

1. Introduction

Fundamentals of Computational Neuroscience, T. P. Trappenberg, 2010.

Lecture Notes on Brain and Computation

Byoung-Tak Zhang

Biointelligence Laboratory

School of Computer Science and Engineering

Graduate Programs in Cognitive Science, Brain Science, and Bioinformatics

Brain-Mind-Behavior Concentration Program

Seoul National University

E-mail: btzhang@bi.snu.ac.kr

This material is available online at <http://bi.snu.ac.kr/>

Outline

- 1.1 What is computational neuroscience?
- 1.2 Domains in computational neuroscience
- 1.3 What is a model?
- 1.4 Emergence and adaptation
- 1.5 From exploration to a theory of the brain

1.1 What is computational neuroscience?

- *“Computational neuroscience is the theoretical study of the brain to uncover the principles and mechanisms that guide the development, organization, information processing, and mental abilities of the nervous systems.”*
- Specialization within neuroscience
- Neuroscience is interdisciplinary studies
 - ◆ Physiology, psychology, medicine, computer science, mathematics, etc.
 - ◆ The brain is one of the most complex systems ever encountered in nature
- Questions
 - ◆ How does the brain work?
 - ◆ What are the biological mechanisms involved?
 - ◆ How is it organized?
 - ◆ What are the information-processing principles used to solve complex tasks such as perception?
 - ◆ How did it evolve?
 - ◆ How does it change during the lifetime of the organisms?
 - ◆ What is the effect of damage to particular areas and the possibilities of rehabilitation?
 - ◆ What are the origins of degenerative diseases and possible treatments?

1.1.1 The tools and specializations in neuroscience

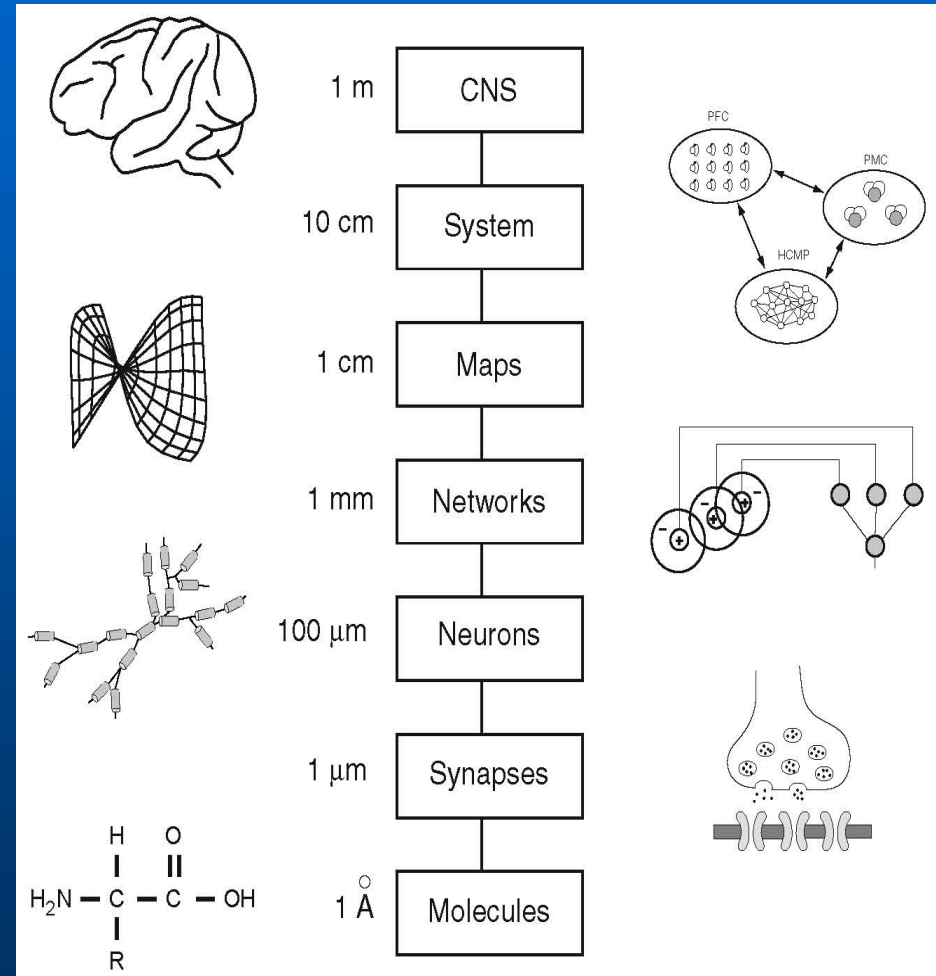
- Techniques
 - ◆ Genetic manipulation
 - ◆ *in vivo* and *in vitro* recording of cell activities
 - ◆ Optical imaging
 - ◆ fMRI
 - ◆ Psychophysical measurement
 - ◆ Computer simulation
- The significance of any technique has to be evaluated with a view to its specific problems and limitations as well as its specific aim of the technique

1.1.2 The focus of computational neuroscience

- Computational neuroscience
 - ◆ attempts to *develop and test hypotheses about the functional mechanisms of the brain*
 - ◆ A specialization within theoretical neuroscience
 - ◆ Employ computers to simulate models
 - ◆ The computational aspects of brain functions
- Analytical techniques
 - ◆ Give us a deeper and more controlled insight into the features of models and the reasons behind numerical findings
- The models have to be measured against experimental data
 - ◆ *Experimental measurements* on the real brain can verify ‘**what**’ the **brain does**
 - ◆ *Computational neuroscience* tries to speculate ‘**how**’ the **brain does it**

1.2 Domains in computational neuroscience

- The nervous system has *many levels of organization on spatial scales* ranging from the molecular level of a few angstroms to the whole nervous system on the scale of 1 meter
- The art of *abstraction*
 - ◆ Making a suitable simplification of a system without abolishing the important features

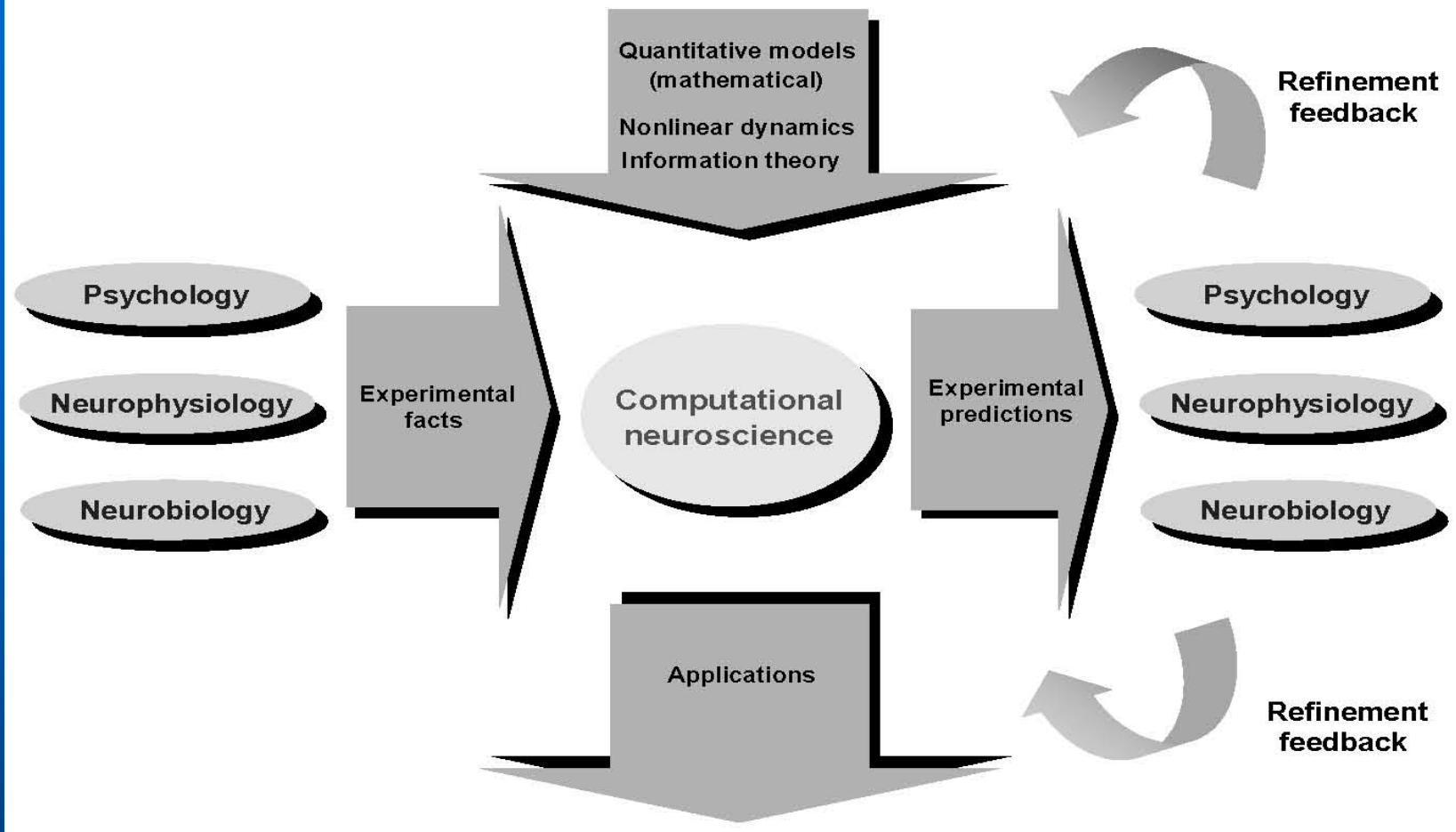


1.2.1 Levels of abstraction

- Which level is most appropriate for the investigation and abstraction depends on the scientific question asked.
 - ◆ Ex) Parkinson disease
 - Caused by the death of dopaminergic neurons
 - A neuronal level with detailed neuron models
 - Full scale of impairment
 - Motor action, a more global system level study
 - Methods of coping with the condition
- The condition must be studied at various levels and connections must be made between the different levels
 - ◆ how small-scale factors can influence the characteristics of large-scale systems.

1.2.2 Level of organization in the nervous system

- Different levels of organization in the nervous system
 - ◆ Molecules, synapses, neurons, networks, maps, systems, CNS
- Neurons contact each others and thereby build networks
 - ◆ Exhibit complex behavior and information-processing capabilities not present in a single neuron.
 - ◆ Ex) Topographic maps of sensory stimuli
- Network with a specific architecture are incorporated into larger structures
 - ◆ More complex information-processing tasks.
 - ◆ Higher-order brain functions, CNS
- Neuroscientists develop a basic *understanding of the functionalities on different scales* in the brain
- Computational neuroscience can help the investigations at all levels of description
- It is important to *comprehend the interaction between the different levels of description*



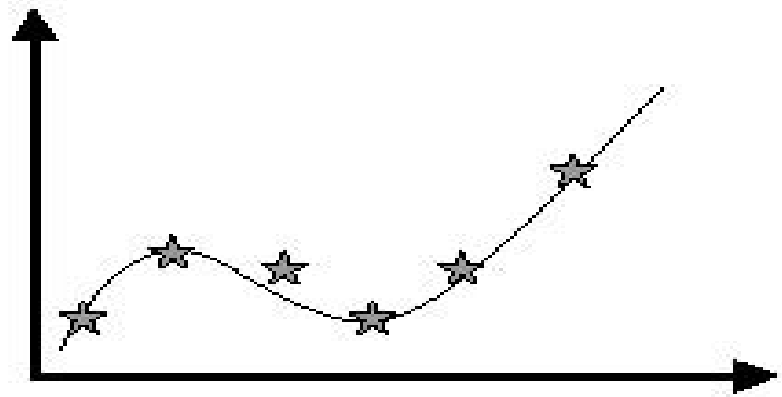
- Integrate experimental facts from different levels into a coherent model (hypotheses) of how the brain works
- Utilise mathematical models for describing the experimental facts
 - ◆ Methods: mathematics, physics, computer science, statistics
- Hypotheses with the aid of models should lead specific experimental predictions
- Comparison of model predictions with experimental data
 - ◆ Refine the hypotheses
 - ◆ Develop more accurate models

1.2.3 The integrated approach (2)

- Computational neuroscience can also help to develop applications
 - ◆ The advanced analysis of brain imaging data
 - ◆ **Technical applications (brain-like computation)**
 - ◆ The develop advanced treatments for patients with brain damage
- Models are able to relate simultaneously to experimental findings on different levels
 - ◆ Single elements: Biologically plausible synaptic plasticity (**neurobiological** mechanisms)
 - ◆ Behavior of the elements: Reflect experimental findings from **electrophysiological** studies
 - ◆ The activity of specific modules: **Brain imaging** studies

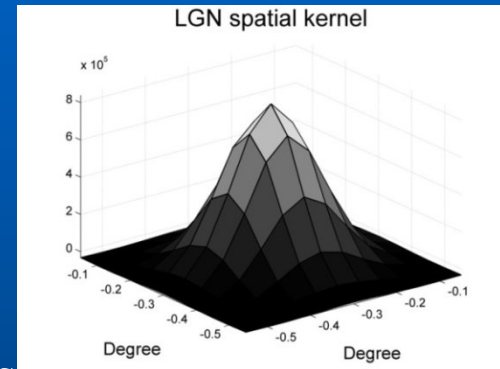
1.3 What is a model?

- *“Models are abstractions of real world systems or implementations of an hypotheses in order to investigate particular questions or to demonstrate particular features of a system or a hypothesis.”*
 - ◆ Ex) A computer model of a house giving a 3-dim impression of the design (left)
 - ◆ Ex) A curve that fits some data points reasonably well (right). The curve can be a simple mathematical formula that fits the data points (heuristic model) or result from more detailed models of the underlying system



1.3.1 Descriptive models

- Represent experimental data in the form of graphs
- Describe these data points with a mathematical function
- Ex) Model of the receptive fields in the LGN
 - ◆ Gabor functions (functional description)
- “Phenomenological model”
- Does not tell us
 - ◆ Biophysical mechanisms of the receptive fields
 - ◆ Why cells respond in the particular way
- Useful to have a functional description
 - ◆ If we want to study a model of the primary visual cortex to which these cells project, then it is much easier to use the parametric form of LGN response as input to the cortical model



1.3.2 Explanatory models (1)

- The basis of the information-processing capabilities of the brain
 - ◆ Single neuron, networks of neurons, specific architectures capturing brain organizations
- Structural equation modeling
 - ◆ Make an educated guess at the functional organization of the brain in order to deduce effective connectivities in the brain from imaging data
- Synthetic models
 - ◆ The principles of information processing in the brain
 - ◆ Building blocks of brain functions

1.3.2 Explanatory models (2)

- Toy models
 - ◆ The level of simplification and abstraction is so crude
 - ◆ Necessary in order to employ analytical methods
- It is difficult to find the right level of abstraction
- **Models are intended to simplify** and thereby to identify which details of the biology are essential to explain particular aspect of a system
- Justifications of the assumptions in models have a high priority in scientific investigations

1.4 Emergence and adaptation

1.4.1 The computer analogy

- Standard computer
 - ◆ One or a small number of complex central processors
 - ◆ Complicate data processing by basic processor function
 - ◆ Programming: Instruct the machine to follow all the steps
 - ◆ The sophistication of the computer reflects basically the smartness of the programmer
- Information processing in the brain is very different
 - ◆ Simpler processing elements, but lots of them (neurons, nodes)
 - ◆ Parallel distributed processing
 - Interaction of nodes not independent
 - ◆ The interaction of nodes is accomplished by assembling them into large networks

1.4.2 Emergence (1)

- Neural networks
 - ◆ Interested in understanding the consequences of interacting nodes
 - ◆ Processing abilities not present in single nodes
 - Emergent property of *rule-based systems*
- *Emergence* is the single most defining property of neural computation
- Interacting systems can have unique properties beyond the mere multiplication of single processor capabilities
- The description of a system on two levels
 - ◆ Basic rules defining the system
 - ◆ Description aimed at understanding the consequences of such rules

1.4.2 Emergence (2)

- Basic rules defining the system
 - ◆ The assumption that natural (neural) systems are governed by a finite set of rules
 - ◆ Ex) Newton's laws, Maxwell's equation, etc.
 - ◆ We do not have a theory of the brain on this level
 - ◆ Even with a given set of rules, not sufficient understanding of the systems
- Understanding the consequences of such rules
 - Even a small set of rules can generate a multitude of behaviors of the systems that are difficult to understand from the basic rules
 - A deeper understanding of emergent properties is becoming a central topic

1.4.3 Adaptive systems

- Adaptation
 - ◆ The ability of the system to adjust its **response to stimuli depending upon the environment**
- Adaptation has two major virtues
 - ◆ The possibility of solving information-processing demands for which explicit algorithms
 - ◆ Concerns our aim to build **systems that can cope with continuously changing environment**
- **Biologically plausible learning mechanisms**

1.5 From exploration to a theory of the brain

- The brain is still a largely unknown territory, and exploring it is still a major domain neuroscience
- The experimental style is slowly changing. It is increasingly important to formulate alternative hypotheses more precisely and to quantify such hypotheses in such a way that experimental tests can verify or disprove them.
- Theory of brain

Conclusion

- Computational neuroscience
 - ◆ The theoretical study of the brain to uncover the principles and mechanisms
 - ◆ Attempts to develop and test hypotheses
- The nervous system has many levels of organization
 - ◆ The art of *abstraction*
- Models are abstractions of real world systems or implementations of hypotheses
 - ◆ Descriptive models
 - ◆ Explanatory models
- Emergence and adaptive systems