On the Development of a Brain Simulator

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Abstract. Developing a whole brain simulator, a computer simulation in modeling brain structure and functionality of human, is the ultimate goal of Brain Informatics. Brain simulator helps researchers cross the bridge between the cognitive behavior/decease, and the neurophysiology. Brain simulators development is still in infant stage. Current simulators mostly consider the neuron as the basic functional component. This paper starts with introducing the background and current status of brain simulator. Then, an extensible brain simulator development framework is proposed. From information technology perspective, we adopt overlay and peer-to-peer network to deal with the complexity of brain network. Moreover, layered design with object-oriented brain class hierarchy forms the flexible development framework of the proposed simulator. The proposed brain simulator is evolved in case-based incremental delivery style. The power of the simulator will grow along with more research cases from cognitive and clinical neuroscience.

Keywords: brain simulator, brain network, object-oriented framework, network analysis.

1 Introduction

The fundamental goal of information intelligence is to understand and develop intelligent systems that integrate all the human-level capabilities and achieve the human-level Artificial Intelligence. The next generation of information intelligence research and development needs to understand multiple features of human-level intelligence in advance such as autonomous context-aware interaction, reasoning, planning, and learning. Web intelligence belongs to this category. Therefore, integrated studying the three intelligence related research disciplinary (deep web intelligence, neuroscience, and cognitive science) achieves truly human-level intelligence, namely Brain Informatics [1, 2], as shown in Figure 1. The objective of brain informatics is to understand the integrated human brain in ways of systematic means, as well as the Web Intelligence centric information technologies. In other words, the ultimate goal is to develop a whole brain simulator, a computer simulation in modeling brain structure and functionality of human.

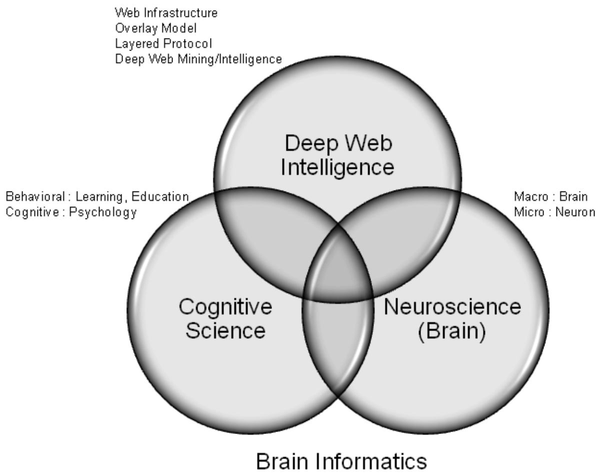

Fig. 1. The Brain Informatics Interdisciplinary.

Scientists have been collecting data about brain activity with brain activity measuring techniques, such as EEG and functional MRI, in the laboratory for many years. They made many remarkable hypotheses but most of them are not feasible in experiments [3, 4]. Brain simulator, a computer simulation in modeling brain structure and functionality, dramatically enhances the scientific method. It's a tool that scientists can use to not only better understand how cognition works, but rapidly test their ideas on an accurate replica of the brain [5]. Brain simulator is an enormous step forward for Brain Informatics. However, the flexibility and dynamicity of the human brain in time and space are challenges in designing a brain simulator [6]. Therefore, our research combines computer science and neuroscience to build up a flexible and dynamic brain simulator. The difference between two best known state-of-the-art brain simulator projects and our proposed brain simulator will be discussed later.

The brain simulator can be applied to many research topics. For example, scientists have long concerned with brain related disease, such as Alzheimer's disease, epilepsy, and schizophrenia. Topological change, accordingly functional dynamics caused by the diseases and the influence of abnormal release of neurotransmitters on functional regions in the human brain can be simulated by the brain simulator. This gives scientists a new insight to brain related diseases. The ultimate goal of the brain simulator is to achieve the simulation of human-level intelligence and helps to find out resolutions of brain related diseases.

In this section, we introduce the importance of designing a brain simulator. We briefly review some backgrounds of brain informatics in section 2 and then summarize the current status of brain simulator in section 3. The proposed brain simulator is presented in details in section 4. Finally, the conclusion and future work are discussed in Section 5.

2 Background

Brain Informatics has been studied as an interdisciplinary research field, including deep web intelligence, neuroscience and cognitive science. Some related research backgrounds are discussed in this section.

2.1 Networks Analysis

Recently, complex network analysis has been developed as an emerging research field. It is based on the classical graph theory and mathematical models [7]. Instead of concerning about the purely random or purely ordered networks, the new research field concerns about the real-world networks such as social networks and computer networks that share same non-trivial topological features or patterns which are only shown in the complex networks. Such networks are not only large in their size, but diverse in topological patterns which may change over time. Now, the trend is rapidly translated to the studies of brain networks due to its complexity [8-10]. In order to reduce the difficulties of analyzing brain networks, we divide them into brain connectivity, processing, causal (overlay), and application (behavior/disease) layers. Each layer shows different characteristics which can be further described by applying complex network analysis.

2.2 The Human Connectome Project

In 2009, the National Institutes of Health of the United States announced the Human Connectome Project [11, 12]. It's a five-year project which aims to map the connectivity of the human brain. It could be a prominent achievement which can help scientists to better understand the mechanisms of cognition and behaviors of the human brain [13]. However, because of the complexity of the human brain, there are many difficulties waiting to be solved. The challenge tasks are not feasible to be accomplished in just five years.

2.3 Brain Networks

Brain functions are the emergence of structural connectivity in human brain. There are three basic networks in the human brain [14]:

- **Thalamocortical Motif:** Thalamocortical motif, as shown in Figure 2(A), is fibers between the thalamus and the cerebral cortex [15]. There are loops consists of projections feed forward from the thalamus to the cortex and projections from the cortex back to the thalamus. Neuronal groups within the cerebral cortex not only connect with each other locally but also connect globally to interact for completing a task. These loops are called “reentrant loops" that map different types of stimuli to corresponding brain regions.
- **Polysynaptic Loop Structure:** The major structure of polysynaptic loops, as shown in Figure 2(B), are the basal ganglia which locate in the center of the human

brain and consist of the striatum, the STN (subthalamic nucleus), the GP (globus pallidus), and the SN (substantia nigra) [16]. These loops receive the connections from the motor and somatorsensory area of the cerebral cortex and send projections back to the premotor cortex though the thalamus. Direct and indirect pathways are between the striatum and the GP. Inhibitory and excitatory signals are passed through respectively. This mechanism can lead to the result of modulating the activity of the thalamus. Same mechanism works on the SNr (substantia nigra pars reticulata).

- **Diffuse Ascending Projection:** As shown in Figure 2(C), there are several value systems in this projecting structure. Each of them has different kinds of neurotransmitters that related to rewards and affects many critical body functions [17]. These systems include the locus coerulues, which release NE (noradrenaline); the raphe nucleus release, which release 5-HT (serotonin); the various cholinergic nuclei, which release Ach (acetylcholine); the dopamineric nuclei, which release DA (dopamine), and etc.. The path ways of these neurotransmitters construct hair-like networks which are in the diffuse ascending pattern.

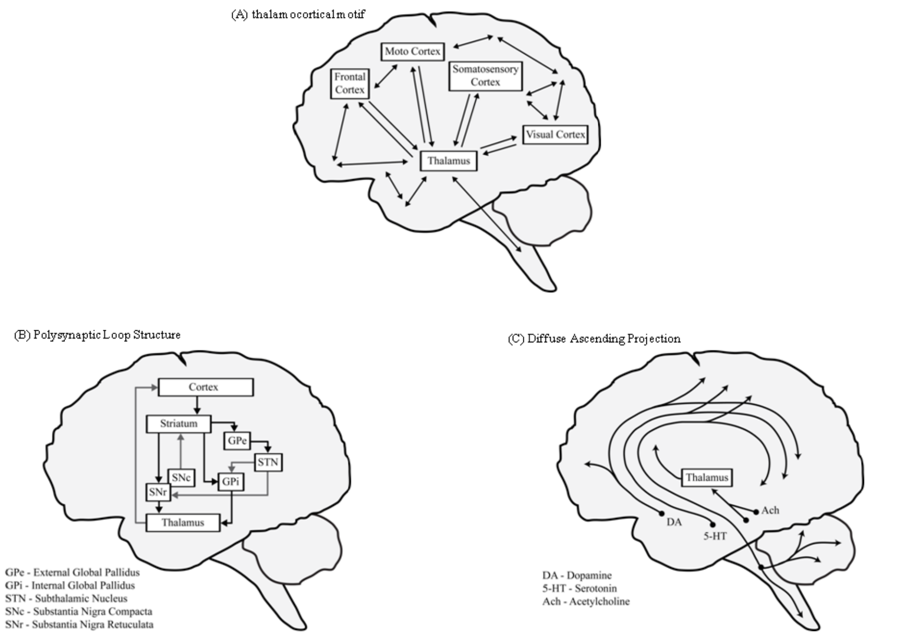

Fig. 2. Three Brain Networks.

2.4 Internet vs. Human Brain

Traditionally, we model the human brain by computers. But recent studies subvert traditional thinking and give us a new insight into the human brain, that is, functions are the emergence of the complex networks. Here, we try to make a comparison of the internet and the brain networks. The internet is a complex network which is composed of hundreds of thousands computers that are linked to each other. In the perspective of higher level, the internet can be viewed as several nets which are inter-connected regionally. The structure is similar to the brain networks. They are not only locally wired but also maintain long-distance connections. Due to their complexity, some common properties such as motif, community, and small structure can be found by applying complex network analysis. And both of them are modeled by layered structure. On the internet, OSI model is a standard which defines us how to implement communication protocols. Likewise, the human brain can be modeled by anatomical structure (nuclei and connectivity), different connection patterns and overlayed networks (three basic brain networks), and output functions and behaviors.

The internet and the human brain are both fault tolerable. They are capable of recovering from the damage to their structure. On the internet, data link and transport layers provide error correction mechanisms that protect the data from unpredictable accidents. On the network layer, disconnection between the routers would trigger a recomputation according to the routing protocol. In the human brain, degeneracy is the ability of structurally different elements of a system to perform the same function or yield the same output.

Although the internet and the human brain share some similarities, they still have some essential differences. Firstly, they are different at scales. The human brain has at least 10^{11} neurons and 10^{14} synaptic connections while the internet is composed of billions of devices. Secondly, the capabilities of the basic elements of the internet and the human brain are quite different. Computers and mobile devices have powerful computational ability which is capable of complex computing tasks such as data analysis or computer graphics. But neurons are only responsible for a single operation which is passing the signals to the others. Thirdly, there are no obvious global functions shown on the internet while diverse functions and behaviors are emerged in the human brain. Finally, the physical structure and the connectivity of the internet are stable, but are dynamic relatively in the human brain due to learning or aging.

Table 1. The comparison of the internet and the human brain.

	Internet	**Human Brain**
Scale	Millions of unit elements	10^{11} unit elements
Layered structure	OSI model	Anatomical structure, network overlay, and functional outputs
Mechanisms of fault tolerance	Error correction, recomputation of routing pathway	Degeneracy mechanism, replaceable functional area
Properties of complex networks	Motif, communities, hubs, shortest path way, etc.	Motif, communities, hubs, shortest path way, etc.
Capability of an unit element	Versatile	Specific
Physical structure	Stable	Dynamic

3 Current Status of the Brain Simulator

In this section, first we introduce two state-of-the-art brain simulator projects, IBM's C2 and Blue Brain [18-21], and then briefly introduce our proposed brain simulator. Finally, a comparison is presented. C2 and Blue Brain, like other ongoing projects, try to create a synthetic brain in the molecular level. A bottom-up approach is adopted to design their brain simulators. C2 has built up 1 billion neurons connected with by 10 trillion synapses, and 10,000 neurons connected with by 100 million synapses are re-created in Blue Brain. IBM's Blue Gene supercomputer supports the huge demands of computation requirement. They develop a brain simulator in modeling the cortical area, not the whole brain structure and functionality. Therefore, current brain simulators development is still in infant stage.

In contrast, our proposed brain simulator takes whole brain networks, neurotransmitters, brain behaviors and brain diseases into account. Then, an extensible brain simulator development framework is proposed from information technology perspective. We adopt overlay and peer-to-peer network to deal with the complexity of brain network. Moreover, layered design with object-oriented brain class hierarchy form the flexible development framework of the proposed simulator. The proposed brain simulator is evolved in case-based incremental delivery style. While many computer simulations have attempted to work in "brain-like" computation or mimic parts of brain area, our proposed brain simulator is considering the whole brain. The comparison among C2, Blue Brain and our proposed brain simulator is shown in Table 2.

Table 2. The comparison among C2, Blue Brain and our propoed brain simulator.

	IBM's C2	**Blue Brain**	**Our Proposed Brain Simulator**
Perspective	Neuron-Level Microscopic	Neuron-Level Microscopic	Brain-Level Macroscopic
Basic Component	Neuron	Neuron	Nuclei, Region, Tracts
Connection	Synapse	Synapse	Communication Pathway
Communication	Electrical Signal	Electrical Signal	Protocol Data Unit
Architecture	P2P Network	layered Architecture	layered Architecture
Focus Area	Cortex	Neocortical column	Whole Brain
Computation	Supercomputer Blue Gene	Supercomputer Blue Gene	Cloud Computing Environment
Granularity	Fine-grained	Fine-grained	Coarse-grained
Approach	Hardware	Hardware and Software	Software

4 The Proposed Brain Simulator

Although the study of brain simulator has made significant progress in computation ability, there are still many challenges in building up brain simulator to overcome. The current research did not consider the dynamic structure and complexity of the human brain from the perspective of time and space. The overlay and P2P (peer-to-peer) network architecture have been successfully applied to dynamic and complex network in IT (Information Technology) field. Hence, our proposed brain simulator provides an overlay and P2P network to represent the complexity and dynamicity of brain in time and space. Moreover, it is a flexible architecture that diverse brain networks or models can be easily applied.

4.1 Case-based Incremental Delivery Approach

Most brain simulators are designed merely for one purpose. Due to this reason, they lack of extensibility. Therefore, the scope of application and ability of brain simulator are limited and underestimated. Compared with other brain simulator, the proposed brain simulator is systematically developed in case-based incremental delivery approach, as shown in Figure 3.

First, the development of our brain simulator is based on some experimental data from related research. In this case, the proposed brain simulator can develop part of the required brain functionality as well as others. Rather than stop development, our brain simulator carry on evolving by later research cases. It is the important characteristic of brain simulator in terms of flexibility.

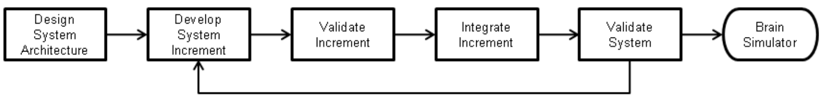

Fig. 3. Case-based Incremental Delivery Approach.

4.2 Architecture

A layered architecture is used to design our brain simulator according to our study on human brain, as shown in Figure 4. The layered architecture consists of the following layer:

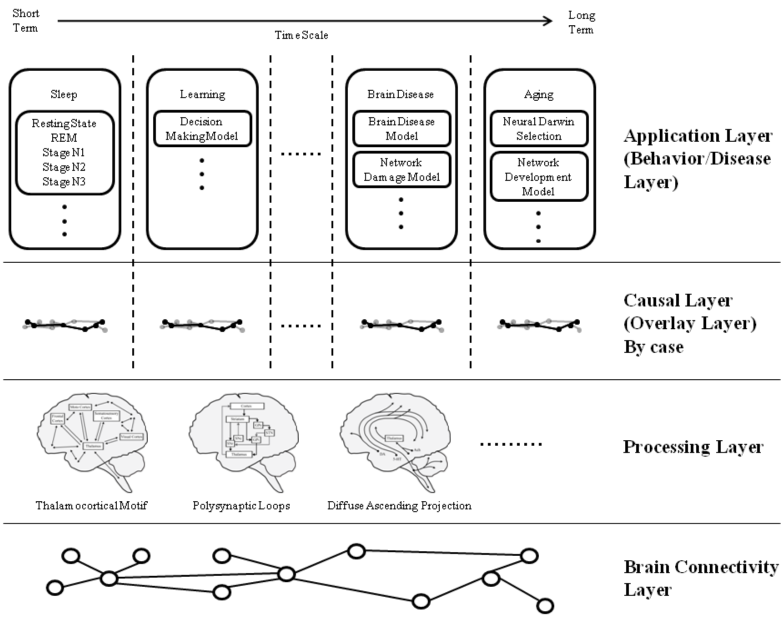

Fig. 4. Proposed layered Architecture.

- **Brain Connectivity Layer:** The lowest layer represents the brain connectivity of physical components. The first step of designing brain simulator is to define the physical computation unit and communication unit. Most researches are taken neurons as computation unit and synapses as communication unit from microscopic point of view. In contrast, we take macroscopic perspective. Considering the common attributes and functions among the components, a hierarchical representation of the brain components is presented by object-oriented design, as shown in Figure 5.

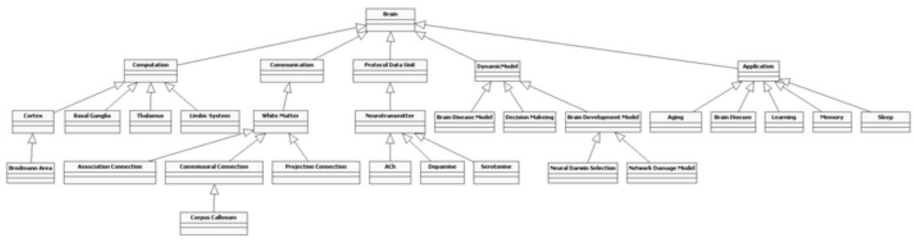

Fig. 5. Brain Component Class Diagram

The hierarchical structure consists of 5 main categories: computation, communication, protocol data unit, dynamic model and application. The computation units include Brodmann's areas, thalamus, and various nuclei. Tracts, such as corpus callosum, are defined as communication unit. Neurotransmitters are taken as protocol data unit. Dynamic model, such as brain disease model and brain development model, is represented as different theoretical brain models. Finally, the application category includes elements for diverse brain behavior and disease, like sleep, learning, disease and aging.

- **Processing Layer:** Compared the brain network perspective with other brain simulators, the significant improvement of our proposed one is that we consider the various brain networks as an integrated network. The processing layer composed of three brain networks, as we mentioned in section 2.3 Brain Network Fundamentals, represents this integrated network, as shown in Figure 4.
- **Causal Layer:** Causal layer is a layer that consists of diverse brain causal network arising from an evolution of brain applications, as shown in Figure 4. A causal network is an overlay network that builds on top of processing layer and brain connectivity layer. Different brain applications have their own causal networks. Means of brain networks analysis can be applied to this layer to see the causal effects of each brain application.
- **Application Layer:** Application layer, also called Behavior layer, is the top layer in the layered architecture. This layer represents various brain application scopes in different time scale, from long-term to short-term. Because the brain constantly changes but operates in the way to balance, each application, such as aging, brain diseases, learning, or sleep, has its own theoretical models to formulate the dynamicity of brain in time and space. For example, the model of neural Darwin selection focuses on the evolution of brain from the microscopic and macroscopic perspective and the network damage model considers the influence to brain networks from brain diseases. As for decision making model, the characteristics of excitation, inhibition and balance needs to be take into account. The purpose of designing the application layer is to provide a flexible strategy that can study diverse brain behaviors efficiently and effectively. Through the assistance of this layer, we can not only verify the accuracy of our proposed brain simulator comparing with the results from other neural imaging technologies. Moreover, we can better understand the evolution of various brain applications.

5 Conclusion and Future Work

In this paper, the importance of brain simulator is pointed out. A brain simulator models brain structure and functionality for better understanding how cognition works and rapidly testing their ideas on an accurate replica of the brain. Then, the current status of brain simulators and the comparison has been presented. The significant shortcomings of ongoing brain simulators are inflexible and maladaptive in time and space. Hence, an extensible brain simulator is proposed. It focuses on the dynamicity of brain in time and space. From the IT point of view, we adopt overlay and peer-to-peer network to deal with the complexity of brain network. Layered design with object-oriented brain class hierarchy forms the flexible development framework of the proposed simulator. Furthermore, the proposed brain simulator is systematically developed in a case-based incremental delivery approach. The proposed brain simulator will be evolved with more research cases from cognitive and clinical neuroscience. These characteristics benefit brain simulator research field significantly.

The development of proposed brain simulator is still ongoing. In order to simulate more accurate human brain structure and function, future research is required. The object-oriented design of brain components has to be refined for better brain structure. The common and specific attributes and functions of different brain components needs further consideration. Then, the theoretical models in different brain applications have to be further studied and implemented into the brain simulator. Decision making is one of the important functions of brain and it is also a complex and difficult design in brain simulator. The achievements in autonomous agent research, such as multi-agent system, game theory, and fuzzy theory provide possibilities for the decision making issue.

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