Introduction to Theoretical Neuroscience

Tentative Course Outline

Fall 2006
Chapter 1  Introduction

1.1  Overview

1.2  A reminder of some biology and a preview of things to come

1.2.1  Neurons are cells

1.2.2  Neurons are connected through synapses and electric junctions

1.2.3  Neurons form active interconnected networks
Chapter 2  Anatomy and Circuitry

2.1  Architecture of the brain at various scales
2.1.1  Gross anatomy of the brain: parts and their function
2.1.2  Circuitry of the cerebral cortex

2.2  Abstracted network models
2.2.1  Feedforward networks
2.2.2  Recurrent networks
Chapter 3  Rate Models of Neural Populations

3.1  Some useful math (dynamical systems, as they call it)

3.1.1  The basic tools: integration and differentiation

3.1.2  Differential equations and flows

3.1.3  Fixed points, limit cycles, and stranger things

3.1.4  Linear equations and stability

3.1.5  One-parameter systems: local bifurcations

3.1.6  Some words on global bifurcations

3.2  Dynamics of neural populations

3.2.1  Phenomenological ‘derivation’ of rate equations (or how to think about neurons without knowing much about them)

3.2.2  Recurrent networks of excitatory neurons

3.2.3  Adding inhibition

3.2.4  Excitatory and inhibitory neurons in spatially extended neural systems: retina and visual cortex
3.3 Rate models of learning

3.3.1 Different kinds of learning: supervised, unsupervised, and reinforcement learning

3.3.2 Learning by a synapse or a neuron: (unsupervised) Hebbian learning rules

3.3.3 Learning without help (‘unsupervised learning’) by a neuron or a network

3.3.4 Unsupervised learning with switch-like (discrete) synapses

3.3.5 Learning with help (‘supervised learning’)

3.3.6 Learning with a little help (‘reinforcement learning’)

3.4 Rate models of memory

3.4.1 Experimental and conceptual background

3.4.2 A memory model with binary synapses: the Willshaw model

3.4.3 Memory models with graded synapses: the Hopfield and Tsodyks-Feigel’man models

3.4.4 How much stuff can I stuff in there (in principle)?

3.4.5 Associations among memories
Chapter 4 Variability, Limitations of Rate Models, and the Relation of Spikes and Rates

4.1 Some useful math (probabilities and stochastic dynamics, as they call it)

4.2 Limitations of rate models

4.2.1 Variability: do neurons play with dices?
4.2.2 Novel dynamical phenomena in networks of spiking neurons
4.2.3 Response function of a neuron: the ‘I-f curve’
4.2.4 Coding information (over short times)
4.2.5 Propagating information (over long distances)

4.3 A compromise: the balanced network — a rate model with variability

4.4 From rates to spikes, and return trips

4.4.1 (Re)Interpretation of rates (now that we know about spikes)
4.4.2 Heuristic ‘derivation’ of rates from spikes: averages over time, population, or trials
4.4.3 Formal ‘derivation’ of rates from spikes: a slow neuron cannot tell the two apart
4.5 Coding and decoding

4.5.1 Why ‘coding’?

4.5.2 Optimization of the transfer function

4.5.3 Optimal linear processing

4.5.4 Optimal non-linear processing: ‘independent component analysis’

4.5.5 Coding by a population of neurons
Chapter 5  Spiking neurons

5.1  Simple models of single spiking neurons

5.1.1  The Poisson model

5.1.2  The integrate-and-fire model (or Lapique and the easy life at the belle époque)

5.2  Networks of spiking neurons

5.2.1  Oscillations, central pattern generators, brain rhythms, and more!

5.2.2  Small networks of spiking neurons: synchrony among two neurons

5.2.3  Large networks of spiking neurons

5.3  Networks of spiking neurons with plastic synapses

5.3.1  Spike timing-dependent plasticity (STDP)

5.3.2  STDP in feedforward networks

5.3.3  STDP in recurrent networks: the world of synfire chains
Chapter 6  The Biophysics of Neural Activity and Communication

6.1  Biophysical models of single neurons

6.1.1  What did Bernstein and Lapicque teach us?  (A reminder of 5.1.3)

6.1.2  The famous giant squid axon recording sessions — Curtis and Cole, Hodgkin and Huxley, and other famous players

6.1.3  The sodium hypothesis

6.1.4  The Hodgkin-Huxley model of 1952

6.1.5  A zoo of ionic channels

6.2  From Hodgkin-Huxley to Integrate-and-Fire (IF)

6.2.1  Subthreshold dynamics: resonate or integrate?

6.2.2  How are spikes generated (and terminated)?  — FitzHugh-Nagumo and Morris-Lecar models

6.2.3  How are spikes generated, again?  — quadratic IF and exponential IF models

6.2.4  Adaptation

6.2.5  Bursting

6.2.6  One-model-fits-all: the Izhikevich model

6.2.7  Which models actually do fit real neuron data
6.3 Biophysical models of synapses

6.3.1 Models of synaptic channels

6.3.2 Short-term depression and facilitation, and their implications for network behavior

6.3.3 Long-term plasticity: how does the switch work?

6.4 Networks of biophysical neurons