MODELLING AND NEUROMORPHIC REALIZATION
OF CORTICAL FEATURE MAPS

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Introduction

Human brain is the most remarkable machine devised by nature. Humans surpass all other species in terms of their advanced cognitive abilities, language skills and their ability of abstraction, understanding, intelligence and awareness. Understanding how the human brain achieves these astonishing feats is considered one of the final frontiers of science. This clearly requires a coordinated multi-disciplinary effort of various disciplines like neuroscience, medicine, physics, psychology, mathematics, computer science etc. It is believed that through such collaborated efforts, we would not only be able to understand how the brain functions and build revolutionary new computing technologies that are inspired by the brain, but would also gain profound insights into what makes us human – our consciousness.

Nature endowed all species with a basic level of intelligence that allowed them to interact suitably with their environments. However, as environments became more complex or threatening for survival, centralized machinery for controlling the bodies became necessary and this led to the formation of brains. Brains became a means through which better and longer survival was ensured. Through brains species could experience the environment, engrave those experiences as memories and evolve. For species without brains evolution was possible only through genetic changes that happened over many generations. Earlier brains were primarily sensory brains, that acquired and processed information about the environment from various external senses such as vision, touch etc. and performed what is called bottom-up processing. These brains were mostly pre-wired for specific functions but allowed a minimum level of adaptability. As the brains evolved, not only did they become more and more adaptable, but also started exhibiting top-down capabilities such as attention, volitional control, ability to observe one’s actions, conscious awareness etc. These top-down factors had a profound role in further evolution of brains and led to remarkable abilities like the ability to abstract, plan, think creatively, appreciate beauty, introspect etc.

Most contemporary neuromorphic models of the brain take inspiration only from the computational aspects of the brain. This includes distributed and parallel processing, low power consumption, fault tolerance etc. Some models also take into account the self-organizational or adaptive aspects of the brain. However, aspects of top-down processing are often overlooked. This thesis has attempted to look at both the adaptation aspects as well as higher order or top-down capabilities in highly evolved brains.
Adaptation in the human brain happens at two levels. The first level of adaptation happens during the early post-natal periods where with proper sensory stimulation the brain develops from a system of many diffuse and redundant connections to a finely tuned system capable of complex behavior and perceptions (Johnson, 2001; Stent, 1973). This is achieved through the formation of structured connections between neurons in different cortical layers in the different sensory modalities like vision, audition, touch etc. These critical interconnectivity patterns are known as feature maps. These feature maps are crucial for normal sensory operation or bottom-up processing in the brain. Since they are spatially limited to specific sensory modalities we refer to them as local feature maps. This arrangement of neurons not only leads to reduced long range interconnectivity between neurons but also allows filling in for loss of signal from damaged brain areas by taking in and processing information from adjacent areas processing similar stimulus (Jain et al., 2008). Local feature maps are formed during a critical learning period (Sur & Leamey, 2001) during which external stimulation causes learning to happen easily but beyond which it becomes increasingly difficult or even impossible to develop some functions. For example, the critical period for a human child to develop binocular vision is three to eight months (Banks et al., 1975). During this time if one of the eyes remains closed, the human child would never develop a sense of binocular vision because the cortical area for the closed eye would be taken over by the operational eye. Similar critical learning periods have been identified for other modalities such as audition, spatial orientation, language processing and other aspects of vision such as orientation selectivity, direction selectivity, perception of depth etc. This form of learning creates highly specialized neurons that serve as the mechanism of neuronal encoding. Such cells are often referred to as feature selective cells because they respond to very specific stimuli. In a layered hierarchy of cortical structure, feature maps in higher layers extract basic features from the lower order maps in lower cortical layers allowing increasingly complex feature detection as we go up the cortical hierarchy.

The second kind of adaptation happens through out the adult life through creation of dynamic brain-wide neural associations/assemblies through which complex multisensory information integration happens (Senkowski et al., 2008). These associations could be related to complex cognitive or perceptual tasks (Ward, 2003; Melloni et al., 2007), sensory motor tasks (König & Engel, 1995) and even complex associative thinking including abstraction, problem solving etc. This form of adaptation is more of an additive process that creates new synapses or strengthens existing synapses rather than eliminating redundant connections. These assemblies involve neurons of both sensory and association areas. We call these brain wide neural associations or assemblies global feature maps. Depending on functional requirements different neurons in distributed areas of the brain, fire
in synchrony and act like a closed system. Individual neurons can participate in different neural assemblies and therefore be involved in multiple computations. For some cognitive tasks that are performed repeatedly, these neural assemblies hardwire, leading to formation of zombie modes (Koch & Crick, 2001), tasks that can be performed in the absence of attention and conscious awareness. It is being conjectured that this ability of delegating repetitive tasks to unconscious processing has had a major role in the evolution of human cognitive abilities, since it releases valuable resources of attention for even more complex tasks (Shine & Shine, 2014). However, how these hardwired neural assemblies or global feature maps form is a question that is still not fully understood. It has been observed that plasticity in the brain depends on synchronized neuronal firing within a critical window of a few milliseconds (Caporale & Dan, 2008), or as Hebb puts it, ‘cells that fire together wire together’ (Hebb, 1949). The plasticity is best when there is a zero-lag synchrony between the neurons. Therefore, if neurons in widely separated parts of the brain have to connect through synapses, they need to synchronize with zero-lag. The role of neural synchrony in developing cortical networks is now gaining a lot of interest (Uhlhaas et. al, 2010). However, this raises a paradoxical situation. For synchrony to arise, some kind of connection is required. But in the absence of any pre-existing direct synaptic connection (as would be in a developing brain), how do neurons in widely separated areas of the brain synchronize? We term this as the Neural Development Paradox. To understand the underlying mechanism of neural synchrony and hence cortical development or global feature map formation, we need to break the Neural Development Paradox.

Most models that have attempted to explain the formation of feature maps (Elliott & Shadbolt, 1999; Swindale & Mitchison, 1999; Markan & Bhaumik, 1999; Martinetz & Schulten, 1991), successfully capture the essence of short-range synchronization between neurons and therefore are able to explain formation of local feature maps. However, the challenge lies in explaining how synchronized oscillations arise in far away neurons and this problem becomes more pronounced when it comes to zero-lag synchrony across hemispheres. Some highly specialized models have proposed different methods that could possibly account for the long distance zero-lag synchrony between neurons. E.g. entrainment from a single source like other cortical or sub-cortical areas, that could synchronize the respective target cells has been proposed by (Steriade, 2006). Another method proposed is the zero phase synchronization based on network effects such as recurrent inhibition, mutual excitation, mutual inhibition and synaptic spike doublet based coupling as proposed by (Ritz & Sejnowski, 1997). Finally some authors also suggest that reciprocal coupling of cortical areas with different thalamic nuclei may have a role in the coordination of distributed
cortical processing (Sherman & Guillery, 2002). However, these approaches have two major caveats. Firstly, they assume that precise connections between various parts of the brain already exist, which may be unlikely in a developing brain. Secondly, axonal transmission delays (due to the inherently slow mechanism of chemical neurotransmission) that could amount to tens of milliseconds are not taken into consideration. While slow oscillations in the delta and theta range (0.1-7 Hz) may be explained using this slow mechanism, problem is faced when it comes to explaining faster oscillations like beta and gamma synchronization (20-80 Hz). Therefore, there is a need for exploring alternate means of rapid communication in the brain by which coordinated activity across wide areas of the brain can be achieved. In addition, there is also a need to look for a possible explanation of higher order or top-down capabilities in advanced brains that, despite of decades of research, neuroscience has not been able to identify.

Some physicists have suggested that answers to these questions, pertaining to higher order capabilities of evolved brains, could be obtained by looking at a finer or quantum level of activity happening in the brain possibly at the sub-neuronal level. According to a recent theory by Sir Roger Penrose and Stuart Hameroff known as the Orchestrated Objective Reduction (Orch OR) Theory of Consciousness (Hameroff & Penrose, 2014), a much superior form of computing, known as quantum computing, happens at the sub-neuronal level (Hameroff, 2007). Penrose and Hameroff suggest that microtubules, sub-neuronal particles that form the cytoskeleton of all cells, are composed of tubulin dimers that can exist in superposition of two different conformational states. These microtubules could therefore act like quantum bits or qubits and hence may be capable of performing quantum computations, allowing multiple computations to happen simultaneously giving the brain tremendous computational capacity. Moreover, if we could have microtubules in distant neurons, interacting non-locally through possible quantum mechanisms like entanglement, sharing a common wavefunction, we could answer many questions related to achieving zero-lag synchrony across areas of the brain that may not be directly connected. With a large number of microtubules participating in any computation, the energy of the microtubule assembly may reach a critical threshold (Penrose, 1994; 1996), causing the wavefunction to reduce or collapse into a single state making the associated neurons fire in synchrony, leading to brain wide coherent activity and also creating moments of conscious awareness. There is a possibility that these continuous collapses give rise to our stream of conscious awareness and thoughts. Therefore, conscious awareness may be attributed to subtler aspects of computing in the brain. They also conjecture that these coherent microtubule states could be conveyed through an alternate route of very fast electrical communication between neurons using dendritic gap junctions or electrical synapses.
forming a subtle quantum network. These gap junctions can connect many widely separated neurons to form ‘hyperneurons’ (neurons that depolarize and fire together) (Kandel et al., 2000), seemingly breaking the Neuronal Development Paradox. The presence of gap junctions has recently been shown to be necessary for proper chemical synapse formation (Todd, 2010) and therefore, this subtle coordinated activity happening at the sub-neuronal level, that is conveyed through gap junctions could be supervising or laying a blueprint for neural development. This quantum network could be supervisory in nature, and may override the classical connections leading to a situation similar to volitional control. Some physicists have also been suggesting that other top-down capabilities such as self-awareness and mind-brain interaction may also have an explanation in quantum physics (Wolf, 1996; Stapp, 1995; Atmanspacher, 2004; Beck, 1994). Therefore, there may be a need to explore subtler aspects of computing in the brain to understand completely both adaptation aspects of the brain as well as origin of higher order, top-down capabilities.

Creating intelligence in machines has been the goal of many engineering disciplines. Over the years various approaches have been taken to realize intelligence at different levels. For example, software methods such as evolutionary algorithms and genetic optimization techniques have been used to capture intelligence at the most fundamental or genetic level (Eiben & Schoenauer, 2002). This is similar to emulating intelligence in living organisms that do not have brains and only evolve through genetic modifications and laws of evolution. Other approaches such as Neural Networks (Kumar, 2004) and Neuromorphic Engineering (Mead, 1990; Lande, 1998) attempt to capture the computational aspects of brains. These approaches emulate the parallel and distributed architecture in brains where interconnectivity between the processing elements or neurons plays a key role, resembling closely species with primitive brains. While Neural Networks have enabled the development of computing paradigms that are far superior to sequential computers due to their ability to perform massive parallel computations, low power consumption, fault tolerance and graceful degradation, the qualities derived from the uniqueness of the brain, however, they are software models and are extremely simplified versions of real neural networks. Neuromorphic systems on the other hand aim at creating hardware for real time applications using analog/digital or mixed VLSI implementations that more realistically capture the complexity of neural hardware. In the past few years, due to advances in semiconductor technology, Neuromorphic Engineering has made tremendous progress (Indiveri et al., 2011; Benjamin et al., 2014). However, while a lot has been achieved in terms of the complexity and computational abilities of neuromorphic systems, they are yet to match the self-organizational capabilities of the brain and therefore efforts are now required to create novel architectures that can truly capture the essence of adaptation and self-
organization that happens in the brain. A major step towards this would be to adaptively create feature maps in silicon. However, the real challenge lies in capturing human like intelligence which seems to be much more complex since it is not only driven by genetic evolution and environmental adaptation like the first two categories, but also internally generated top-down factors.

According to Sir Roger Penrose, computational models of the brain fall into two distinct categories: Top-down models and Bottom-up models (Penrose, 1994). Top-down models, work according to a well defined or clearly understood procedure, providing a clear-cut solution to some problem at hand. Intelligence is programmed into the system and the individual elements behave in accordance to the defined rules to achieve a particular task. On the other hand, in bottom-up models, clear rules of operation and knowledge store are not well defined. The system learns and improves its performance according to experience. Penrose emphasizes that any attempt to capture human cognition artificially should be a combination of both the bottom-up and top-down approaches. If we can combine the two different aspects of computing in the brain discussed earlier i.e. bottom-up sensory processing and top-down executive or supervisory control, into a unified framework we could attempt to explain aspects of human intelligence. This could be done by creating a model that harnesses the subtler sub-neuronal or quantum aspects of computation in the brain and interfaces this quantum level to supervise the development of the classical level. In some sense, the higher order rules that guide neural development would be maintained in the quantum level and therefore this kind of arrangement takes advantage of both bottom-up and top-down processing in the brain. However, even before we can think of creating machines that could posses human like intelligence or awareness, we first need to understand how these phenomenon arise in human brains and therefore understanding human consciousness may be the need of the hour.

**Thesis Objectives**

The research work commenced with the below stated objectives, however during the course of research, some additional problems were explored which included understanding various aspects of the brain from an evolutionary perspective.

1. To design, refine and fabricate the basic building blocks for competitive learning using non-volatile analog memory based “synapses” in CMOS technology.
2. To develop methodology of building artificial adaptable feature maps for visual features such as ocular dominance, orientation selectivity, direction selectivity etc.
3. To explore application to other sensory modality maps and hierarchically higher layers.
4. To explore possible mechanisms, in both the classical and quantum domains, that could potentially break the Neural Development Paradox
5. To explore the area of quantum computation and quantum neural networks and to understand how quantum information can benefit neural computation.
6. To explore a quantum mechanical model/framework for feature map formation that could address formation of both local and global feature maps.

**Thesis Outline**

This thesis is a suitable conglomerate of the various problems undertaken during the course of this PhD and is broadly divided into two parts. The first part of the thesis, deals with modeling the bottom-up aspects of processing in the brain. In accordance with the state of the art in neuromorphic systems, innovative analogue VLSI designs for artificial neural structures have been proposed that can adaptively learn from sensory experience just like the biological brain. These designs are based on local (intra-modality) or near neighbor interaction between neurons leading to clustering of cells with similar feature preference. Some of the widely studied feature maps that have been observed in the visual cortex e.g the Ocular Dominance Map and the Orientation Selectivity Maps have been recreated artificially.

The second part of the thesis deals with the limitations of the bottom-up approach in explaining brain-wide interaction between neurons, or the Neural Development Paradox, and attempts to explore how invoking subtler sub-neuronal quantum processes can address this limitation. Based on the understanding of quantum aspects of information processing in the brain a unique Quantum Hebbian Model of learning has been proposed that assumes that the quantum aspects of human brain play an important supervisory role during the development of the brain. This model is applicable for brain wide or global interaction between different areas of the brain which may or may not be connected by physical means. Invoking this subtler level of activity inside the brain allows us to address issues such as volition, awareness, self-observation and other aspects related to higher order capabilities in advanced brains. How the brain evolved and how higher order capabilities became visible in evolutionarily more recent brains is also explored in one of the chapters. The chapter wise organization of the thesis is as follows.

**Chapter 2:** In order to realize cortical plasticity, through the synapse elimination algorithm in
hardware, a novel analogue CMOS design of a cortical cell has been presented in this chapter. The cell computes weighted sum of inputs and exploits the adaptation dynamics of floating gate pFET ‘synapses’ to perform competitive learning amongst input weights as *time-staggered Winner Take All (ts-WTA)*. When learning ends, the cell’s response favors one input pattern over others to exhibit feature selectivity. Due to its close similarity with biological networks in terms of adaptability and long-term memory the cell is ideally suited for analogue VLSI implementation of Self-Organizing Feature Map (SOFM) models of cortical feature maps.

**Chapter 3:** This chapter discusses the *Ocular Dominance* feature map observed in the visual cortex and proposes a design for an adaptive circuit that emulates the biological Ocular Dominance feature map using the ts-WTA learning cell as a basic building block. Embedded on a 2-D RC grid, the ts-WTA cells are able to develop under the influence of a neighborhood forming clusters of similar feature selectivity. Over a large cortical surface through diffusive interaction, these cells are able to form symmetry breaking patterns similar to the biological Ocular Dominance Map.

**Chapter 4:** This chapter discusses another novel use of the time-staggered Winner Take All cell, to develop an adaptive cortical cell that demonstrates *Orientation Selectivity*, a well-known biological phenomenon observed in the visual cortex. The cell performs competitive learning, refining its weights in response to input patterns resembling different oriented bars, becoming selective to a particular oriented pattern. Different analysis performed on the cell such as orientation tuning, application of abnormal inputs, response to spatial frequency and periodic patterns reveal close similarity between our cell and its biological counterpart. Embedded in a RC grid, these cells interact diffusively exhibiting cluster formation, making way for adaptively building orientation selective maps in silicon.

**Chapter 5:** This chapter discusses some of the open issues in neuroscience in particular the problem of how neurons in distant areas synchronize with zero lag in the absence of a direct connection: *Neural Development Paradox*. Two kinds of processing in the brain: conscious and unconscious have been highlighted and it has been discussed how conscious processing seems to have an inherent advantage. This is followed by a discussion on some of the other open problems in neuroscience such as volition, self-awareness and top-down causality. It is then highlighted that Quantum Physics has the potential to answer some of these questions. Salient features of some of the most famous Quantum Theories of Consciousness have been elucidated and an argument as to how major aspects of these different theories can be combined to get a better and more holistic understanding of the brain and higher order capabilities has been put forward.
Chapter 6: In this chapter a framework for the formation of global feature maps or brain wide neural assemblies that is based on the interaction of Quantum i.e. top-down and Classical i.e. bottom-up processes in the brain has been proposed. A model of a Quantum Neural Computer has been built to understand quantum computations in the brain. A Quantum Hebbian Equation has been developed using which different states of the brain like learning, zombie, mind wandering and volition have been explained. The model highlights the role of attention and subjective experience in developing our neural circuits and shaping our personalities and therefore is a preliminary step towards understanding how top-down processes like attention and awareness lay a blueprint for the development of the brain.

Chapter 7: This chapter highlights the possibility of having two distinct regimes in brain function separated by a threshold marked by the limit of axonal communication. The Classical Regime is where processing speed is at or below the limit of axonal communication and the Quantum Regime is where processing speed is higher than the limit of axonal communication and is controlled by collapse rate determined by Penrose-Diosi relation, $T=\hbar/E$. Quantum Regime can be exploited for increased efficiency in learning and adaptation and hence better survival. Using the principle of sampling, an attempt has been made to explain the presence of a mind-like observer in the brain. Higher order capabilities such as self-awareness, top-down causality and volition have also been explained under this new premise.

Chapter 8: In this chapter the significant contributions of this thesis towards modeling and understanding brain function are highlighted and the scope for future research is discussed.

Thesis Contributions

The most significant contribution of the thesis has been

2. Understanding the subtler quantum aspects of information processing in the brain and creating a Quantum-Hebbian Model of learning applicable for brain-wide or global interactions of neurons.

More specifically, many unexplored aspects in the field of neuromorphic engineering and in understanding of the brain function have been addressed
1. A novel time-staggered Winner Take All circuit has been developed which performs competitive learning between two competing inputs and declares a winner based on which input is statistically more significant, emulating very closely the process of synapse elimination in the brain. When many such cells are connected diffusively, they are able to form symmetry breaking patterns similar to cortical feature maps.

2. A circuit with a three layered topology consisting of the retina, the LGN and the cortex, inspired by the visual system, has been developed that learns and recognizes different oriented bars, closely emulating the orientation selective cells present in the visual cortex.

3. Quantum physics has been invoked for the very first time in the process of creating neural assemblies.

4. An evolutionary model of the brain that describes how the brain function can be divided into two distinct regimes, Quantum and Classical, and that attempts to explain levels of awareness in different species and puts forth a possible mechanism for volition, self-awareness and top-down causality has been proposed for the first time.

Publications

The research conducted has been appreciated at many national and international forums and has resulted in the following publications.

Journals


4. Priti Gupta, C.M. Markan. On Evolution and The Quantum and Classical Regimes in Brain Function, J. of Consciousness Studies (accepted for publication)

Conferences

QANSAS, 28 Nov – 2 Dec, Dayalbagh Educational Institute, Agra, U.P., India.


References


