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# Information Processing in Brain Modeling: Challenges and Opportunities

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## ABSTRACT
Computational Neuroscience deals with the study of information dynamics inside brain. Neuron as unit of the brain is modeled through different assumptions by researchers. Challenges of neuronal modeling and analysis are discussed; a mathematical framework of information theory is presented in context of characterizing neuronal behavior.

## Keywords
Computational Neuroscience, neuron models, information theory.

## 1. INTRODUCTION
Today world have challenge to understand the brain and nervous system. It is a latest promising interdisciplinary area. Understanding encoding and decoding of information through electrical and chemical signals in the brain and processing of information is the vital objective of computational Neuroscience. Importance of computational Neuroscience is now realized by Barak Obama, President of America and he announced the collaborative research initiation (Brain Activity Map Project) on April 2, 2013 with funding of $300 Million per year for ten years.

The term Neuroscience usually stands for the study of the nervous system. In the beginning it was completely the branch of biology. But, now it is a multidisciplinary science that includes chemistry, mathematics, physics, psychology, computer science and many more fields.

In the computer science field, study of Neuroscience is termed as Computational Neuroscience. In this, to study the functioning of brain that how it is able to process the information which make up the complete nervous system of human we use computer simulations and theoretical models that depict the functioning of the nervous system. [1, 14]

The basic unit of the brain is neuron which is involved in information processing in brain. There are one billion to one trillion neurons present in the brain that form a complex network in it with numerous interconnections. A neuron has different parts. The three main parts of a neuron that has been found are Dendrites, Soma or cell body and Axon.

## 2. CHALLENGES OF BRAIN MODELING
There are following challenges of brain modelling those require great effort to understand and to be modelled .

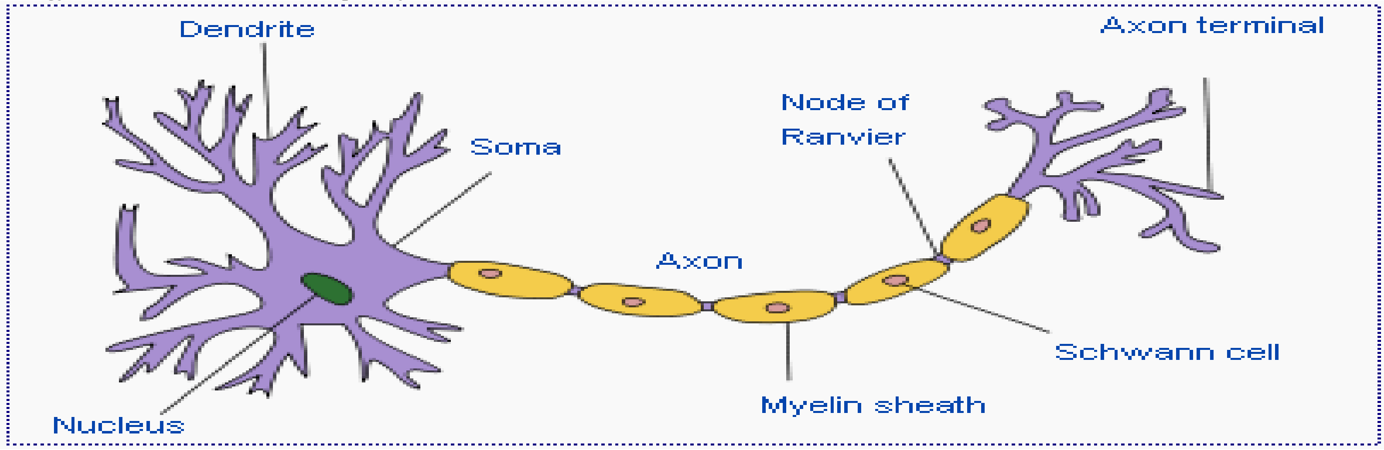


**Figure 1:Structure of Neuron (Source: http://en.wikipedia.org/wiki/Neuron)**

### 2.1 Understanding response of the brain in natural environment
To predict the action of brain in natural environment is a big challenge of Neuroscience. If we understand the working of the brain, we may be able build robots & it may also help in the treatment of many neurological diseases. Experimental studies are also not very effective because in laboratories, the stimulus and duration of stimulus are simulated through instruments and target remains in a constant position[1,2,3].

On the other hand in natural environment stimulus are of a different nature and works for varying duration and context of stimulus working also may change, targets are moving and acts very fast.

We cannot prove the behavior in laboratories as we need to control the stimuli on one hand and on the other hand we have to handle the complexity of behavior.

Sometimes neurons response to a stimulus in an ambiguous manner and thus there is an illusion of false target. We have to design such algorithm which detects and removes these false target illusions. This is again a challenge.

Involvement of memory, kind of attention and validity effect (chances of false target) is a non sensory influence on actions. The actions of the brain do not depend only on auditory information but also depends on visual information when the target is visible. The actions are combined output of information taken by all sensory organs so it is hard to predict and understand in a natural environment.

## 2.2 Fast and accurate response of brain

The reaction time of the human being shows us that our brain is very fast in spite of slow speed of neurons. There was an experiment done on human being to test the quickness of brain. The human subject was allowed to sit in front of a screen where there were real world images coming one after another constantly. The human subject was given a button which he needs to release every time he saw a picture having an animal. Now the response time is measured by recording the image shown on screen time and the response time. The measured response time was in the range of 400 milliseconds. Some good responses were around 200 milliseconds. There is no such machine till now that can do calculations and make decisions so fast in spite of high configuration and computational speed.

## 2.3 Understanding Coding and Decoding in Neuron

Neural code is the code which is used and processed by the brain to represent the information. Understanding this neural code is equivalent to understand the whole functioning of the brain that has a very complex structure and contains the intricate network of neurons. In Neuroscience field it is well agreed that information in brain is carried by the spike trains. These spikes are signal consists of a short electrical pulse also called an action potential that propagates from one neuron to its all neighboring neurons through synapse. If a stimulus is given, then most of the information about the stimulus is carried in different ways by the spikes which are fired by neurons in getting the input. Based on this, neural code can be either a rate code, temporal code or population code. In rate code, the firing rate of neuron contains the information of stimulus. In temporal code, information of stimulus is carried by the precise spike timing and in population code, information about stimulus is obtained by combining the several spikes of a set of neurons[1, 3].

## 2.4 Divergence of neuron for specific computation

This question gives birth to the presence of specialized neurons such as neurons that have existed in the auditory system of the brain to encode temporal information with great accuracy. But here it is not definite that whether all neurons in the brain are specialized neurons and whether these are necessary to perform all types of task. To find out the answer of this it is required first to know the functionality of single neuron entirely. In the auditory system, temporal coding is important as the timing of firing neurons carries information which is used for both understanding and localization of sound. It also directly affects the behavior of the subject. If any sound is coming from one side of the body then definitely it reaches in that side's ear first and then in the other ear. The auditory system of subject uses this time difference known as interaural phase difference to find out the location of the source producing sound. The predators that are active at night such as owl have strong ability to localize sound.

## 2.5 Neural Code in Sensory Systems

An important challenge of Neuroscience is that – can we generalize the single neural code for some species or for certain kind of stimulus. In nervous system all sensory information and the status of brain is kept in the form of codes called neural codes. The question arises here is that what is the nature of these codes? How these neural codes are created? Why some strategies for creating codes are preferred over others in some situation? In which manner the neural codes created by different strategies, are different for same situation?

Coding strategies may be differentiated on the basis of species and on the basis of different stimulus. Although some analogies in neural codes provided by the same sensory system exists, but can we generalize them, without giving importance to unique problem? If we can generalize neural codes then to what extent we can generalize? Which specific cases can be generalized?

## 2.6 Computation in visual cortex

Even after many researches it is unclear that which calculations take place in visual cortex to take action and to solve problems. Which are these computations? Are these computations being similar to computations performed by digital computer? In digital computer we can perform functions using logical circuits (AND, OR, NOT). If neural circuits can perform these basic primitive (AND, OR, NOT) then they also can perform any function by combining the basic primitive functions. This idea is a basic foundation for building computation in neural networks[4,5].

The above suggested strategy is not only sufficient because an effective pairing between logical operations and synapses is also required which is a very complex task. There exists many possible combinations of logical operations and it leads to different "logical gates" so the proper required combination of operations is a complex task and again a challenge. It is unclear that how problem and computation are related?

The logical circuits are different from neural circuits, as in neural circuits the synapses and generation of spikes are random.

If we want to find a solution by neural computations then we must know what to represent and how to represent? The knowledge of the domain in which problem is defined is also an issue.

Another challenge is that, can we find the "time complexity function" required to solve problem by neural computation?

## 2.7 Analyzing a scene with sound

Auditory scene analysis (ASA) is a process of auditory perception. In this the human subject or animal subject listen several things at a given time. The auditory scene analysis is done by the auditory system of the subject that must be able to separate those sounds that comes from a single source. The source of sound is called as auditory object. It has been experimentally proved that most of the animals work on same principles for auditory scene analysis and are capable of separating a stream of con specific song from a background of simultaneously presented songs of other species[3,4].

## 2.8 Finding correlation between neuronal activity and consciousness

Consciousness is itself a very mysterious thing related to human brain. The required neural architecture that is sufficient enough for conscious sensation is commonly known as NCC. It basically tells us what kind of sensation a human brain feels for something. There is a term Qualia used that is basically an individual experience (conscious) say the redness of sky, the taste of wine etc. The things that go in our brain are mostly unconscious but can also lead to conscious activities. The question that came in picture is that, what is the difference between the neural activities for consciousness and unconsciousness. A human subject is conscious when he reacts to a situation in a new way without any pre assumed opinion. Consciousness can also be affected by attention. It might lack in a human subject if attention is not paid or may increase if attention is focused on a human subject. Actions like driving vehicle, swimming, running in morning are usually unconscious but human subject can be conscious for them too. There are parts of cortex that are essential for many things like faces, colors, motion etc. These are essential nodes in human brains for all the conscious activities. If node for a particular activity is damaged then human subject become unconscious for that. So the question is what constitutes these essential nodes.

# 3. BRAIN MODELING AND DYNAMICS OF INFORMATION

Modeling as a whole brain is impossible task in current scenario because of its complexity in structure and function so scientists are trying to model single neuron and studying behavior of ensembles of neuron to understand information processing. Various attempts have been made to understand behavior of neuron where one of the most popular and historical experiment was done by Hodgkin and Huxley. H-H model is proved to be basis for many other neuronal models. Later on neuron is tried to understood with point process, neuron as single processing unit and as cable theory where the structure of neuron and structural attributes of neuron also have a significant role in the modeling of neurons. To understand neural information processing dynamics, Koch[2] suggested to study electrical property of nerve cell by physical variable. This physical variable is named as membrane potential which describes the rapid neural response in the brain. Most popular abstract neuron model hiding complexity of large number of equation is Integrate and fire models.

# 4. INTEGRATE AND FIRE MODEL: SPIKING NEURONS

Spiking pattern of neuron is the key factor to study the behavior of neuron. Spiking pattern is analyzed on the basis of time and space, but arrival time of action potential is of interest for researchers [10, 12]. They found temporal coding of information in spiking patterns is useful in encoding of stimulus. Randomness in neuronal firing is characteristic of neural code and represented by temporal coding.

This class of models is very useful to capture characteristics of neurons i.e. spike trains and information transmission [11,12]. We study two types of models:

(i). Perfect Integrate and Fire Neuron Model

(ii). Leaky Integrate and Fire Neuron Model

## 4.1 Perfect Integrate and Fire Model

Membrane potential is stochastic in nature. The stochastic dynamics of membrane potential is given by[12,15]

$$d\emptyset(t) = \mu(t) + \sigma dW(t), \qquad \emptyset(t=0) = V_0$$

Where, W(t) is Wiener process. Here μ represents drift which is defined in terms of excitatory and inhibitory rates. The parameter σ denotes the strength of fluctuations. In order that the membrane potential reaches the threshold with probability one, the drift parameter $\mu > 0$.

In order to obtain the Inter spike interval (ISI) distribution, we are required to compute the first passage time distribution (FPT) for the membrane potential to reach the threshold.

Mathematically, FPT is defined as

$$T = \inf\{t \geq 0; \emptyset(t) > \emptyset_{th}, \emptyset(0) < \emptyset_{th}\}$$

It is important to note that for this model, the explicit form of FPT is known in terms of inverse Gaussian distribution i.e.

$$f(t) = \frac{\emptyset_{th} - \emptyset_0}{\sqrt{2\pi\sigma^2 t^3}} \exp\left[-\frac{\langle\emptyset_{th} - \emptyset_0 - \mu t\rangle^2}{2\sigma^2 t}\right], t > 0$$

## 4.2 Leaky Integrate and Fire Model

Lapicque(1907) described model in terms of RC circuit and membrane potential is given by following equation[12,15]

$$\frac{d\emptyset}{dt} = -\frac{\emptyset}{\tau} + \mu + \sigma\xi(t), \emptyset(t=0) = \emptyset_0$$

Where, τ denotes the time constant (RC)-1. Hence ξ (t) is the white noise and μ represents the deterministic part of current. Mathematically the stochastic variant Ø(t) satisfies Ornstein-Uhlenbeck process expressible as solution of SDE

$$d\emptyset = \left(-\frac{\emptyset}{\tau} + \mu\right) dt + \sigma dw(t).$$

To find analytical solution for above equation is very difficult and not known. So to solve this researcher used Monte-Carlo simulation technique.

# 5. INFORMATION TRANSMISSION IN SPIKING NEURONS

Deco and Schurmann [6,7,8] have discussed information theoretic framework for measuring information transmission as mutual information when an external stimulus is applied.

Poisson cdf with mean rate λ is used to model number of events at time t.

$$P_n(t) = \frac{e^{-\lambda t}(\lambda t)^n}{n!}, \qquad n = 0,1,2,\ldots$$

The corresponding entropy is given by

$$H_{in} = -\sum_{n=0}^{\infty} p_n(t) \ln p_n(t)$$

$$= -\sum_{n=0}^{\infty} \frac{e^{-\lambda t}(\lambda t)^n}{n!} [-\lambda t + n \ln \lambda t - \ln (n!)], n = 0,1,2, \ldots$$

Where, time precision ε such that $\lambda\varepsilon << 1$.Entropy per spike of input train is $H_{in}$=(λ)[1-ln(λε)].

From probability distributions we know Poisson arrivals with rate λ, the inter arrival time is given by the probability density function

$$f(t) = \lambda e^{-\lambda t}, \lambda \geq 0$$

Where, $\lambda^{-1}$ mean time interval.

## 6. ENTROPY: MEASUREMENT OF UNCERTAINTY

The concept of entropy was given by Claude Shannon in 1948 [13] in the context of communication theory. Shannon answered following two questions:-

What is the ultimate achievable data compression?

What is the ultimate achievable rate of transmission of Information?

These questions gave rise to information theory through the classical paper "A Mathematical Theory of Communication" by Shannon [13].

Shannon introduced entropy, mutual information and channel capacity etc. and provided a measure of uncertainty in the form of entropy. These concepts are found vital important in computational neuroscience as brain also form a complex network of communication.

Shannon considered the random variable X associated with random experiment which assumes values say$\{x_1, x_2, x_3, \ldots, x_n\}$ with corresponding probability distribution

$P = \{p_1, p_2, p_3, \ldots, p_n\}$

We have,

$P_k = P(X = x_k)$, k=1, 2, 3,…,n

Such that,

$$\sum_k p_k = 1, \quad 0 \leq p_k \leq 1.$$

Shannonproved that the information associated with the event(X= $x_k$) is – $\log p_k$.

$$I(x_k) = \log \frac{1}{p_k} = -\log p_k$$

Compute information content in event xk represented by probability distribution pk. It is easy to see that for a 'certain' outcome, there is no surprise and

$I(X_k)=0$ for $p_k=1$.

Entropy

The amount of average information is given by

H(X) = H (p1, p2, p3….pn)

$$= -\sum_{k=1}^{n} p_k \log p_k$$

Shannon named above notation as entropy as it is similar to entropy being used in statistical mechanism in physics [7].

If take 0log0=0. This implies that entropy remain unchanged if we introduce some impossible events in the scheme.

It would be useful to know that the maximum entropy in is equal to log n, where

$$p_1 = p_2 = p_3 \ldots. = p_n = \frac{1}{n},$$

This can be easily seen as follows.

$$\text{MaxH}(X) = -\sum_{k=1}^{n} P_k \log p_k$$

Such that,

$$\sum p_k = 1$$

We construct Lagrangian

$$L(p_1, \ldots. p_n) = -\sum p_k \log p_k - (\lambda - 1)(\sum p_k - 1)$$

Where,λ is Lagrange's undetermined multiplier.

## 7. CONCLUSION AND FUTURE SCOPE

Information processing in the brain could not be revealed till now. In coming future humanity will need a good understanding of information dynamics of the brain. The stochastic nature of neuron makes difficult to model and analytic solution of processing is still not available. Researchers are trying to solve by approximating simulation technique. Information processing can be modeled by Shannon's entropy and appropriate probabilistic model of neuron. It is still challenging to model different type of neurons and analyzing collective operation of those neurons as operated in the brain.

In future we can propose a model that can predict the response of neurons to any stimulus as the combined output of information taken by all sensory organs after considering all the non sensory influences on actions. It will help in the prediction of the action of the brain in a natural environment.

The process being used for creating neural codes in the brain can be known and some generalizations can be provided to these codes. This understanding of neural code can be helpful in understanding and simulating the whole functioning of the brain.

Some techniques can be formalized to find "time complexity function" required to solve a given problem by neural computations.

In the future, by understanding and implementing the behavior of neuron using computational techniques and different models we are able to perform the functioning of brain through machines. The area that can be covered in this is sound localization, visual perception and learning process of brain.

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