Cortical Processor - Toward Deciphering Cerebral Code.

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Cerebral cortex is the most prominent feature of human brain and it is relatively easy to assign to it the key role in perception, cognition, and behavior[i]. Furthermore, from computational neuroscience point of view it is very tempting to postulate emergence of intelligence from an array of massively interconnected but relatively simple and uniform cortical minicolumns. However, most vertebrates including fish and lizards exhibit rudimentary behaviors that obviously require perception, while most mammals, and to a lesser extent some avians, possess behavioral properties related to cognition and intelligence[ii]. Yet, regarding cognition, in his 1988 "The society of mind" Marvin Minsky once said, "It often does more harm than good to force definitions on things we don't understand." Attributing cognition to cortical function alone may have some problems because of the following:

- Most warm-blooded vertebrates including many avians (crows, pigeons[iii], parrots, etc.) and certainly rodents[iv] demonstrate complex behaviors including navigating labyrinths, using tools, and migrating across the globe even though they lack large association cortices. However, their small brains have well defined sensory and motor regions as well as developed hippocampi and thalami.
- Furthermore, cortical trauma rarely results in loss of consciousness and cognition, while trauma to deep subcortical areas most of the time results in vegetative state.
- And lastly, cerebral cortex is a relatively late edition to vertebrates' brain and there must be a point in vertebrates' evolution when complex behaviors and cognition emerged in primitive brains.

Brain have evolved as a tool to mitigate the environmental and later societal pressures to survive and procreate. Brains in various species have developed from bottom up while preserving their basic architectonics - in other words neocortex had developed under the mediating guidance from the lower level structures, specifically thalamus; while the latter had evolved as a sensory conduit that is found even in fish and lizards.

I conjecture that advanced cerebral performance in mammals can be traced to three levels of brain evolutionary development:

First - Neurophysiological selfishness: for the lack of better term, this definition is used here to delineate the unique relationship between the animal's body and its environment. S_elfishness:_ this is "me", and that is "the rest of the world". Foreign objects cannot occupy the space where my body is located without causing pain, discomfort, and sensation of fear - emotional responses that are regulated by amygdala in mammals. This is one of the basic survival instincts that must be supported by simple brain structures available even to low vertebrates [v]; and indeed, all vertebrates including fish, reptiles, birds, and mammals have structures similar to human hippocampus [vi] with its characteristic _place_ and _grid cells_ in CA1 and CA3 areas. Amygdala is located at the base of fornix and hippocampus - it receives sensory inputs and modulates various brain areas; as the main emotional center, it is responsible for annealing emotion-related memories.

I am making a conjecture here that in addition to _place_ and _grid_, hippocampus contains an ensemble of cells that represents the physical space outlined by the surface of "my" skin - "me". Penetration by a foreign object into "me" causes fear, and that explains why amygdala is co-located with hippocampus. Additionally, the shape of hippocampal representation of "me" changes based on

proprioceptive inputs that represent motions of "my" limbs as well as eyes and head gazing directions. When not asleep or anesthetized, "I" is always present in "my" hippocampus.

It is known that higher levels of visual ventral stream (V4), auditory (A3 and A4) and somatosensory (S2) pathways merge within the temporal cortex where sensory integration is taking place; this area is also adjacent to hippocampus. There is strong experimental evidence that hippocampal area particularly associated with CA1 and CA3 cells [vii] is the holding place for virtual representation of the physical world that immediately surrounds "me".   Based on somatosensory inputs, a specific subset of hippocampal grid cells is activated when I change my body position, head orientation, and eyes gazing direction. After being processed in V1, V2, V3 and V4, the retinal image of the physical object becomes associated with the corresponding previously activated subset of hippocampal grid cells. This subset specifically represents the virtual object I am looking at, as well its 3D location as related to spatial configuration of *my* body. Therefore, what "I" see is not what is projected on my retinae, but instead what is present in my hippocampus. I can close eyes and still imagine everything around me, albeit with lower fidelity. Saccadic eye motions constantly reinforce the virtual representation of the real world that surrounds "me". The similar mechanism may govern auditory perception [viii].

If "*me*" sells do exist, they should be tightly bundled in one relatively small volume of hippocampus and be associated with the origin of frame of reference of "*hippocampal virtual world.*"

Furthermore, it may be reasonable to predict the existence of "*them*" cells as well. "*Them*" cells redefine *objects* in hippocampal virtual world sensory field as *subjects* that may act upon physical world and can be communicated or interacted with using some sort of linguistics. Unlike very localized single cluster of "me" cells, "t*hem*" cells would be evenly distributed among hippocampal CA1 and CA3 cells, but remain inactive for as long as the corresponding physical volume is not occupied by a potentially acting subject.

Second - Consciousness [ix]: "I" can coherently operate in this world by using past experiences that were previously stored in prefrontal cortex - the long-term memory reservoir.

Prediction - if "I" have already been here, then the previous environment and experiences will be pre-fetched from prefrontal cortex via thalamus into hippocampus and all possible scenarios begin to "play" concurrently in "my" prefrontal, sensory, and motor cortices without reaching consciousness or actually driving my muscles. Based on actual inputs from vision, hearing, and somatosensory systems, thalamus orchestrates and selects the most likely and potentially successful action, and most of this is happening sub-consciously. If there is a discrepancy between the image or sequence of virtual images loaded into hippocampus and the actual ones based on sensory inputs, the thalamus elevates it to the conscious level and updates the corresponding event representation in frontal cortex.

Third - Intelligence - is when to survive, "I" not only able to coherently respond to rapidly changing world, but also can learn and modify the world using "my" motor capacities and to communicate "my" experiences to other members of "my" family as well as to learn from their experiences. However, this definition brings many other spices capable of tool-making and teaching their offsprings to do the same into the category of intelligent beings. These species include birds (crows and parrots), raccoons and many others. They have non-convoluted cerebral cortices and yet are capable of intelligent behaviors indicating that rudimentary intelligence can be housed in such brains. All these species, however, have very well developed thalami and hippocampi indicating that

thalamus and hippocampus are important for coordinating cortical activities leading to emergence of intelligent behaviors.

Brain's structural connectivity as the basis for its function:
Brain is the known-good solution for processing temporal and spatial information as well for optimizing system behavior based on partial and fragmented sensory feed. The paper attempts to make a point deciphering and replicating brain-based functionality in hardware would require direct involvement of subcortical structures. However, to emulate brain, we would first need to understand what factors lead to evolution from worm cerebral ganglions to mammalian cortices.

With the exception of olfaction, all sensory information including vision, sound and proprioception is routed to cortex via thalamus. Thalamus also has the capacity to rewire sensory inputs; for example, in case of loss of retinal function it can redirect somatosensory inputs from touch receptors in fingers to the primary visual cortex to enable Braille reading, etc. It is known that cortical damage rarely results in loss of consciousness; instead it produces just a loss of specific function, i.e. vision, hearing, speech, or one or several motor functions. Therefore, none of the localized damages to neocortex results in permanent vegetative state. However, it is also well known that damage to thalamus or some other deep subcortical regions leads to permanent loss of consciousness.

In addition to routing sensory inputs, thalamus "orchestrates" cortical activities based on hippocampi-resident spatiotemporal representation of the immediate physical world; this happens via thalamocortical loop. Hippocampi contain *grid*, *place*, and possibly, mentioned earlier *me* and *them* cells as well as cells strongly associated with head and eye direction. On its way to mammillary bodies, fornix envelopes the thalamus integrating emotional responses from amygdalae with immediate spatial representation stored in hippocampi. Mammillary bodies, hippocampi and thalamus are known to be critical to consciousness and memory [ˣ].

Visual areas are the most studied part of sensory cortex; however, it is sufficing to say that basic microarchitecture of auditory and somatosensory cortices are very similar.   The vast majority of surface area of the primary visual cortex is dedicated to a very small field of view - just approximately two angular degrees - that is projected onto the foveae. Our visual attention is "focused' on the point of ocular convergence. Similarly, at any given moment our auditory attention is also steered to a specific auditory cue [VIII]. It appears that visual and auditory perception is accomplished in the manner similar to investigating a dark room with a flashlight - by scanning one small spot at a time and registering narrow-field visual/auditory stimuli to a 3D map presented by hippocampal *place* and *grid cells*.

Brain is often compared to an orchestra. Each instrument can play a different melody, but at any given moment in time all of them are synchronized to play a specific musical piece inspired by real world events. An orchestra needs a conductor who does not produce music, but instead synchronizes all the instruments; the thalamus as well as hippocampus, fornix, claustrum, and amygdala act as such a conductor.

I stipulate hear that one of the *primary attributes of consciousness is the sensory convergence on an object of interest*.   Ocular convergence and saccadic eye motions can be described as a separate sensory system responsible for depth perception, even though it is intimately related to vision. At any given moment in time our visual attention is "focused" on the point of our eyes' optical convergence. Similarly, while in a room full of conversing people -cocktail party- our auditory attention "focuses" on a specific conversation [viii]. Additionally, at any given time we concentrate

our attention on a small patch of skin while investigating tactile stimuli; somatosensory cortex is adjacent to motor cortex as limb positions and tactile information are closely related to motor controls. All sensory inputs are routed by thalamus to primary visual (V1), auditory (A1) and somatosensory (S1) cortices [xi]. From there raw sensory information undergoes filtering and decomposition into sensory invariants representing simple properties that later are being reintegrated into virtual representations of many aspects of real world.

At any given time, cortex "plays" various scenarios by varying direct sensory inputs and associating them with previously stored experiences without elevating the results of these trials to consciousness. In the meantime, thalamus constantly weighs this unfolding cortical activity with respect to emotional inputs from amygdala, and sensory directly from retinae and cochlea elevating only one of many outcomes to conscious level.

All this is because the "conductor" - thalamus selects a single task from a myriad of memories and possible action plans stored in cortex. This complements Jeff Hawkins statement that "… the story is stored in your head in a sequential fashion…" Using the example from "On Intelligence" - when "I" recall the memories of "my" house and specific locations of numerous items in it, "I" will first recall the map of "my" house into the hippocampal ensemble of *place* and *grid cells*, and then place "myself" outlined by "my" skin surface into a subset of this ensemble defined as "me." Now "I" can move across this 3D hippocampal ensemble recalling the memories of all the items in "my" house. Memory recall is sequential because there is one and only one instance of "me" in hippocampal representation, "I" can "see" only objects that surround "me" as "I" move in hippocampal virtual world.

Another worth mentioning structure is dorsal striatum including caudate nucleus and putamen that is located between thalamus, motor, and frontal cortexes - it is responsible for defining the *cue-based* behavioral strategy, while fornix is for *place* strategy [xii].

If the bove hypothesis is correct, then cortex is an array of 2D highly parallel processors, all running individual pieces of a puzzle, while thalamus is the judgment system that connects the pieces into a story based on the history of sensory inputs and on weighing numerous permutations of many pieces of sensory puzzle produced by cortex at any given moment of time.

These are just several aspects of brain structure outlining highly parallel lateral processing between adjacent and distal cortical areas and high bandwidth radial interconnects with subcortical structures via thalami-cortico-thalamic loop.

Question arises – how this machinery actually works? Below discussion attempts to provide one possible algorithm:

Human motor response to an unexpected sensory input may be as short as several hundred milliseconds, while the maximum firing rate of cortical neurons is about one spike per 30 milliseconds. This frames the question of how can a complex sensory event be analyzed and an appropriate motor response produced by a chain of only several sequentially connected neurons? It must be mentioned here that hippocampal and thalamic neurons can fire at much faster rate with ~10msec period.

The answer to this challenge may be in the following: Each cortical minicolumn, especially in higher-order sensory and associative cortices, contains approximately 150-200 pyramidal cells. Multiple cells in each column may fire with variable delays and in different sequences, creating much more complicated columnar activity representing specific cortical activity in response to sensory input.

As mentioned earlier in _Consciousness_ section, cortex may be "throwing millions of simultaneous dice" while thalamus watches the outcomes and compares them with the hippocampal model, quickly selecting the most appropriate one to be elevated to the conscious level and to be acted upon. This mechanism, however, requires precise temporal synchronization and that is why we find apical dendrites of pyramidal cortical neurons are not straight but rather take a very convoluted way to their targets - the propagation delay of a depolarization event to the neuron's body is the function of the length of the dendrite!!! Is it possible that memory is encoded in length of dendritic connections within and between minicolumns? If so, then specific memory experience may be encoded by 2E8 snapshots of from all minicolumns registered by thalamus Figure-1.

Assuming that:
- each minicolumn contains 200 pyramidal neurons,
- average brain rhythm cycle period is 10 Hz, and
- thalamic temporal correlator has resolution of 10% of pyramidal cell cycle.

Figure-1

Then, each pyramidal cell can produce three action potential events per 10Hz brain cycle and thus may encode up to 30 states. This translates into each minicolumn encoding, and thalamus discriminate capacity of up to 200^30 or 1E69 (observable universe contains ~10E80 atoms) events for a specific brain cycle. Furthermore, considering that cortical activity is modulated by chemistry of the brain, that number may be significantly higher.
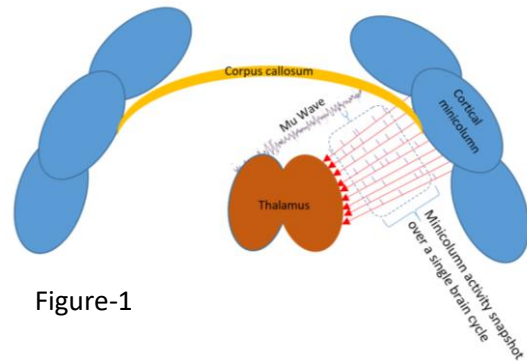
Delta rhythm (up to 4Hz) believed to originate in thalamus and is associated with deep sleep. Theta rhythm (4-7Hz) is present in hippocampus. Alpha rhythm (8 to 12 Hz) is associated with sleep cycle and, depending on state of arousal, is present in visual or associative cortices; it is in the same frequency range as Mu rhythm in motor cortex, suggesting the importance of vision to motor controls. Most of the above rhythms are originating in thalamus indicating the importance of this structure to cortical activities.
Three remaining rhythms are of the most importance for this discussion:
Beta rhythm (12- 30Hz) is an antagonist to Alpha and is associated with normal waking consciousness
Gama rhythm (30- 100+Hz) believed to be correlated with consciousness; these frequencies are originating in thalamus and propagate from associative to primary visual cortex; _thalamic origin of conscious-related activity further confirms the importance of this ancient structure to intelligence_
Mu rhythm (8-13Hz) is found in motor cortex while producing voluntary movements or even while observing another person performing motor actions, known as neural mirroring. Mu rhythm is similar in frequency to Alpha rhythm that is present in visual cortex.

It is conceivable that Beta rhythm present in sensory cortex and Gama found in associative cortex act as thalamic reset clocks to capture spatiotemporal snapshot of each minicolumn in related cortices and comparing them with corresponding representations in hippocampus. This opens the opportunity to exploring global spatiotemporal activity in microcolumns during a single period of the specific rhythm. Thalamus may be taking snapshots of all activated pyramidal cells in each minicolumn and records timing relationships between all action potentials [xiii]. This snapshot may represent a very strongly encoded feature of a visual and acoustic images as well as encoded results of predictive cortical activity further modulated by thalamic, hippocampal, amygdala, claustrum, as well as hormonal and chemical modulations.

What it would take to design and built a system of comparable performance? First step is to estimate bandwidth requirements for thalami-cortico-thalamic loop:

The required communication bandwidth associated with thalami-cortico-thalamic radiation can be estimated based on the assumption that most cortical pyramidal cells fire at below 30 Hz (but up to 100 Hz for some hippocampal cells) and each minicolumn contains around 150-200 pyramidal cells resulting is 15 Giga Events per sec, where event is a single action potential.

However, as conjectured here, the information in minicolumns may be encoded as a snapshot of phase shifted outputs of all pyramidal cells exiting cortex. If a 1% resolution between Event delays is required, then total thalami-cortico-thalamic bandwidth can be estimated as 1.5 Terra bits/sec.
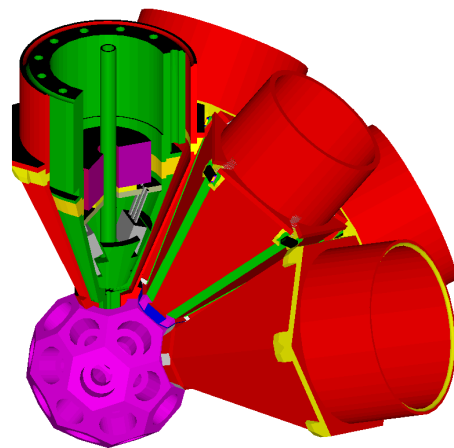
The proposed solution will allow implementing ideas ranging from Donald Hebb's reverberating cells assemblies and synaptic plasticity, to Stephen Grossbergs' Adaptive Resonance Theory, to William Calvin's cerebral code and to Jeff Hawkins Hierarchical temporal memories.

The proposed 3D macro-architecture emulates brain's large scale structure including sensory, motor and associative cortices, thalamus, and hippocampi. It consists of a quasi-spherical array of identical pyramidal processing units resembling a Fullerene topology, aka MIND - Massively Interconnected NoDe [xiv]. MIND delivers high density radial and lateral optical interconnects as well as integrated cooling and power supply subsystems while balancing the functional requirements of traditional digital and non-traditional neuromorphic technologies.

The concept of a poly-Si based neuron [xv] utilizes charge redistribution in isolated poorly-doped floating gate structures under the influence of multiple capacitively coupled synaptic electrodes. Axonal and dendritic propagation delays are occurring naturally due to the relatively low charge mobility in poorly-doped poly-Si facilitating implementation of spatiotemporal processing [xvi], [xvii]; the latter is required to emulate neural dynamics of cortical columns. The proposed structure allows spike-time dependent plasticity and dynamic synaptic weight adjustments.   The use of poly-silicon as information processing medium permits multilayered integration with direct axodendritic, dendro-dendritic, axo- and dendro-somatic, and reciprocal coupling between multiple Si neurons, while utilizing standard semiconductor fabrication techniques.

A successful Cortical Processor would have to include underlying subcortical structures emulating thalamus, fornix, putamen as well as hippocampus; all these components with their important interconnect would have to be included into the Processor model.

The proposed architecture consists of a _primary_ MIND [1] assembly as the hardware platform that emulates thalamus by receiving all sensory information via its various pyramidal arrangements and routing the information via radial optical connections to the appropriate "cortical" structures. The _primary_ MIND comprises of 20 hexagonal and 12 pentagonal pyramids assembled into a truncated icosahedron body. A trapezoidal chip carrier is attached to each pyramidal surface. Chip carriers contain neuromorphic, digital ASICs (FPGA, CPU, etc.) dies as well as two optical communication links - one for lateral, or close neighbor pyramid-to-pyramid interfacing and another one for radial, or
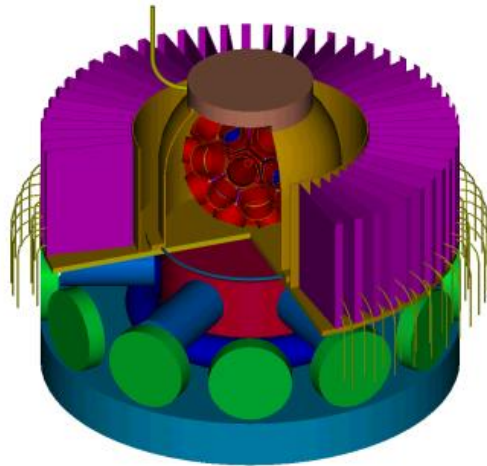
long-range communications aka thalami-cortico-thalamic loop Each pyramidal assembly includes a dedicated power supply and cooling module.

The cortical structures are arranged as the *secondary* MIND layer encapsulating the *primary* MIND. P*rimary - thalamus* and *secondary - cortex* MINDs are forming a Russian doll-like topology with their mutual interconnects resembling thalami-cortico-thalamic radiation.

Radial thalami-cortico-thalamic interface between the *primary* and *secondary* MINDs is accomplished via 180 (20*6 + 12*5) *primary* MIND edges, resulting in bandwidth requirement per *thalamocortical vector* to a reasonable 1.5Tbit/sec / 180 = 8.4Gbit/sec.

In case of *primary* MIND several dedicated pyramids emulate:

- Ventral posterior nuclei for somatosensory inputs,
- Lateral Geniculate Nuclei for vision, and
- Medial Geniculate Nuclei for hearing with neural chips mounted on their pyramidal faces.

The *secondary* MIND assembly includes visual, auditory, somatosensory, motor, temporal, and prefrontal cortices. Several dedicated pyramids emulate hippocampal region where place and grid cell ensembles are implemented and where the "me" resides. The hippocampus will likely include both neuromorphic chip assemblies emulating CA1 and CA3 cells and their interconnects and digital circuitry that retrieves long-term memories from a separate storage into neuromorphic hippocampus and uploads the hippocampal memory back into the long-term storage. Pyramids dedicated to emulation of prefrontal cortex also include saccade generators that control the Self-converging Saccade-capable Binocular Vision System [xviii,xix] that is being developed by the author of this paper. The need for such vision system is dictated by the fact that the corresponding cerebral models have evolved to receive inputs from moving eyes.

Further discussion is related to microarchitecture of various cortical and subcortical, specifically thalamic and hippocampal, areas and to the concept of physical implementation of Si neuron based on giant poly-Si floating gate structures.

Interconnection diversity of biological neurons and an approach to recreating it using available fabrication processes

Vernon's Mountcastle seminal work on columnar organization of cerebral cortex [xx] had been proven by direct recordings as well as by histological and neurophysiological evidence [xxi]. The beauty of the concept leads to relentless pursuit for understanding the underlying principles of brain plasticity. However, the existing approaches to simulations and device fabrications have several limitations that hinder the development of Cortical Processor:

a) Dendrites as well as unmyelinated axons are essentially heavily branched transmission lines with non-uniform propagation delays being a function of their cross-section, length, and densities of various ion channels and pumps built into the cell membrane. For example - *if a distal synapse is activated and a depolarization event is progressing toward the neuron's soma, the effect of this event will either be attenuated or amplified depending on activation time of another post-synaptic site that is proximal to the soma.* The effect of propagation

delays on temporal aspects of cortical dynamics is often admitted [xxii,xxiii], but is rarely considered in large scale simulation models due to enormous computational complexity. It will be beneficial to have a reconfigurable hardware capable of emulating instead of simulating such events.

b) Basic CMOS fabrication techniques do not allow introduction of physiologically significant delays; the use of RC networks require large die area and is not adjustable. Additionally, CMOS devices depend on high purity single crystal substrates and, with the exception of multiple wafers bonding, do not allow 3D integration of processing structures [xxiv].

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