Basics of Computational Neuroscience
1) Introduction

The Basics – A reminder:

1) Brain, Maps, Areas, Networks, Neurons, and Synapses

The tough stuff:

2,3) Membrane Models
3,4) Spiking Neuron Models
5) Calculating with Neurons I: adding, subtracting, multiplying, dividing
5,6) Calculating with Neurons II: Integration, differentiation
6) Calculating with Neurons III: networks, vector-/matrix- calculus, assoc. memory
6,7) Information processing in the cortex I: Neurons as filters
7) Information processing in the cortex II: Correlation analysis of neuronal connections
7,8) Information processing in the cortex III: Neural Codes and population responses
8) Information processing in the cortex IV: Neuronal maps

Something interesting – the broader perspective

9) On Intelligence and Cognition – Computational Properties?

Motor Function

10,11) Models of Motor Control

Adaptive Mechanisms

11,12) Learning and plasticity I: Physiological mechanisms and formal learning rules
12,13) Learning and plasticity II: Developmental models of neuronal maps
13) Learning and plasticity III: Sequence learning, conditioning

Higher functions

14) Memory: Models of the Hippocampus
15) Models of Attention, Sleep and Cognitive Processes
Literature (all of this is very mathematical!)

**General Theoretical Neuroscience:**

„Theoretical Neuroscience“, P. Dayan and L. Abbott, MIT Press (there used to be a version of this on the internet)

„Spiking Neuron Models“, W. Gerstner & W.M. Kistler, Cambridge University Press. (there is a version on the internet)

**Neural Coding Issues:** „Spikes“ F. Rieke, D. Warland, R. de Ruyter v. Steveninck, W. Bialek, MIT Press

**Artificial Neural Networks:** „Konnektionismus“, G. Dorffner, B.G. Teubner Verlg. Stuttgart

„Fundamentals of Artificial Neural Networks“, M.H. Hassoun, MIT Press

**Hodgkin Huxley Model:** See above „Spiking Neuron Models“, W. Gerstner & W.M. Kistler, Cambridge University Press.

**Learning and Plasticity:** See above „Spiking Neuron Models“, W. Gerstner & W.M. Kistler, Cambridge University Press.

**Calculating with Neurons:** Has been compiled from many different sources.

**Maps:** Has been compiled from many different sources.
What is computational neuroscience?

The Interdisciplinary Nature of Computational Neuroscience

The Methods
- General Computer Science
- Theoretical Physics

The Applications
- Artificial Neural Networks, Chip Design
- Special Computer Science (Computer Vision, Robotics)

The Brain (Substrate)
- Neuroanatomie
- Neurophysiology

The Sciences (Fundament)
- Physics
- Chemistry
- Biology
- Mathematics

The World (Problems)
- Cognitive Sciences (Psychology, Psychophysics)
Different Approaches towards Brain and Behavior

Neuroscience:

Environment  →  Stimulus  →  Brain  →  Behavior  →  Reaction
Psychophysics (human behavioral studies):
Neurophysiology:

Environment → Stimulus → Brain → Behavior → Reaction
Theoretical/Computational Neuroscience:

\[ f(x) \pm \int dx \sum \overrightarrow{U} \]

Environment → Stimulus → Reaction → Behavior
Levels of information processing in the nervous system

1m  CNS
10cm  Sub-Systems
1cm  Areas / „Maps“
1mm  Local Networks
100μm  Neurons
1μm  Synapses
0.1μm  Molecules
CNS (Central Nervous System):

- Molekules
- Synapses
- Neurons
- Local Nets
- Areas
- Systems

[Diagram of brain and spinal cord with labeled parts such as Corpus callosum, Diencphalon, Mesencephalon, Cerebellum, Pons, Medulla, Rückenmark.]
Cortex:
Where are things happening in the brain.

Is the information represented locally?

The Phrenologists view at the brain (18th-19th century)
Results from human surgery

'Whoa! That was a good one! Try it, Hobbs — just poke his brain right where my finger is.'
Results from imaging techniques – There are maps in the brain
Visual System:

More than 40 areas!

Parallel processing of „pixels“ and image parts

Hierarchical Analysis of increasingly complex information

Many lateral and feedback connections
Primary visual Cortex:
Retinotopic Maps in V1:

V1 contains a retinotopic map of the visual Field. Adjacent Neurons represent adjacent regions in the retina. That particular small retinal region from which a single neuron receives its input is called the receptive field of this neuron.

V1 receives information from both eyes. Alternating regions in V1 (Ocular Dominanz Columns) receive (predominantly) Input from either the left or the right eye.

Each location in the cortex represents a different part of the visual scene through the activity of many neurons. Different neurons encode different aspects of the image. For example, orientation of edges, color, motion speed and direction, etc.

V1 decomposes an image into these components.
Orientation selectivity in V1:

Orientation selective neurons in V1 change their activity (i.e., their frequency for generating action potentials) depending on the orientation of a light bar projected onto the receptive Field. These Neurons, thus, represent the orientation of lines oder edges in the image.

Their receptive field looks like this:
Superpositioning of maps in V1:

Thus, neurons in V1 are orientation selective. They are, however, also selective for retinal position and ocular dominance as well as for color and motion. These are called „features“. The neurons are therefore akin to „feature-detectors“.

For each of these parameter there exists a topographic map.

These maps co-exist and are superimposed onto each other. In this way at every location in the cortex one finds a neuron which encodes a certain „feature“. This principle is called „full coverage“.
Local Circuits in V1:

Selectivity is generated by specific connections

Orientation selective cortical simple cell

stimulus
Layers in the Cortex:
Local Circuits in V1:

LGN inputs

Cell types

Circuit

Spiny stellate cell

Smooth stellate cell
Considerations for a Cortex Model

• Input
  – Structure of the visual pathway

• Anatomy of the Cortex
  – Cell Types
  – Connections

• Topography of the Cortex
  – „X-Y Pixel-Space“ and its distortion
  – Ocularity-Map
  – Orientation-Map
  – Color

• Functional Connectivity of the cortex
  – Connection Weights
  – Physiological characteristics of the neurons

At least all these things need to be considered when making a „complete“ cortex model
At the dendrite the incoming signals arrive (incoming currents).

At the soma current are finally integrated.

At the axon hillock action potential are generated if the potential crosses the membrane threshold.

The axon transmits (transports) the action potential to distant sites.

At the synapses are the outgoing signals transmitted onto the dendrites of the target neurons.

Structure of a Neuron:
Different Types of Neurons:

Unipolar cell

(Invertebrate N.)

Retinal bipolar cell

Bipolar cell

Spinal motoneuron

Hippocampal pyramidal cell

Purkinje cell of the cerebellum

Different Types of Multi-polar Cells
Cell membrane:

Ion channels:

Membrane - Circuit diagram:

Organic Anions

Net negative charge

Net positive charge

K⁺

Na⁺ Cl⁻ A⁻ K⁺

0 mV

98 mV

V_{rest} g C V_{m}