
3.3.2 Communication Infrastructure	76
3.3.3 Software Framework	77
3.3.4 Executable System Specification (ESS)	78
References	79

4	Dynamics and Statistics of Poisson-Driven LIF Neurons	83
4.1	Probability Theory: Essentials	84
4.1.1	Random Variables and Probability Distributions	84
4.1.2	Joint and Conditional Distributions	85
4.1.3	Moments of Probability Distributions	86
4.1.4	Continuous Random Variables.	87
4.2	Closed-Form Solutions for the LIF Equations	88
4.2.1	Reformulation of the LIF Equation with an Effective Membrane Potential	88
4.2.2	Analytical Solutions for the LIF Equations: CUBA Synapses	90
4.2.3	The High-Conductance State I: First Observations	93
4.2.4	Analytical Solutions for the LIF Equations: COBA Synapses.	95
4.2.5	The High-Conductance State II: PSP Shapes	99
4.3	Single-Neuron Statistics	100
4.3.1	Statistics of Additive Poisson-Driven Processes	100
4.3.2	The Gaussian Approximation	106
4.3.3	Current and Conductance Statistics.	107
4.3.4	Free Membrane Potential Statistics.	109
4.3.5	The High-Conductance State III: Theory Versus Experiment	111
4.4	Shared-Input Correlations of Neuronal Dynamics.	114
4.4.1	Multivariate Distributions and the Correlation Coefficient	114
4.4.2	Derivation of the Free (Subthreshold) Membrane Potential CC	117
4.4.3	Subthreshold Shared-Input Correlations: Theory Versus Simulation	121
4.4.4	The Symmetric Uncertainty as a Spike-Based Correlation Measure.	123
4.4.5	Spike-Based Correlations from Free Membrane Potential Statistics	130
4.4.6	Spike-Based Correlations: Theory Versus Experiment	136
4.5	Conclusions and Outlook	139
	References	142
5	Cortical Models on Neuromorphic Hardware	143
5.1	Investigated Distortion Mechanisms	145
5.2	Characterization and Compensation of Network-Level Distortions: a Systematic Workflow	147
5.3	Cortical Layer 2/3 Attractor Memory	148
5.3.1	Architecture	149
5.3.2	Network Scaling	151

5.3.3	Functionality Criteria	152
5.3.4	Neuron and Synapse Model Translation	155
5.3.5	Synapse Loss	159
5.3.6	Synaptic Weight Noise	161
5.3.7	Non-configurable Axonal Delays	167
5.3.8	Full Simulation of Combined Distortion Mechanisms	169
5.3.9	Emulation on the Spikey Chip	175
5.4	Synfire Chain with Feedforward Inhibition	177
5.4.1	Architecture	177
5.4.2	Network Scaling	178
5.4.3	Functionality Criteria	180
5.4.4	Synapse Loss	182
5.4.5	Synaptic Weight Noise	182
5.4.6	Non-configurable Axonal Delays	184
5.4.7	Additional Simulations	185
5.4.8	Full Simulation of Combined Distortion Mechanisms	186
5.4.9	Further ESS Simulations	189
5.4.10	Emulation on the Spikey Chip	191
5.5	Self-sustained Asynchronous Irregular Activity	194
5.5.1	Architecture	194
5.5.2	Network Scaling	196
5.5.3	Functionality Criteria	196
5.5.4	Non-configurable Axonal Delays	199
5.5.5	Synaptic Weight Noise	201
5.5.6	Synapse Loss	201
5.5.7	Compensation Strategies	201
5.5.8	Full Simulation of Combined Distortion Mechanisms	209
5.6	Conclusions and Outlook	212
	References	214
6	Probabilistic Inference in Neural Networks	219
6.1	Graphical Models	222
6.1.1	Directed Graphs: Bayesian Networks	223
6.1.2	Undirected Graphs: Markov Random Fields	226
6.1.3	Factor Graphs	228
6.1.4	Inference in Factor Graphs	230
6.1.5	The Sum-Product Algorithm in Forney Factor Graphs	234
6.2	Liquid State Machines	235
6.2.1	Network Model	236
6.2.2	A Multitasking Neuronal LSM	238
6.2.3	Neuromorphic Implementation	240

6.3	Rate-Based Belief Propagation with LIF Neurons	243
6.3.1	A Neural Implementation of Binary Forney Factor Graphs	243
6.3.2	Training Readouts for Message Passing	247
6.3.3	Implementation of the Knill–Kersten Illusion.	251
6.3.4	Discussion: Pros, Cons and Ideas for a Neuromorphic Implementation	254
6.4	Spike-Based Stochastic Inference.	257
6.4.1	Hopfield Networks.	258
6.4.2	Boltzmann Machines and Markov Chain Monte-Carlo Sampling	260
6.4.3	MCMC Sampling with Spiking Neurons.	266
6.5	Stochastic Inference with Deterministic Spiking Neurons	274
6.5.1	From a Deterministic Model to a Stochastic One	274
6.5.2	Membrane Dynamics in the HCS and the Ornstein– Uhlenbeck Process.	276
6.5.3	Derivation of the Activation Function.	283
6.5.4	Translation of Biases and Recurrent Synaptic Weights.	291
6.5.5	LIF-Based Boltzmann Machines	294
6.6	Applications of LIF Sampling	298
6.6.1	Image Denoising	299
6.6.2	Handwritten Digit Recognition	302
6.6.3	Microscopic Magnetic Systems	313
6.7	Sampling in Discrete Spaces with Spiking Neurons	320
6.7.1	Bayesian Networks as Boltzmann Machines	321
6.7.2	Characterization of the Auxiliary Neurons.	323
6.7.3	Lateral Interaction	323
6.7.4	Bayesian Model of the Knill–Kersten Illusion	327
6.7.5	Robustness to Parameter Distortions.	328
6.7.6	Robustness to Noise Correlations.	328
6.7.7	General Bayesian Networks.	329
6.8	Neuromorphic Neural Sampling.	330
6.9	Conclusions and Outlook	337
	References	344
7	Epilogue	347
	Appendix	351

<http://www.springer.com/978-3-319-39551-7>

Form Versus Function: Theory and Models for Neuronal
Substrates

Petrovici, M.A.

2016, XXVI, 374 p. 150 illus., 101 illus. in color.,

Hardcover

ISBN: 978-3-319-39551-7