Lecture 1. Design Principles of the Brain

—A Thought of a Physiologist

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The subtle design of the brain implies certain computational principles. Nevertheless, such design was not determined a priori, but it has developed through a long course of evolution. Two obvious features of the brain arise for this reason. First, the perceived design of the brain must depend on biological material available during evolution, i.e., largely neurons. It is apparent that evolution proceeded from single neurons to ganglion- or nucleus-types of neuronal assemblies, and eventually to the multilayered structures that acquired the capability of parallel distributed information processing. Here, we find a rationale for presently thriving molecular and cellular neurosciences that try to work out every detail of the neurons. Second, while the brain consists of an enormous number of neurons, local rules for interneuronal relations often govern overall structural-functional features of the brain. The currently developing "computational neuroscience" ensures that local rules such as the Hebbian synapse, Gaussian distribution etc. lead to formulation of a novel capability of information processing, as represented by Perception, an Adaptive Filter, a Neurocomputer based on Back Propagation Principles etc.

Each division of the brain contains a characteristic neuronal network. Local networks are allied to form complex systems which are devoted, each to a certain brain function such as cognition, motor control, emotion, memory-learning or consciousness. The third characteristic feature of the brain is a hierarchical organization of brain systems. At the bottom of this organization, numerous reflexes operate, while compound reactions such as posture, locomotion, saccade etc are higher-order systems above reflexes. Upon the automatic machinery provided by reflexes and compound reactions which are functions of the spinal cord, medulla and midbrain, further higher-order brain functions are superimposed. For example, the cerebellum seems to have emerged originally as an organ which endows reflexes and compound reactions with adaptive capability. Current knowledge of neurophysiology also suggests that the basal ganglia make up an organ that stabilizes compound reactions. Above these, the diencephalon and cerebral limbic system developed. While the amygdala evaluates biological significance of external stimuli, the hypothalamus expresses emotion and organizes innate behavior of an animal according to the biological implications of the stimuli. The midbrain reticular formation could be the site of vigilance that controls functional levels of the whole brain. It has been a major theme of neurophysiology to identify the functional purposes of each division of the brain and to reveal their mechanisms.

While the brain evolved initially in a bottom-up manner, from reflexes, to compound reaction, to innate behavior, later development appears to have taken place in a reversed top-down manner, owing to expansion of the neocerebrum. Thus, evolution appears to have switched from bottom-up systems governed by peripheral stimuli to top-down systems dominated by cerebral signals, as it proceeded from non-mammals to mammals. This dualistic development is the fourth principal feature of design principles that underlie evolutionary elaboration of brain functions culminating in human mental activity. Recent investigation of the cerebral visual system has revealed intricate computer-like mechanisms devoted to visual information processing. However, the cerebral cortex is also devoted to voluntary motor control for which command signals must be generated within the brain. The cerebral cortex is also devoted to evaluation of cultural and social significance such as truth, beauty and virtue, for which criteria must be laid down somewhere in the brain. Such generation and evaluation of information must imply unique designs of the human brain that have never been adopted in construction of man-made computers.