Self-Organization in the Nervous System

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20.07.2007

Abstract

Self-organization refers to a process in which the internal organization of a system increases in complexity without guidance from the outside world. In brain development many aspects of self-organization are involved. Although development of the nervous system depends on external stimulation, pattern formation in the brain is considered to be a result of internal interactions through unsupervised learning.
Self-organizing maps generally perform a projection from a high-dimensional to a low-dimensional data space. As part of the visual system, the primary visual cortex manages to reduce the complexity of input stimuli by developing spatial patterns called cortical maps. These biological maps are role models in computational research, especially in the field of artificial neural networks.

1 Introduction

The term self-organization generally describes the process, in which the elements in a system organize their communal behavior by interactions among each other rather than through external intervention.
There are remarkably many examples of systems, which use self-organization to establish a complex structure. In chemical science an example would be molecular self-assembly. It is a crucial concept for the function of cells and exhibited e.g. in the formation of the double helical DNA through hydrogen bonding and van der Waals forces.
Self-organization is not only present in the microcosm but even in the macrocosm of life: Flocking behavior such as the formation of flocks by birds or schools of fish is a product of self organization (Fig. **??**). Even in human society occurrences of self-organizing behavior can be observed. Herd behavior, group think or economics are thought to be a product of self-organization.
In brain development the formation of structural patterns is done by self-organization. These patterns play an important role in processing high amounts of data like sensory input by producing a low dimensional representation of incoming signals while preserving topographical information.

This paper gives a general introduction to the biological context of those self organizing maps. The nervous system, especially the primary visual cortex, shapes the basis of this presentation. Nevertheless, since the matter of self-organizing maps is strongly connected to computational investigations, we try to lead over from the biological viewpoint to a more artificial representation of the topic at the end.

Figure 1: Examples of self-organizing behavior in nature (Picture from http://www.faculty.iu-bremen.de/mhuett/images/)

2 Self-Organization In The Nervous System

The nervous system is a particularly interesting example of self-organization. Since the brain contains about 10 billion neurons with around 100 trillion connections between them, it seems extremely unlikely, that the genome alone holds all necessary information about the position, function or cell neighborhood of each single cell. A more probable thought is that the genome merely holds the rules of development that specify the general features of the system, leaving the fine details to be arranged by local interactions.
Although the term “self-organization” suggests the absence of any outside influences, the organization of the nervous system nevertheless depends on some external stimuli, either from other parts of the nervous system or from sensory stimulation. However, these outside world stimuli can be considered as being a part of the whole system. Thereby, together with the interactions between the neurons, the structure of the brain develops using unsupervised learning (meaning that there is no a priori test to see if the build network works or not) and therefore maintaining the most dominant feature of self-organization.

2.1 Cerebral Cortex

The Cerebral Cortex is the part of the nervous system, where most of the sensory stimulation arrives. It is responsible for many important brain activities like thinking, perceiving and information processing, whereas it is divided into lobes that each have a specific function.
The structure consists of only a thin layer of cells on the surface of the brain (Fig. **??**). Histologically the cortex can be divided into six layers but the response properties of the neurons seem to vary mainly laterally only and are roughly identical in all layers.

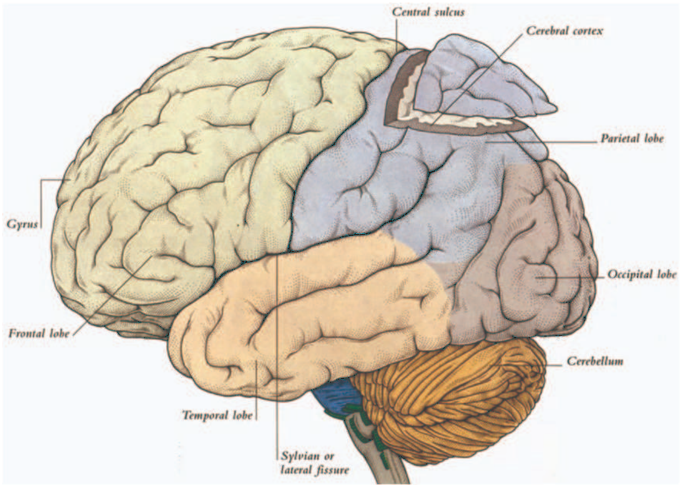

Figure 2: Cerebral Cortex: a thin layer of cells on the surface of the brain, divided into functional lobes.(Picture from http://www.coheadquarters.com/coOuterBrain1.htm)

Although the cortex contains many folded bulges to increase the area of the surface, a layer is actually a two dimensional structure. Each layer contains different cell types and forms different types of connections among their neurons. The layers then are vertically organized to have a columnar architecture, meaning each of the planar layers are connected, so that neurons stacked on top of each other have similar response properties. This type of vertical structure is called a cortical column and represents a basic functional unit for sensory processing or motor output.

2.2 Cortical Maps

Since the cortical surface is typically planar, meaning two-dimensional, arriving sensory input has to be simplified to keep all information intact: A single stimulus triggers only a single response in the cortex. The position of this response remains the only piece of information left. This position alone has to be sufficient for the cortex to conclude which part of the body initiated the stimulus in the first place. This type of connectivity pattern is called topographic map.
The mapping process is slightly divergent. Neighboring stimuli are mapped to neighboring nodes, but if the stimuli are too similar, then they can be projected onto the very same nodes.
Figure **??** is a simplified model of the cortical map. It visualizes in an abstract way, that the cortex prioritizes certain regions of the body over others by giving them more space on the cortical surface. Thereby important areas, e.g. the surface of the fingertips, which have to distinguish sensory input in close proximity, are granted a finer (neural) resolution.

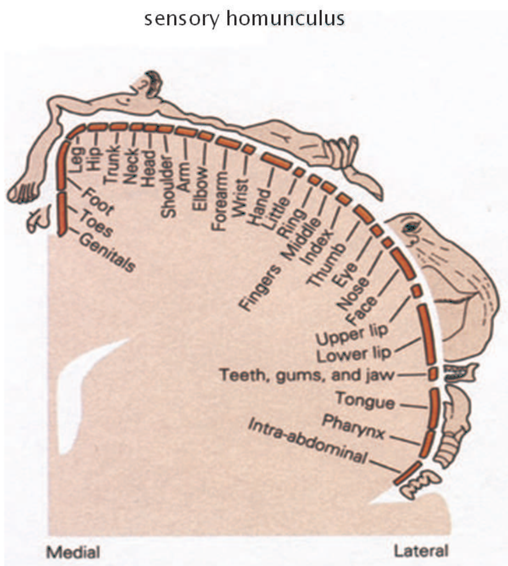

Figure 3: Allocation of the cortical surface for sensory input.(Picture from http://pharyngula.org/ pzmyers/neuro/chap9)

2.3 Visual Path

A very important example of how high dimensional stimuli are projected on cortical maps is the way of processing visual information.
The nerve fibers from ganglion cells in the retina project via the thalamus to the primary visual cortex. They do that as said in a topographic manner, such that nearby locations in the retina project onto neighboring locations in the cortex. The mapping process now has to be rather sophisticated, since a natural scene contains a lot of information, e.g. contours, color, movement or location in space. All this data has to be preserved when mapped onto the two-dimensional layer that is the visual cortex.
There are two prominent features of cells in the visual cortex that illustrate how mapping from a high to a low dimensional space is realized.
Since we have two eyes, two different pictures arrive at the cortex. Nevertheless both eyes project to the same area of cortex. During the development of the cortex a pattern formation has evolved that is able to distinguish between stimuli from the left or the right eye. This effect is called ocular dominance. It means that some cells will response only to stimuli from the right, others only from the left eye.
Orientation selectivity is another example of self organized mapping in the visual cortex. The cortex is formed in a way which ensures that some cells will only respond if the object which stimulates the retina has the correct orientation. In Figure **??** a visualization of an orientation map is shown. Pictures like this one are the result of experiments in which small bars of light are shown to a test animal while measuring the cortical response. The cortex apparently has developed a structure, so that specific cells only respond to their corresponding orientation.

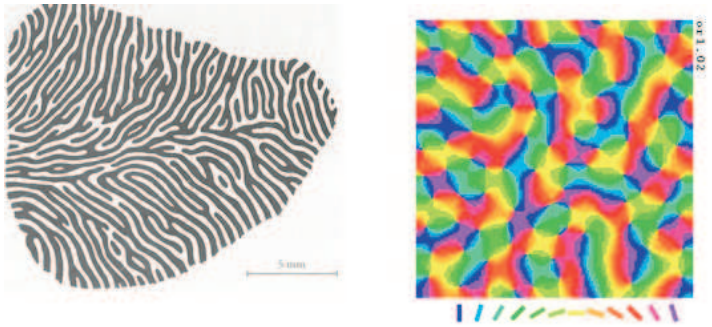

Figure 4: Spacial patterns of ocular dominance(left) and orientation selectivity(right) in the cortex.(Pictures from http://hubel.med.harvard.edu and http://www.vnc.brain.riken.jp/simulator)

Ocular dominance and orientation selectivity are only two examples that show, how a simple planar layer of cells can handle high dimensional information.

3 Neural Networks

In order to develop complex cortical maps, a system has to be able to organize itself and to change its structure if necessary. The Hebbian theory provides an explanation how a neural network is able to learn and therefore how it is able to organize itself.
The theory says, that if the axon of a cell A manages to excite a cell B and does that often enough, there will be some growth process or metabolic change so that A's efficiency to excite B increases.
A possible way how Hebb's theory is applied in nature is the following. Cell A and B are connected via a synapse. The axon of Cell A releases a sufficient amount of a neurotransmitter to excite the dendrite of Cell B. After some more excitations, Cell B releases a retrograde transmitter that binds on Cell A and helps releasing more neurotransmitter next time the cell fires. With this, the synapse between has been intensified.
Generally, Hebbian learning can be seen as an unsupervised training algorithm in which the synaptic strength (in a computational model the weight of a connection) is increased if both the source neuron and the target neuron are active at the same time. A simplified phrase is: "cells that fire together, wire together".
In Figure **??** the two cells with exactly the same action potential patterns will increase their synaptic strength so that in the future a path through those particular neurons in a network will be more likely.

3.1 Inspiration For Computer Science

The understanding of natural neural networks is rather limited. To gain more knowledge one can try to derive simplified models from observations of cortical structures and develop algorithms that simulate neuronal behavior.

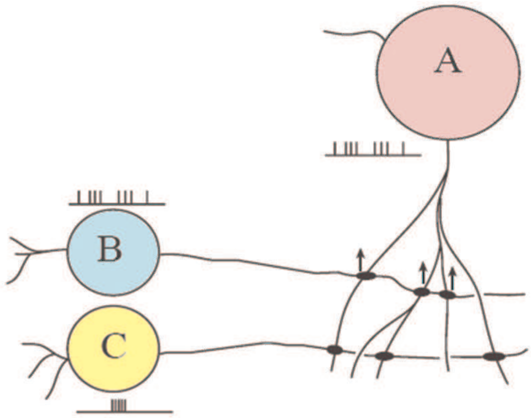

Figure 5: Hebbian learning: Cells in close proximity that fire at the same time (same set of action potentials) increase their synaptic strength.(Picture from http://openwetware.org/images/thumb/e/ed/)

Furthermore the principles of neural networks can be transferred to technical appliances, which have proved to be of considerable significance for example in pattern recognition. Self organizing maps in particular solve a problem often regarded in technical fields: reducing a flood of data from a high dimensional feature space to its low dimensional core whereby retaining important information.

To approach an abstract description of self organizing maps, firstly a mechanism has to be assumed that shapes the structure of cortical maps. Among others one of the theories is that the patterns use unsupervised learning to form their structures. These models are based on competitive learning networks, meaning the cells within the cortex are strongly coupled and the coupling itself describe each cells properties and the pattern that they form.

A model that provides a rather sophisticated description of neural pattern formation is the Kohonen algorithm. It explains the development of cortical maps with unsupervised learning and builds up structures that map from a high dimensional feature space onto a two dimensional surface.

Altogether one might conclude that there is a close cooperation between two rather different areas of research: the biology of the nervous system on the one hand and the technical adaption of data reduction on the other. Both areas make use of self-organizing maps and both depend somehow on the other: gaining knowledge in one field can be of great importance for future research in the other.

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