ISSN: 2321-7782 (Online)
e-ISJN: A4372-3114
Impact Factor: 6.047

Volume 5, Issue 7, July 2017

International Journal of Advance Research in Computer Science and Management Studies

Research Article / Survey Paper / Case Study

Available online at: www.ijarcsms.com

A Review on Human Brain Computation

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Abstract: The Human Brain and its functioning has always been at the apex of research work. Scientists have kept on investigating to decipher how the human brain works since time immemorial. Understanding the complete operation of the human brain would be a tremendous achievement for the world. Although we have progressed but there still lies huge hurdles in this particular field due to its technical boundaries and limitations. This paper aims at enabling the reader to develop knowledge about the developments and challenges we are currently facing in Human Brain Computation and a study on how they can be overcome using different research methodologies and with the help of more advanced computing technology in the recent future.

Keywords: Central Nervous System, Sensory Information, Machine Learning, Cognitive Neuroscience, High Performance Computing.

I. INTRODUCTION

The Human Brain is highly deceitful. It is anatomically so simple yet its functioning is highly complex. Scientists have been able to understand the functioning of every part of the human body except the Human Brain. Neuroscience is still a vast area of research. Human Brain Computation (HBC) is the process by which the human brain can be simulated using a computer model and we can replicate the exactly same capabilities that a human brain has on a computing device. If the human brain can be correctly analyzed and replicated on a computing device, we would be able to accurately model the entire Central Nervous System including the neurons, and brain systems, explaining all the questions of neuroscience. The HBC system will be the pathway to developing brain controlled AI devices. All modern technologies would be disrupted due to the invention of "copy-able" brains, which would have huge economic and social consequences giving every person's brain a digital immortality even after his physical death. HBC would result in a new era of the development of the human race, as brains can be copied, upgraded, updated, and even combined. Humans may come and go but, their brains would live forever to develop and progress on their ideas. The logical relevance of death would cease to exist. Hence, for all these factors it is invigorating to discuss on Human Brain Computation.

II. BACKGROUND

Even though the anatomy of the brain is understandable, explaining its exact functioning is highly complex. To understand a complex system such as the human brain, computation is inevitable. In this respect, it is a fact that, our world has been "revolutionized" by Computer Science and Technology in the past couple of decades. Hence cutting-edge computing devices have already been used by researchers time and again to simulate or emulate the human brain, but the result has not been fruitful. In a generalized abstract view point this can be explained as, "If the brain is the creator of each and every creation man (human brain) has created, then we are trying to understand the creator using one or more of its creations." Now this doesn't mean that using these creations we cannot understand the creator, but this can be interpreted in numerous different perspectives. Conflicting arguments have come up between scientists whether this problem can really be solved using the concepts of reverse engineering. This review paper aims to identify the hurdles and challenges we face at a juncture where opportunities are endless but the capabilities are limited.

III. HUMAN BRAIN ANATOMY

The Nervous System of the human body is classified into 2 sub-systems [1] :

1. Central Nervous System – Consisting of the brain and the spinal cord. The human brain is the primary organ of the Central Nervous System.
2. Peripheral Nervous System – Consisting of the peripheral nerves emanating from the spinal cord and the cranial nerves.

The brain controls almost all activities of the body and its different lobes are responsible for processing, integrating and co-ordinating different sensory information it receives. Sensory Information can be a memory or an emotion created by our consciousness or the sense organs of our body when we interact with our surroundings. The processing, analysis and storage of this sensory information occurs at the cellular level of the brain, which the paper is concerned about. The cells of the brain consist of neurons and supportive glial cells (glial cells surround neurons and provide electrical insulation to the soma).[2] These neurons (almost 86 billion neurons and an equal number of support cells) are all interconnected by neural pathways which makes up the circuitry of the human brain.

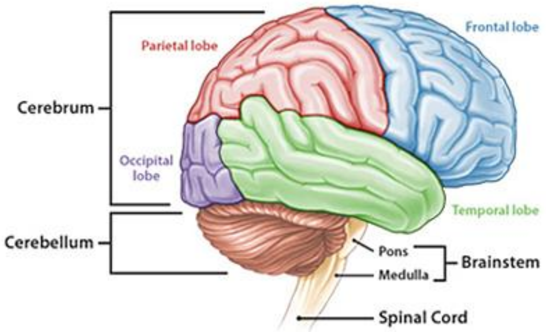

Fig 1 : Parts of the Human Brain [1]

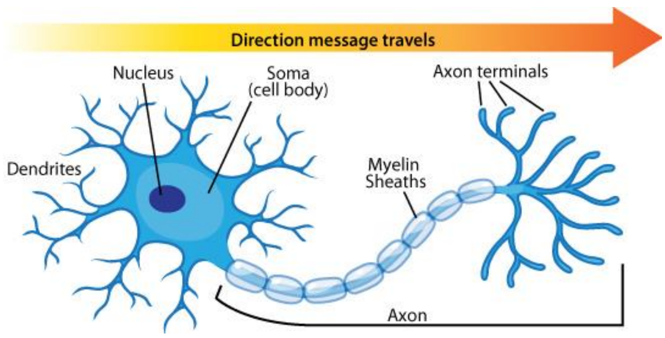

Fig 2 : Structure of a Neuron [1]

The information transmission occurs by synaptic transmission (neurotransmission) between the axon terminals of the preceding neuron and the dendrites of the succeeding neuron (this junction is known as the synapse) in a particular neural connection pathway by exchange of electrical impulses between chemical ions. [2]

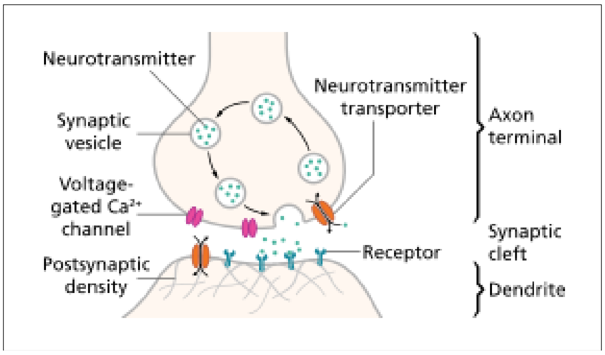

Fig 3 : Detailed Diagram of the Synaptic region [1]

Memories are stored in the brain as molecular changes within the synapses of millions of neurons in a specific cluster. Memory on the basis of characteristic can be sensory, short-term or long-term. Whereas, on the basis of content can be classified as follows:

- Declarative Memory (also known as Explicit Memory)
  - Episodic Memory **-** Relating to a particular incident / episode
  - Semantic Memory – Relating to a particular logical question
- Non-declarative Memory (also known as Implicit Memory or Procedural Memory)
  - Procedural Skill – Relating to a particular skill
  - Associative – Related to associating different memories / sensory information together. Consists of Classical Conditioning & Fear Memory
  - Non-associative – Related to habituation / sensitization
  - Priming – Related to the ability of innate suggestion skills

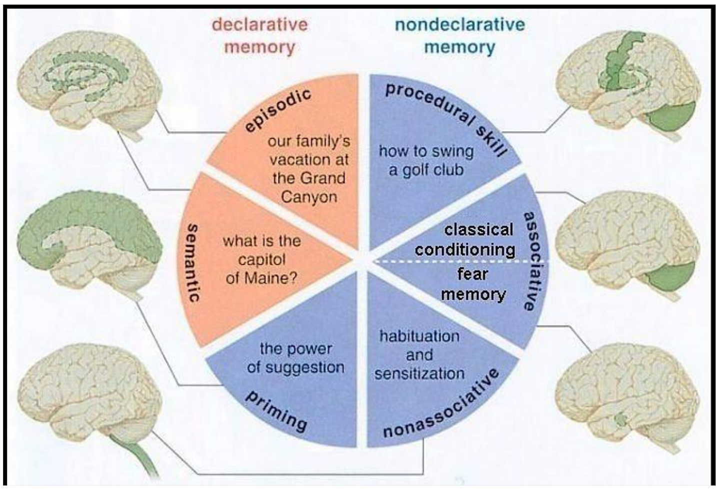

Fig 4 : Memory classifications and their functional areas (coloured in green) inside the human brain [17]

Although it has still not been possible to exactly define how our memory or consciousness is stored in such a neural cluster. Researchers from MIT have recently discovered that specific memories or emotions are stored in a specific cluster of neurons. These specific neurons when stimulated makes the person remember that memory or feel that emotion and when the stimulation was stopped, the person forgot the memory or stopped feeling that emotion. These neurons within these clusters are interlinked. The links may join or break thus losing or forming a memory. From current research advancements we can derive that the memory is stored in the form of a chemical exchange of ions between the synapses of consecutive neurons in a neural cluster.

IV. Human brain and Current Technologies

In the process of developing a technologically replicable human brain we need to look at the current technologies which are in use. Some of these aspects which we are to cover include the memory storage and functioning, efficiency with respect to direct connectivity, speed of fetching data/memory, capacity of memory storage and the capabilities. It is quite obvious that this project is much bigger than to just think of creating computer software which would function like a brain and then just copying down the contents is impractical. We may need to re-think our technologies, how we transfer and store data, and implement processing. Hence this comparison is very important.

- Memory – The brain stores a particular memory in a particular cluster of neural cells as found out recently. But the process in which the memory gets converted into a specific chemical impulse and how it gets stored and corresponding location of the neural cells are still unclear. Whereas within a computing device, the memory is stored in a cluster of memory spaces allocated to it logically by the CPU. Hence we need to focus more importantly on how the conversion of the sensory memory is taking place and where exactly it is being stored. We have been able to gather idea on the approximate location as shown in Fig. (last fig), but there is further scope of improvement. It is also important to note that the Human Brain cannot voluntarily delete or overwrite memory (data) like computing devices, unless because of a chemical imbalance within the body (Na-K imbalance) or external stimulation such as injury or electrical shocks or illnesses such as Parkinson's etc.

- Storage Space – In order to simulate a human brain we also need to have a similar amount of storage space on the simulating computing device. The average brain consists of 100 billion neurons whereas the latest intel icore7 has only 731 million transistors (which is an electronic switch). One synapse itself, is similar to a microprocessor having both memory storage ability and information processing elements rather than a simple on-off switch such as the transistor. In fact, 1 synapse might consist almost 1,000 molecular sized switches. Stephen Smith, renowned Professor of Stanford University says, "A single human brain has more switches than all the computers and routers and Internet connections on Earth." (Stephen J. Smith, 2012). Now one can argue that considering Moore's Law, calculations show that we would be able to reach similar computing capabilities by 2030. But, in recent times, even the validity of Moore's Law is questionable as per the current data of processing capability of transistors and the modern instruments' inability of compacting any more Silicon atoms crunched within a single IC chip. That leads us to probe the feasibility of HBC on computing devices made of Silicon based IC circuits. On the other hand, recent research-work on the Quantum computing is optimistic and throws a plethora of opportunities, if it is found commercially feasible.

- Efficiency – Efficiency quantifies the memory retrieval process on the basis of direct connections. Each and every neuron inside the brain is connected on an average to almost 10,000 other neurons. But unlike the human brain, a typical Silicon transistor connection between gates on a computing device circuit have very few interconnections. Dr. Dana H. Ballard, Computer Science Professor at the University of Texas at Austin, in his book on Brain Computation as Hierarchical Abstraction states, "The major factor separating silicon and cellular neurons is time. The switching speed of silicon transistors, which limits the speed at which a processor can go, is in the nanosecond regime. Whereas neurons deliver messages to each other using voltage pulses (spikes)."[14] Neurons can send these spikes at a top speed of 1000 spikes per second, but in the main processing areas the average rate is 10 spikes per second, with 100 spikes/second, regarded as a very high rate.

- Speed – As the human brain has highly interconnected neurons, the memory can be very precisely tracked but the retrieval process is very very slow due to the exponential traversal of neural pathways. In a computing device circuit, the memory retrieval is very fast. The mathematical reasoning is that the neurons, which are the elements for principal computing within the brain are very slow, over a million times slower than silicon. A reasonably estimated size for n is 1,000,000, and neurons can compute at the rate of 10 binary bits/second, so it can be seen why an O(n log n) algorithm is not a possible solution. An algorithm which has to serially poll each cell one-by-one would take an impractical 100,000 seconds.

- Capacity of Information Storage – It has not yet been possible to estimate the maximum memory storage capacity of the human brain. But it is arguably estimated to be much higher than what an average typical commercial computing device can store. Within 1011 (random data) nerve cells, only around 1010 send spikes at 10 Hz. By compressing this data by a factor of 10, approximately 100 seconds of a brain's neural ring can be saved in 1 TB of storage. The unsolved task for brain scientists is to break this code.

- Logical Processing Capability – To replicate the logical processing capability which a human brain has, we need to develop a fully functional Artificial Intelligence, which will complement the Control and Arithmetic & Logic Units that are present in a modern computing device.

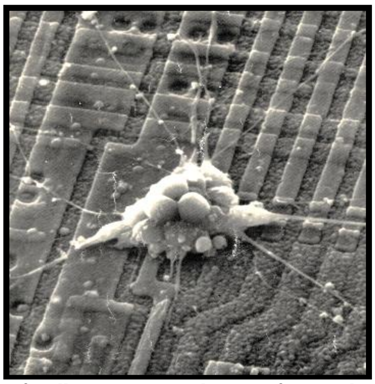

Fig 5 : An exotic electron micrograph of a neuron artificially grown on a silicon wafer reveals the comparable scales of the two technologies. [16]

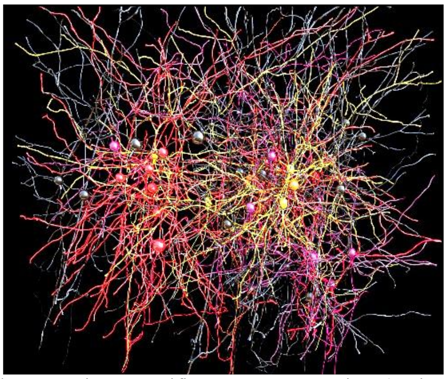

Fig 6 : A Neural Cluster storing a specific memory or emotion. (Artist's Impression) [16]

As shown in Fig 5, the sizes of the gates in silicon are comparable to the processes of a living cell. It is the neuron's huge connectivity that gives it one of its biggest advantages over silicon chips. The raised clump is the neuron's body or soma. One of the spider-like processes coming out of the soma (neuron-body), is its axon which connects it to an average of 104 other cells. In contrast silicon transistor connections between gates are limited to a handful.

V. Human Brain Computation Projects and their Outcomes

In the recent past ambitious projects like the Human Brain Project and Whole Brain Emulation were taken up by Government and private firms to achieve Human Brain Computation. But after spending millions, the results found were not fruitful. Although, the research findings have made scientists gain insightful knowledge, yet the actual target of Human Brain Computation was not achieved. Right, from the beginning, these projects have been vehemently criticized by eminent scientists & HBC researchers across the globe.

One of the most notable project co-founded by the European Union is the Human Brain Project which is a "H2020 FET Flagship Project" Although it started off with the aim of Human Brain Computation but now it aims at accelerating the scientific fields of neuroscience, brain-related medicine & computing. Henry Markram, Director of HBP, and his team has always emphasized on solving the problem of Human Brain Computation by considering to build a supercomputer, considering a Bottom Up Approach. It is important to note that the K computer required 82000 processors to simulate 1 second of brain activity & required 1Petabyte memory storage to store that data. This takes us back to the same point where we started. By aiming to build something piece by piece for eg. A map of a locality which is 100% precise on cm scale (i.e. every cm on the map is every cm on the actual ground) then, one can imagine how large the map is. Bottom-Up aims at collecting the pieces of this map and putting them together until the map covers the entire locality, which is an impractical solution. It comes down to the statement, "If a simulation is so complex in reality that we need the simulation itself or something even better to understand it, can we ever understand it?" This is a recursive mobius strip analogy of modelling the brain while the brain is modelling.

Scientists have criticized this approach and the authorities' inabilities of analysing the risk before spending millions of public money. Sister concerns of the HBP such as the Blue Brain Project, which tries to compute the rodent brain and the Green Brain Project, computing the drosophila and bee brain have also succumbed to failure due to the same Bottom-Up Approach.

VI. Current Developments

"Digital Reasoning", a company based in Franklin, Tenn., performing research and development in cognitive computing, recently announced that it has successfully trained a neural network which is more than 10 times larger than all previous neural networks having 160 billion parameters. The neural network created by Digital Reasoning overcame all previous records held by others such as Lawrence Livermore National Laboratory's 15-billion parameter system and the 11.2-billion parameter system created by Google. It also had improved accuracy over previous neural networks in handling an "industry-standard dataset" consisting of 20,000 word analogies. This model created by Digital Reasoning showed an accuracy of almost 86%; which is significantly higher than and Stanford University's 75% and Google's previous record of 76%.

Henry Markram, Neuroscientist & Director of Blue Brain Project and professor at the EPFL in Lausanne, Switzerland, in a recent development said that he along with his team have come across a new scientific discovery. They refer to an unexplained term "object" which are present in tens of millions even in a small speck of the brain, ascending to seven dimensions creating a universe of multidimensional spaces and geometric structures. In few neural networks they even found structures with up to eleven dimensions.[7] This discovery was made possible because of applying algebraic topology in a completely new way using neuroscience. This research, published very recently in "Frontiers in Computational Neuroscience", explains how these structures arise when a group of neurons forms a clique. Every single neuron connects to every other neuron in a one-to-many process in the group in a very specific way that generates a precise geometric object. More number of neurons within the clique results in a higher dimension of the geometric object. [10]

Department of Energy, U.S. Govt., has very recently announced on May 23,2017 that it will invest money in Human Brain Computation, to put the United States again at the apex of supercomputer development. Rick Perry, Secretary of Energy, United States of America has detailed plans to invest $258 million in funding which is to be distributed via the Department of Energy's "Exascale Computing Project" [11]. The "PathForward" program will distribute the money to 6 leading technology firms in USA to help them with their research & advance into exascale supercomputers. AMD, Cray Inc., Hewlett Packard Enterprise, IBM, Intel, and Nvidia are the six companies chosen to receive financial support from the Department of Energy. This funding will be issued to them within a three-year time period, with each company providing around 40% of the overall project cost, thus contributing to a total investment of $430 million in this project alone.

Data for HBC research is always massive. Cognitive Neuroscientist Dr. David Schnyer and his team created the high-performance computing (HPC) which they needed for their research purposes at the Texas Advanced Computing Center (TACC), hosted by the University of Texas at Austin, where Dr. Schnyer is a professor of psychology and aims to solve the early detection of brain disorders within humans. TACC's machine, which is known as Stampede, was not a generic supercomputer. It was made possible only because of a $27.5 million grant, issued from NSF. Stampede is one of the nation's most robust & powerful HPC machine built in collaboration with Intel & Dell, to augment scientific research. Stampede consists of 6,400 nodes. Each node has high-performance Intel Xeon Phi coprocessors. A typical desktop computer has 2 to 4 processor cores; Stampede's cores numbered 522,080. [12]

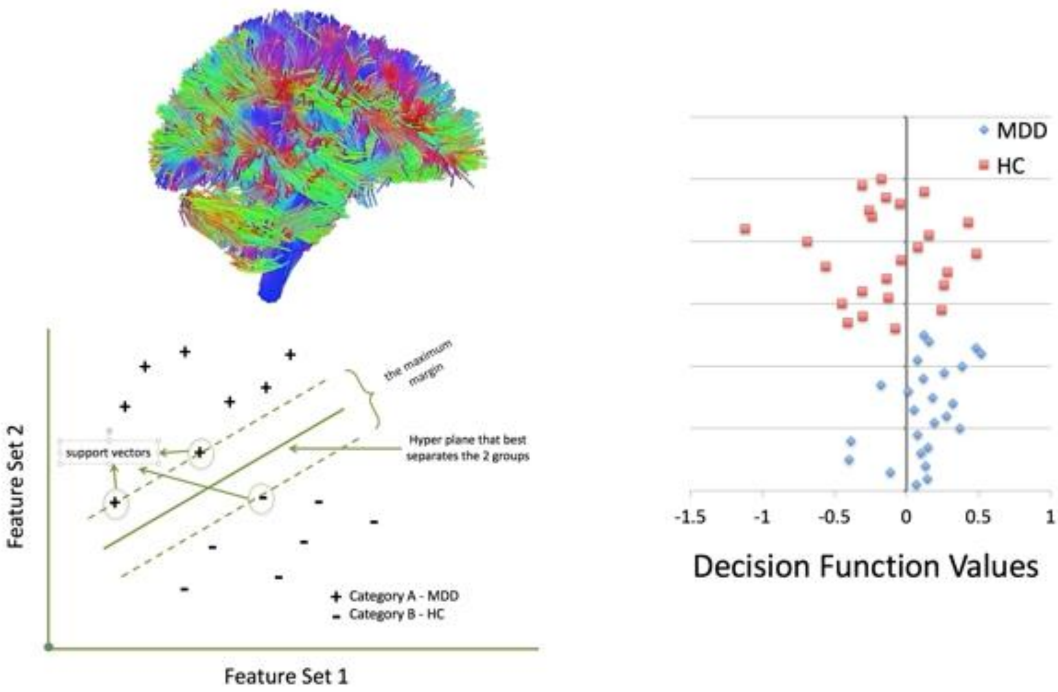

Fig 7 : Dr. Schnyer's MDD Analysis [13]

Top Left – Whole brain white matter tractography map collected from a representative participant.

Bottom Left – A hypothetical graphical application of support vector machine(SVM) algorithms in order to classify 2 categories. Two feature sets have been plotted and a hyperplane generated that best separates the groups based on the selected features. The maximum margin represents the margin which maximizes the divide between the groups. Cases which lie on this maximum margin define the support vectors.

Right - Results of the SVM (Support Vector Machine) classification accuracy. Normalized decision function values are plotted for MDD (Major Depressive Disorder) (blue triangles) and healthy controls (HC, red squares). The zero line shown in the graph represents the decision boundary.

Dr. Schnyer's analysis of the brain data from a select random group of treatment-seeking individuals having depression and heathy controls predicted major depressive disorder with a remarkable 75 percent accuracy as shown in Fig #. This has proved the possibility of creating something even better than the MRI.

According to Dr. Schnyer Brain Cancer tumor diagnosis is an area where machine learning and high processing computation are quite close to reality. In this area various algorithms use CT (computerized tomography) or MRI scans to classify tumor types. "We're trying to differentiate among human brains that, on gross anatomy, look very similar", Dr. Schnyer explains. "Training algorithms to identify tumors may be easier than figuring out fine-grained differences in mental difficulties." Regardless, progress in tumor studies contributes to advancing brain science overall. [13]

In fact, the equivalent of research and development in machine learning is underway across commercial as well as scientific areas. In Dr. Schnyer's words, "there's a lot of trading across different domains. Google's Deep Mind, for example, is invested in multi-level tiered learning, and some of that is starting to spill over into our world. The powerful aspect of machine learning," he continues, "is that it really doesn't matter what your data input is. It can be your shopping history or brain imaging data. It can take all data types and use them equally to do prediction." [13] His own aims include developing an algorithm, testing it on various brain datasets, then making it widely available. In demonstrating the probable results on what can be discovered with machine learning and HPC as tools, Dr. Schnyer's powerful proof of concept offers a hopeful path toward diagnosing and predicting depression and other brain disorders.

VII. Conclusion and Future Scope

Dana H. Ballard, from the analysis in his book concludes, the consensus is that the way the brain must do it is to have most of the answers pre-computed in some tabular format so that they just have to be looked up, similar to Content Addressable Memory. Evidence in favour of this view comes from the rich connectivity between nerve cells. Each neuron connects to about 10,000 other neurons, compared to connectivity between gates on a silicon chip of just a handful. [14]

Failure of multiple Brain Projects have made conventional scientists realise that the key lies in Top-Down Approach, considering Theoretical Neurology and Artificial Intelligence to be the pillars of a successful Human Brain Computation Project.

There needs to be subjectivity and variability in the Neuro-Science logics of Brain Computation in order to develop such a HBC system and we cannot be mono-theistic to solve this important problem. To develop a quintessentially replicable human brain on a computing device it is important that we focus on developing new technologies by changing the perspective of approach and match the requirements for Human Brain Computation. It is also important that we focus on developing AI systems with Computer Vision enabled with technologies such as Face Recognition and Analysis and much more and also implementing Artificial Neural Networks to develop the HBC.

The future scope of HBC includes tremendous amount of opportunities. The intersection of High Performance Computing and AI is becoming more and more practical with availability of faster processors and compact memory and the advent of Quantum Computing. Complex Problems of the real world can be solved by Artificial Neural Networks. Deep Neural Nets (DNNs) having huge number of hidden layers, clever training and HPC systems will all make HBC possible in the future. We will be able to develop 100% reliable systems of Contextual Interference, Speech Recognition, Facial Recognition, Fraud Detection and autonomous robots & vehicles. We would be able to understand complex medical problems of the human brain and treat several diseases. A successful HBC system will enable us to create copies of our brain and store, analyse, transfer the information. In the distant future, we will even be able to transfer the data to other humans, thus completely eliminating the need for the person to “understand” / ”perceive” the information. Theoretically this will mean, a person may die, but his entire life’s work and experiences will remain to exist forever.

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