Biological Inspiration - Neurodynamics

Marko Puljic and Robert Kozma

September 17, 2005

There are more than ten billion neurons in a human brain organized in the populations. Populations interact with inhibitory and excitatory influences. A brain mostly has two kinds of neurons; a projection neuron with the long range connections up to a meter, and a local neuron with the short range connections in its neighborhood. Each neuron connects to about ten thousand or more neurons. Walter Freeman describes the architecture and dynamics of neurons necessary for the neural organization that lead to the intentional actions of animals. The neural populations, with their activity, form the multiple basins of chaotic attractors or the brain states. One state for each class of stimuli. The brain states jump between each other by state transitions in chaotic itinerancy creating the intentional behavior. Tools to analyze a complexity of neurons are the brain imaging and nonlinear brain dynamics. With the architecture of dense connections, the brains are small world networks, in which almost every neuron can reach any other within just a few connections. Neurons create the populations just as the humans create societies or the firms economies. If the neurons create the intentional behavior, do societies and economies have intentionality created by humans' and firms' interactions? If there is an intentionality, how do we see it?

1 Neurons Make Up the Brains

1.1 Introduction

Neurons make up the brain. Figure 1 shows an extreme schematic simplification of a neuron. There are more than ten billion of them in the human brain. Neurons interact with the synapses that are attached to the dendrites. Through the synaptic interactions the neurons cease to be the isolated entities and start to participate in the populations. View of neurons through the populations is a mesoscopic view. Alternatively, a view of a neuron as a single cell is a microscopic view. Neurons mutually excite or inhibit each other, creating states that are seen as the background activity. Since the neurons can either inhibit or excite, the negative or positive influences of a neuron or a neural population exist. A negatively influential neuron or population sends primarily the negative influences, and a positively influential neuron or population sends primarily the positive influences. Two neurons or populations influencing each other are in the loop. Negative loops mix the inhibitory and excitatory neurons or populations, while the positive loops are of same kind, either mixing inhibitory or excitatory neurons or populations. As the neurons interact, the brain activity stabilizes around stable points and trajectories, called the attractors or states. The brain activations switch quickly among the states, and thus cause the state transitions with each switch. A state transition between attractors is a way in which itinerant trajectories of brain activity arise the behaviors. The landscape of attractors formed by learning, through the modifications of synapses, is responsible for the sequences of goal-directed behaviors. The attractors and behaviors are constructions of the brains and neural receptors, which evolve through the interactions with a world.

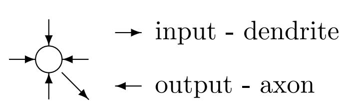

Figure 1: An extremely simplified schematic view of neuron. The dendrites collect input. An axon sends output.

1.2 Conceptual Description of Neuron

An input or electric potential comes to a neuron through its dendrites and an output leaves through an axon, [1]. There are two main types of neurons; a projection neuron and a local neuron or interneuron. The projection neurons have dendritic branches to a diameter of up to a millimeter and their axons can extend up to a meter. The local neurons have dendritic branches to a tenth of a millimeter, which is 25-50 times the diameter of the cell body. A local neruon's axon does not reach as far as a projection neuron's axon. In an analogy with a road system, the interneurons are the local streets, whereas the projection neurons are the interstate roads. An axon transmits an output to synapses, which are attached to the dendrites of the other neurons. The synapses are the places where neurons receive the excitation or inhibition. Most projection neurons are excitatory, whereas interneurons are either excitatory or inhibitory. There are several thousand synapses on the dendritic tree of each neuron. A competition for synaptic space is intense. The inactive synapses decay and disappear and a neuron without enough synapses may vanish. The growth and maintenance of connections, through the modifications of synapses, are responsible for the learning, remembering, and adapting. Typically there are a million or more other neurons within the radius of the dendritic tree of a given neuron. Each neuron connects with about one percent of the neurons within its reach.

1.3 Neural Connections

In figure 2, the connections apply to a neuron and to the populations of neurons. Sensory neurons, (somatic, auditory, gustatory, olfactory), transmit in parallel with divergence, and with no interaction. Cortical neurons interact, so they form the neural populations.

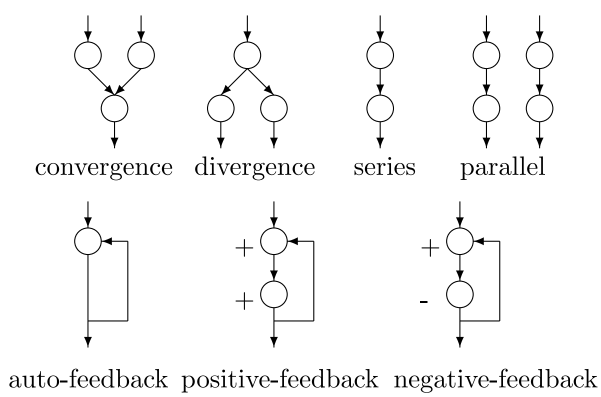

Figure 2: Possible connections among the neurons and the populations of neurons. +/- indicates excitation/inhibition. Figure is redrawn from [1].

2 Activities of Neurons

2.1 Single Neuron States

Electrical potential, or energy, is generated by a neuron across the neural membrane. A neuron acts on another by sending its electrical potential via axons. An axon expresses its state in the frequency of its action potentials or pulse rate. Energy sent across an axon is provided over the entire length with a short delay, one pulse at the time, because an axon needs a recovery time. Dendrite takes the input. It expresses its states with the intensity of its synaptic current or wave amplitude. Dendrite integrates the pulse inputs. Neuron's dendritic wave is proportional to the total number of pulses neuron's dendrite receives. In a neuron, wave of a current can be superposed on top of the currents from other synapses. In short, neuron converts incoming pulses to waves, sums them, and transmits the pulse train to all its axonal branches. Important inhibitory synapse turns the current, so it decreases the firing probability and the axonal pulse rate of active neuron.

2.2 Microscopic vs. Mesoscopic

Single neuron activation is expressed with the flow of the loop current inside the neuron. It is private, intracellular, microscopic view. Microscopic pulse and wave state variables describe the activity of the single neuron. In microscopic view, time and space scales are measured in thousandths of a second and thousandths of a millimeter. Mesoscopic state variables describe the collective neural activities that are public, with time and space scales in tenths of a second and tenths of a millimeter. The mass activity in a local neighborhood is described by a pulse density, which is a simultaneous firing of the pulses of many neurons in a neighborhood.

3 Building Blocks of Chaotic Neurodynamics

3.1 Short Description of Building Block of Neurodynamics

The building blocks of neurodynamics are described in detail in [1]. The blocks describe the architecture and dynamics of neurons necessary for the neural organization that leads to the intentional actions of animals. The first block is the first step by which neurons start to participate in a group collectively. Activity level of a group of neurons is determined by a sum of all neural activities in the group. The neural populations can have the negative and positive influences. When the populations mix, through the negative and positive influences, they create the oscillations of their activation levels, figure 3 bottom. The oscillations of population activity are the second building block of neurodynamics. Other building blocks of Freeman describe how the smaller modules interact and build larger modules up to the whole brain and body. For example, the stimuli for the neurons are required to start the oscillations. The oscillations can be prolonged by the modifications of the neural connections, which is a form of learning and another building block. If the populations, which oscillate with different frequencies, communicate between each other, the chaos as the background activity is formed. Other building blocks include: a distributed wave of chaotic activity across the neural populations, a destabilization of neural activity by the input, a dependence of neural activation on the context and history, a shaping of amplitude modulation patterns of neural activity by learning, an attenuation of microscopic sensory-driven activity to enhance the macroscopic amplitude modulation patterns, a multisensory convergence of input into entorhinal cortex, and a formation of sequence of global amplitude-modulation patterns of chaotic activity. Below are the additional explanations about couple building block of intentionality, which are modeled in this work. A focus of the examples below is towards the topics that this study is about, which are the models of first four building blocks of neurodynamics by Freeman. For more details on all of the building blocks of neurodynamics, [1] should be studied.

3.2 Figures of Couple Building Blocks of Neurodynamics

The first building block happens when the neurons start to act as a part of a group, figure 3 top. With the second building block, the oscillations occur due to the interactions between the excitatory and inhibitory populations, figure 3 bottom.

The populations oscillate because the input is a shock to the neural populations. Populations' activation suddenly increases when perturbed. The excitatory population gives the surge of excitation to the inhibitory population. This increased inhibition reduces the activation of excitatory population, which then decreases the excitation of inhibitory population, and so on. The population cycles through the time, but with the diminishing activation amplitudes. Once there are coupled populations of the negative and positive influences the chaotic behavior can be produced. General description of the chaos is well described in [2]. The negative feedback in the coupled populations provides the oscillations. But different coupled populations, in general, have different frequencies. If the three different oscillating populations are influencing each other they cannot agree on the unique frequency and thus generate the chaotic background activity, figure 4.

4 State Space of a Cortex

4.1 Itinerancy of Brain States

Oscillating population modules can generate a chaotic activity, but normally they do not. Each module has only a point attractor and a limit cycle attractor with its characteristic frequency. The chaotic activity

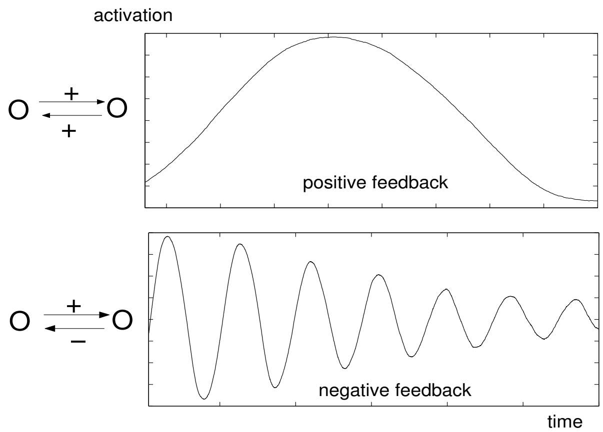

Figure 3: The first two building blocks of neurodynamics redrawn from [1]. A positive feedback prolongs an activation (top). A negative feedback creates the oscillation (bottom). + is for the excitatory influences and − is for the inhibitory.

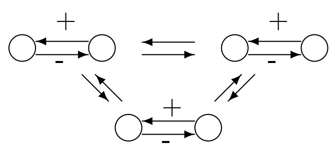

Figure 4: Schematic view of three coupled oscillating system, which can produce chaotic activity. The fourth building block of neurodynamics.

results from the coupling of the modules. Neural populations consist of many coupled populations with the different oscillating behaviors. Together, the neural populations form the multiple basins of chaotic attractors, [1, 3]. A state space of a brain comprises attractor landscape with several adjoining basins of attraction, one for each class of stimuli. The basins of attractors are the brain states. Kaneko, Tsuda and Freeman described the activity of a brain with an itinerant trajectory over its landscape of attractors. There is succession of momentary pauses in the basin of attractors or states to which a brain travels once a learned stimulus arrives. The states jump between each other by the state transitions in a chaotic itinerancy. So, each itinerant step is a global state transition, and it occurs several times a second. A step is experienced as a jump of thought. The basal chaotic behavior keeps the system in a state of readiness to move in any direction. The system is always close to any of its basins of attraction. A state transition to a neighboring basin can take place with a small but significant perturbation of the system. The attractors are shaped by the stimuli and by previous experience with those stimuli. An input modifies the synaptic connectivity and consequently the attractor landscape. A state transition arises activity of itinerant trajectories of brain, and governs the behaviors. A landscape of attractors is responsible for the reliable sequences of goal-directed behaviors.

5 Intentionality and Meaning Created by Brain

5.1 Tools to Study the Brain

How do the humans and animals experience their minds? How do the experiences influence and change the brains? And how do the cells in a brain create the thoughts and intentional actions? An apparatus where the experiences and thoughts are created is a brain, figure 5. The tools needed to answer the questions posed are brain imaging and nonlinear brain dynamics and they describe self-organization and the patterns of brain activity. A knowledge accumulated by applying the brain imaging techniques and nonlinear dynamics are used in this work to build the models which can produce the brain like dynamics.

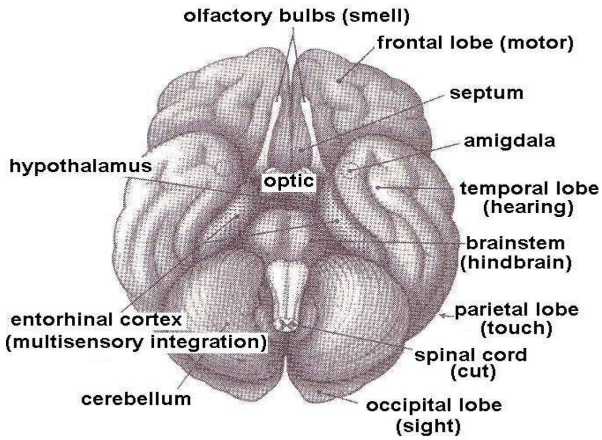

Figure 5: A schematic view of a human brain redrawn from [1]. Different modules are associated to different functions.

5.2 Intentionality and Meaning

Brain dynamics is created by self-organizing interactions among the brain cells, neurons, which give to each of us the intentional behavior. Process of intentionality creates the meanings. When it comes to meaning, an individual is a unique universe. The experiences and knowledge is constructed within an individual. A basic activity of biological creatures is a search for meaning, which is realized through the constant activity, where the action consequences are revealed as joy or pain in the minds. There are three main properties of intentionality; unity, wholeness, and purpose. A unity dimension unifies the brains and bodies, which are entirely committed to the action of projecting into the world with the perceptions unified across all the senses. A wholeness dimension brings the entirety of life's experience to each moment of choice. A purpose dimension directs all the actions to some end. To comprehend the brain dynamics and its intentionality, the brain mechanisms through which neurons construct the choices need to be understood. There has to be an explanation of what is occurring with the neural organization at moments of choice, and an explanation of awareness and consciousness. There is a good knowledge about how the brains do it, [1, 3, 5], so it should be possible to mimic the principles of biological brains to create the artificial models, which behave in a brain-like fashion.

6 Brains and Societies

6.1 Brains are Small Words

The neurons rapidly enter into a cooperative state, which persists for about a tenth of a second before dissolving and transforming to the next state. The macroscopic chaos develops by interacting brain parts of their own frequencies of activation. The parts are synchronized as long as their phases of oscillation are synchronized. An example of the synchrony of two oscillators is in figure 6. During the state transitions the activation phases of brain parts are out of synchrony, and while in the state the brain parts are synchronized. The synchronization of the brain parts and the state transitions occur very quickly, because each cortical neuron is a few synapses away from any other.
The brains are small worlds, [4]. The transmission distances over which cooperation is established are thousands of times greater than the diameters of spread of the axons and dendrites of all but a few neurons. There are two creations that support the rapid formation of unified global states in the mammalian brains. The first one is a large projection neuron. The second one is a continuous sheet of neuropil, or densely packed neurons, covering each brain part. The long dendrites penetrate all layers and spread widely in all directions in the sheet. The large projection neurons integrate the neural activity over the large cortical areas. The architecture of a brain reminds of the architecture of the satellite links between the cities that all have local telephone networks.

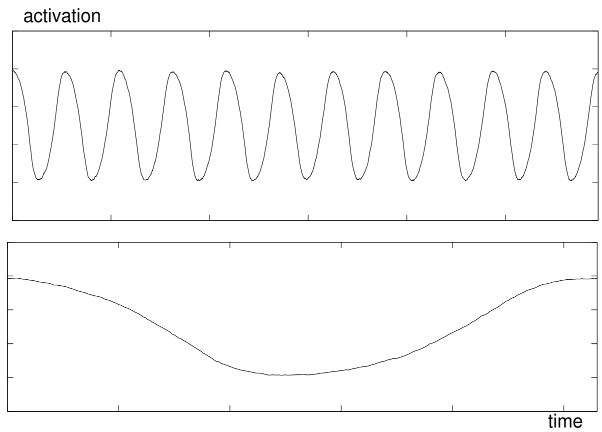

Figure 6: Schematic view of the two oscillators. Different brain parts oscillate with different frequencies. The two populations in figure are in the synchrony at first and last point.

References

[1] W. J. Freeman, *"How Brains Make Up Their Minds,"* Columbia University Press, New York (1999)

[2] K. T. Alligood, T. D. Sauer, J. A. Yorke, *"Chaos - An Introduction to Dynamical Systems,"* Springer-Verlag New York Inc. (1996)

[3] K. Kaneko, I. Tsuda, "Chaotic Itinerancy," *Chaos,* 13 926-936 (2003)

[4] D. J. Watts, *"Small Worlds: The Dynamics of Networks between Order and Randomness (Princeton Studies in Complexity),"* Princeton University Press, Princeton (1999)

[5] D. O. Hebb, *"The Organization of Behaviour,"* John Wiley & Sons, New York (1949)