Theoretical Neuroscience

Vorlesung vom 23. Oktober 2002

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0 Overview

- How does the brain work? → (Neuro-) Biology
- How can we build intelligent machines? → (Neuro-) Informatics

Common subject: Neural networks – Neuronale Netze

Originally: Networks of biological nerve cells

Around 1940	Parallel computing technology
And since 1990	Processes = artificial neurons, primitive features of biological neurons, adaptive (Adaption ist wichtigste Übernahme aus der Biologie)

Computational Neuroscience:
Theory based on computer models and simulations of neural networks

Connectionism:
Artificial neural networks in AI, psychology, linguistics, robotics, related to human brains

I History

1. Neural Networks

   - McCulloch & Pitts (1943): A logical calculus of the ideas immanent in nervous activity
   - Hebb (1949): The Organization of behaviour (cell assemblies; simple learning rule for synapse = Hebb rule)
   - Rosenblatt (1958): The perception: A probabilistic model for information storage and organization in the brain (simple two-layered neural networks with fixed and adaptive connections; perception learning rule)
   - Hopfield (1982): Neural Networks and physical systems with emergent collective computational capabilities (neural networks as physical systems (spin glasses) used for combinatorial optimization (TSP); travelling salesman problem)
   - Rummelhart, Hinton & Williams (1986): Learning internal representations by error propagation (learning rule for fully adaptive, multilayered nns) (already developed in 1974 by Paul Werbos)

2. (Biological) Cybernetics

   - Wiener (1948): Cybernetics or control and communication in the animal and the machine (feedback principle for error correction, e.g. helmsman (Steuermann) of a ship; biological feedback systems: body temperature, blood temperature)

3. Brain Research

- 19th century: localization of mental abilities in different regions
- Ramon y Cajal (1906): The structure and connection of neurons (anatomical studies of brain areas; staining methods; brain as network of neurons)
- Sherington (1906): The integrative action of the nervous system (physiological understanding of synapses; excitation or inhibition)

II Research Disciplines

- Brain Research
  - Perception, memory, movement control, higher mental functions
- Computational Neuroscience
  - Mathematical analysis and computer simulations for modelling the structure and function of nervous systems
- Artificial Intelligence
  - Intelligent behaviour in machines (computers, robots etc.)
- Cognitive Psychology
  - Mental abilities as information processing systems, models not necessarily neural
- Connectionism
  - Models of human mind and behaviour
  - Parallel distributed systems of neuron-like elements
  - Not necessarily realistic
- Philosophy
  - Mind-body problem, consciousness
- Cognitive Neuroscience
  - Clinical data, brain imaging, human cognition, single cell recording in animals

Interaction between Modelling and Experiment:

Frog: two behaviours: - approaches small moving objects
- flees from large moving objects

Model:

Perception:	small, large
Action:	approach, flee

Perception		Action
Small	→	approach
Large	→	flee

Hypothesis about brain regions:

tectum:	perception of small objects
Pretectum:	perception of large objects

Experiment: Lesion of the pretectum

Conjecture: small objects → normal action
large objects → no action

Result: frog approaches small AND large objects

Need of a new model:

Tectum:	perception of moving objects; activate approach
Pretectum:	perception of large objects; activate fleeing AND inhibit approaching

III Introduction

Computational (= Theoretical) Neuroscience

- theoretical study of nn and brain
- uncover principles and mechanism that guide
- development, organization, information processing, and mental abilities of the nervous system

Questions

- How does the brain work?
- What are the biological mechanisms?
- How is it organized?
- What information processing principles are there in perception?
- How did the brain evolve?
- How does the brain change during lifetime?
- What is the effect of damage?
- How can its diseases be treated?

Tools

- genetic manipulation
- in vivo, in vitro recording of cell activities
- optical imaging
- functional magnetresonance scanning
- psychophysical measurement
- computer simulation

Focus

- develop and test hypothesis about nn
- develop and evaluation of models:
    - formulas, systems of equation, computer programs, computer hardware
- synonymous to Theoretical Neuroscience:
    - theory = formal models + computer simulations + mathematical proofs
- compare with Theoretical Computer science
- mostly analytically intractable models
- measure models against experimental data

Levels of organization

CNS	1 m	dynamic interaction of several brain areas
System	10 cm	perform higher mental functions (e.g. visual system)
Maps	1 cm	distributed representation of information (e.g. of sensations, e.g. somatosensory map)
Network	1 mm	perform complex tasks not present in single neurons
Neuron	100 µm	basic processing units
Synapses	1 µm	plasticity of nervous system
Molecules	1 Å	electric potential of neurons; signal transmission between neurons

Models

- simplification (evaluations, test, predictions)
- equations, computer programs, prose (not recreations of reality)
- are necessary:
    - to investigate particular questions,
    - to demonstrate particular features of complex real world systems

Models in Theoretical Neuroscience

- single neurons
- networks of neurons
- architectures capturing brain organization

→ interpret experimental data

→ reveal information processing principles in the brain

Computer-Brain Analogy

Computer

- small number of processes
- logical gates (as and, or, not; operate on bits 0,1) as elementary units
- complex processors
- variety of basic operations
- information stored in separate memory
- must be programmed

Brain

- many (ca. 10^{10}) processing elements
- more complex units than logical gates
- connected in networks
- has emergent capabilities (not found in smaller parts)
- information stored in connections
- learns from experience (examples, trial and error)