# Sleep Physiological Dynamics Simulation with Fuzzy Set

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**Abstract.** Neuroscientists have investigated into the functional-structural mechanisms of sleep for a long time. However, the sleep physiology is so complex that the relations to brain structure are still mostly unknown. In this paper, we integrate the brain sleep switch model with fuzzy methodology, more specifically, combining the the mutual inhibition system of the sleep switch with a rule-based fuzzy reasoning system. Based on the extension of sleep switch, a model for sleep physiological dynamics is proposed. In addition, we implement the sleep mechanisms and integrate them into an object-oriented brain simulator. With the brain simulator, we can demonstrate sleep dynamics of the brain network with 3D-rendering system is demonstrated. The sleep physiological dynamics in brain become more intuitive and easier to realize.

**Keywords:** sleep physiology, fuzzy methodology, brain, simulation.

## 1 Introduction

The sleep switch model is the most famous model which illustrates the functional-structural behavior of sleep [1]. The sleep switch adopts an abstract flip-flop to describe changes of the sleep-related brain components which cause transitions among different states during wakefulness and sleep. Related studies also discovered mechanisms and operating patterns of sleep in the human brain; such as pathways of neurotransmitters, mutual inhibition mechanism, and firing patterns of neuron clusters. The sleep switch model is considered as the candidate tool to demonstrate the brain sleep physiology. However, the sleep switch model cannot describe the dynamics of sleep in detail because some essential parts are still missing, such as quantification of neurotransmitter and the threshold of the sleep switch control. Instead of investigated into brain sleep physiology, most researchers discover activity patterns from external observations, and describe internal operations without quantified data.

Fuzzy concept and methodology are popular in several domains, such as electrical controlling, temperature regulating, decision making, and artificial intelligence. Coincidentally, fuzzy could be applied to describe some behavior in the brain. Fuzzy concept is good at modeling learning behavior and the growth of understanding. Since the pattern of the brain operations are not as rigorous as the computer, fixed reactions modeling of the brain simply cannot apply in various environments. The fuzzy theory provides a reasoning methodology with flexibility and vagueness.

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Inspired by the vagueness of the brain and fuzzy methodology, we combine the sleep switch model with the fuzzy theory to propose a feasible method to model the internal sleep brain operations. We also use 3D-rendering visualization system to present sleep physiological dynamics with a brain simulator. In next section, we will introduce the sleep mechanisms and model. Then, describe the fuzzy concept and its applications. In section 4, we illustrate how to combine the fuzzy theory with the sleep switch model. The design and implementation of the simulator is introduced in section 5.

## 2 Background

The brain sleep dynamics simulation requires knowledge of sleep physiology and fuzzy control. In this section, these related backgrounds are discussed.

### 2.1 Sleep

Sleep is an essential state of most animals including mammal, birds or even invertebrates. The characteristics of sleep include reducing the body movement, lack of consciousness and decreasing the sensitivity and reaction to external stimuli. Sleep can help the body growth or recovery, such as revitalizing immune systems, increasing the growth of skeletal-muscular systems and reorganize memory of the brain. Regular sleep is necessary for health and survival especially for human beings. The quality of sleep will affect not only physiological but also psychological situations.

There are two phases of sleep: namely Rapid Eye Movement (REM); and Non-Rapid Eye Movement (NREM) sleep. The American Academy of Sleep Medicine (AASM) further defines three stages of the NREM sleep (four stages previously). These three stages are N1; N2; and N3. The N3 stage is also called Slow-Wave Sleep (SWS) [2]. By analyzing captured physiological signals, sleep science professionals can determine the subject's sleep stage or even diagnose sleep problems [14, 15].

### 2.2 The Sleep Switch Model

In 2001, Saper, Chou and Scammell [1] proposed a sleep mechanism named flip-flop switch, which describes the sleep/wake state transitions based on the concept of mutually inhibitory circuits. The sleep switch is a homeostatic regulating system of sleep, which describes changes between different systems, including neurotransmitter and their pathways will cause different sleep/wake stages and stabilize the state transitions of wakefulness and sleep. It can be divided into three main systems: The ascending arousal system, the NREM sleep-promoting system and the REM sleep-promoting system. Each system contains different neurochemicals, brain regions and networks. Interactions (excitation/inhibition) between these systems can regulate wakefulness, NREM and REM sleep of the brain.

- **Ascending Arousal System:** Ascending arousal models are based on observations from Moruzzi and Magoun [3]. They discovered that activities of paramedian reticular formation, especially in the midbrain; cause the state of arousal. Subsequent studies also found that a group of tissue at the junction of the caudal midbrain and rostral pons plays a critical role on maintaining wakefulness. Based on these discoveries, studies found that cell groups at the mesopontine junction project monoaminergic and cholinergic neurotransmitter to the forebrain. In detail, there are two major types of neurons involved in the wake-promoting system; the cholinergic neuron and the monoaminergic neuron. Cholinergic neurons are found in pedunculopontine nucleus (PPT) and laterodorsal tegmental nucleus (LDT). There existing projecting pathways not only from the mesopontine junction to the thalamic relay nucleus, intraluminal and reticular thalamic nucleus, but also to the lateral hypothalamus, basal forebrain, and prefrontal cortex [4]. Cholinergic neurons fire rapidly during wakefulness and REM sleep, and fire much slower in the state of NREM sleep. Thus firing of cholinergic neurons is considered help promoting cortical activities [5]. The monoaminergic neurons include several nucleus and project different neurotransmitter to the forebrain. Neurons of the locus coeruleus (LC) contain noradrenaline (NA), neurons of the dorsal and median raphe nucleus contain serotonin (5-HT), neurons adjacent to the dorsal raphe nucleus contain dopamine (DA) and neurons of the tuberomammillary nucleus (TMN) contain histamine (HIST). These monoaminergic cells have similar projecting targets and firing patterns. The pathway contains the brainstem, lateral hypothalamus, basal forebrain, and cerebral cortex. Neurons of this group generally fire most rapidly during wakefulness, less active during NREM sleep, and almost silent in the state of REM sleep. On the other hand, there's another kind of neurons in posterior half area of the lateral hypothalamus, these neurons produces neuropeptides named orexin (or hypocretin). Some studies found that there are excitatory receptors in cell groups of the arousal system such as TMN, basal forebrain, raphé nucleus and mesopontine reticular formation.

  The orexin neurons fire during wakefulness and fire briskly during some survival-related behaviors, such as exploration of environment and foraging behaviors in hungry animals. Thus, the orexin neurons are suggested that play an important role in promoting arousal from the sleep and stabilizing the state of wakefulness.
- **NREM Sleep-Promoting System:** In 1996, Sherin et al found that a group of neurons in the ventrolateral preoptic nucleus (VLPO) and which control the activity of the TMN during sleep [6, 7]. Moreover, this phenomenon is not observed during wakefulness. The VLPO contains inhibitory neurotransmitters named GABA (or γ-Aminobutyric acid) and Galanin. Neurons of the VLPO release these two neurotransmitters and inhibit components of the ascending arousal system such as the LC, TMN, raphe nucleus and lateral hypothalamic area [8]. Another research found decrease of NREM, REM, and total sleep time from animals with lesions of the VLPO [9]. These observations suggested that the VLPO is important in promoting sleep and which contains pathway to

innervate the wake-promoting system. On the other hand, neurons of the VLPO release the GABA and Galanin to inhibit components of the wake-promoting system. Oppositely they are also be inhibited by neurotransmitter projected from the wake-promoting system, such as acetylcholine, norepinephrine, dopamine and serotonin. That is, the sleep- and wake-promoting systems are mutually antagonistic.

- **REM Sleep-Promoting System:** In 1950s, the REM sleep was discovered and defined, subsequent studies started to research the mechanism of the REM sleep. Currently, the pedunculopontine nucleus (PPT) and laterodorsal tegmental nucleus (LDT) at the junction of the midbrain and pons are considered to be critical for the REM sleep [10]. Further, researchers found other factors and define two kinds of neurons: REM-on and REM-off neurons. In addition to the PPT and LDT, the sublaterodorsal nucleus (SLD) and precoeruleus region (PC) are classified as the REM-on neurons. The REM-off neurons includes ventral periaqueductal gray matter(vlPAG) and lateral pontine tegmentum (LPT), which are considered the main region of preventing REM sleep, because vlPAG and LPT receive inputs from the extended VLPO and the lateral hypothalamus [11]. Similar to the relationship between the VLPO and ascending arousal system, the REM-on and REM-off neurons have a mutually inhibitory relationship; interactions between them will cause the on/off switching of the REM sleep.

The flip-flop switch can model the mutually antagonistic relationship among the above systems. Switches of electrical circuits have the characteristic of rapid and complete state transitions. In the brain, transition of sleep states must be quick enough to increase the chance of survival, thus two halves of the 'switch' must inhibit the other side strongly and have stabilizing mechanism to avoid the intermediate states. On the other hand, large scale effects, such as circadian regulation and accumulated homeostatic need for sleep, are also important in regulate balance of mutual inhibition. With the slower large scale effect, state transition of the switch can keep dynamic equilibrium. Thus, damage or lesions of the sleep-related systems may break the balance and cause sleep problems, such as insomnia, narcolepsy or other sleep disorders.

### 2.3 Fuzzy Concept and Fuzzy Logic

The fuzzy logic comes from "fuzzy set theory" proposed by Lotfi A. Zadeh in 1965 [12]. Traditional logic represents clear and specific logic of contexts, that is, completely true or completely false (i.e. two-value or binary logic). Fuzzy defines logical values in a range and allows values between 0 to 1 rather than "0 or 1" (many-valued logic or probabilistic logic). Fuzzy reasoning, extended from the fuzzy logic, which is similar to human reasoning; it provides approximate results from incomplete or ambiguous data to deal with problems that difficult to solve by traditional logic methods. It has been applied to many applications, such as control theory, and artificial intelligence; that used to handle applications of logics with truth values range between completely true and false.

To implement a fuzzy reasoning system, fuzzy set and membership function should be designed first. Membership functions contain linguistic variables and truth values. Variables in mathematics are usually numerical values; in fuzzy logic applications, the non-numeric linguistic variables are often used to be the expression of rules and facts [13].

Fuzzy reasoning is usually based on rules, which described as IF-THEN rules or fuzzy associative matrices. In addition, operators of boolean logic such as AND, OR, NOT are able to use in fuzzy logic. With fuzzy sets and logical operators, we can design rules for the reasoning system. For example, a rule-based fuzzy regulating system of room temperature can be defined like this:

***Rule 1: IF** temperature **is** very cold **THEN** stop air conditioning*
***Rule 2: IF** temperature **is** normal **OR** little hot **THEN** maintain air conditioning*
***Rule 3: IF** temperature **is** hot **THEN** speed up air conditioning*

After designing fuzzy sets and rules, the reasoning system will have abilities to make decisions according to status of environments.

In Brain Informatics field, some related studies [14, 15] have applied fuzzy methodology and neuron network approaches to classify sleep stages from measured physiological signals, such as brain wave, eye movement and muscular tone, etc. In this research, we apply fuzzy approach into the human brain in nucleus-level, attempting to speculate sleep stages according activity of sleep-related nucleus.

## 3 Design of the Sleep Switch

The 'flip-flop switch' describes the mutually antagonistic relationship among neurons of wake, NREM, and REM promoting systems. There are three sleep states: wakefulness, NREM sleep, and REM sleep; and two state transitions (that is, two switches) in this model:

- **Wake-Sleep Switch:** The wake-sleep switch is affected by mutual inhibitory interactions of monoaminergic system (wake-promoting) and the VLPO (sleep-promoting) system. For example, when activity of VLPO is strong, the monoaminergic system will be inhibited and weaker. As the pressure of change is heavy enough; the switch will change rapidly to NREM sleep state. However, the direct inhibition of these neuron groups is relatively unstable [16]. In the human brain, there exist neuron groups which are responsible for stabilizing the wake-sleep switch, such as orexin neurons in LHA and neurons of extended VLPO.
- **REM-NREM Switch:** After switching to the NREM sleep state, the REM-NREM switch will be launched and start to regulate REM and NREM states of the brain. The main neuron groups are SLD/PC(REM-on) and vlPAG/LPT (REM-off). Similar to previous switch, the mutual inhibitory interaction produces the REM-NREM flip-flop switch and promotes state transitions. On the other hand, either REM-on or REM-off neurons are controlled by other neurotransmitter systems respectively. For example, the noradrenergic, serotoninergic and orexin neurons inhibit REM sleep by exciting REM-off

neurons; whereas cholinergic neurons and the VLPO promote REM sleep by inhibit REM-off neurons.

We combine the Wake-Sleep switch and REM-NREM switch into a single system. Figure.1 shows the integration of two switches and the relationship between wake-promoting, sleep-promoting, REM-on, and REM-off neuron groups. In this study, the design and implementation of sleep case will base on this integrated switch model.

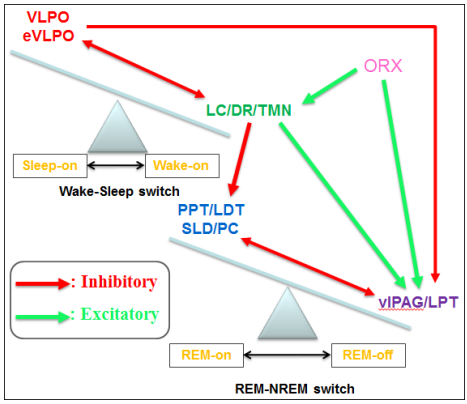


**Fig. 1.** Integrated Sleep Switches and Relationship between Neurons

**Mutual Inhibitory Interactions:** To implement the integrated sleep switches, we should firstly design the mutual inhibitory mechanism of neuron and neurotransmitters. When a nucleus is active, it will project neurotransmitter to other brain regions through specific pathways. The amount of neurotransmitters depends on number of single projection and the projection cycle. On the other hand, neurons of nucleus contain receptors of different neurotransmitters. That is, each nucleus is affected by specific neurotransmitter either excitatory or inhibitory. Therefore we describe this phenomenon for each nucleus as follow:

$$n(t) = \alpha(t) \times A(t) \tag{1}$$

$$\gamma(t) = \begin{cases} \overline{E}_n(t) \\ \overline{I}_n(t) \end{cases} \tag{2}$$

$$\overline{E}_n(t) = \frac{\sum_{j=1}^{Ne} n_j(t)}{N_e} \quad , \quad \overline{I}_n(t) = \frac{\sum_{j=1}^{Ni} n_j(t)}{N_i} \tag{3}$$

In the above equations, $A(t)$ represents activity of the nucleus, which is, projecting number in a unit time (1/t). $\alpha(t)$ is the transmission amount of the neurotransmitter of each projection (molecular weight). $n(t)$ is the amount of neurotransmitter projected by nucleus per unit time (molecular weight/t). With the first formula, we can get the

number of each neurotransmitter in a unit time. The $\gamma(t)$ is the proportion of excitatory and inhibitory of nucleus, which depends on excitatory/inhibitory activities from other nucleus. $\bar{E}_n(t)$ is the average number of excitatory neurotransmitters, and $\bar{I}_n(t)$ is the average number of inhibitory neurotransmitters.

For example, the sleep-promoting neurons are inhibited by wake-promoting neurons (i.e. DR, LC and TMN nucleus) and excited by neurons of extended VLPO. Thus, the parameters of $\bar{E}_n(t)$ must take activity of extend VLPO into account (for sleep-promoting neurons, extended VLPO are excitatory); and consider activities of wake-promoting neurons as parameters of $\bar{I}_n(t)$ (for sleep-promoting neurons, wake-promoting neurons are inhibitors). During each iteration, the system calculates the number of serotonin; norepinephrine; histamine; and other related neurotransmitters according to active values of these nucleuses. Then, we can use these results to calculate the excitatory-inhibitory proportion. Finally, the activity value of each nucleus of next iteration $A(t+1)$ is shown as follow:

$$A(t+1) = A(t) \times \gamma(t) \tag{4}$$

However, from above formulas we can find that if the weight of one side of the switch is very heavy, the other side will keep suppressing without any chance to move the switch. Thus, there must an external controlling mechanism to regulate the balance of the switch. In this study, we add the decay coefficient $\Phi(t)$ into the formula of calculating activities of nucleus as follow:

$$A(t+1) = [A(t) \times \gamma(t)] \times (1 - \Phi(t)) \tag{5}$$

Whether in wake, NREM or REM sleep states the decay coefficient is always available. In the beginning of each state, the $\Phi(t)$ will be initialized. As time goes by, this coefficient increases over time. The $\Phi(t)$ will weaken the activity of dominant neurons and relieve the inhibition of the other side of sleep switch. Finally, the pressure of the inhibited side will be stronger and make the switch change to other sleep states. In our simulation, the initial state is set to "wakefulness"; and Table 1 shows initial value of each nucleus and neurotransmitters.

**Table 1.** Initial Values of Nucleus and Neurotransmitters

| Nucleus | Activity( $A(t)$ ) | Neurotransmitter | Amount ( $\alpha(t)$ ) |
|---|---|---|---|
| DR | 1.0 | Serotonin | 0.4 |
| LC | 1.0 | Noradrenaline | 0.4 |
| TMN | 1.0 | Histamine | 0.4 |
| PPT | 0.3 | Acetylcholine | 0.6 |
| LDT | 0.3 | Orexin | 0.2 |
| LHA | 1.0 | GABA | 0.5 |
| VLPO | 0.1 | | |
| SLD/PC (REM-on) | 0.1 | | |
| vlPAG/LPT (REM-off) | 0.1 | | |

## 4 Combination of Fuzzy Theory and Sleep Switch

The sleep switch model describes the homeostatic regulation mechanisms of sleep in the human brain. However, the threshold of sleep switches can only be inferred by collect statistics data from observing subjects. In this study, we take the fuzzy theory as a tool to calculate the threshold of the sleep switches. The fuzzy system is consisted of three parts as follow:

**Fuzzifier:** Before starting fuzzy reasoning, the inputs should be converted into fuzzy sets. Thus the first step is to define membership functions of inputs and controlling operations. In the sleep case, we select four kinds of nucleus as inputs (activities of wake-promoting, sleep-promoting, REM-on, and REM-off neurons), and use the change of "sleepy index" as controlling operations. On the other hand, we defined the activity of nucleus with three states: rapid, slow and stop. We also set the control of sleepy index with three states: increase, maintain and decrease. After setting states of each element, then we define membership functions of each state. Parameters of fuzzy sets are set as follow:

- Firing rate of nucleus
  1. Rapid: $F_{Rapid} = \int_{0.6}^{0.8} (5x-3)/x + \int_{0.8}^{1} 1/x$
  2. Low: $F_{Low} = \int_{0.1}^{0.4} (2.5x)/x + \int_{0.4}^{0.6} 1/x + \int_{0.6}^{0.7} ((-10)x+7)/x$
  3. Stop: $F_{Stop} = \int_{0.1}^{0.2} ((-10)x+2)/x$
- Control of sleepy index
  1. Increase: $S_{\text{Increase}} = \int_{0}^{1} (x)/x$
  2. Maintain: $S_{\text{Maintain}} = \int_{-0.5}^{0} (2x+1)/x + \int_{0}^{0.5} ((-2)x+1)/x$
  3. Decrease: $S_{\text{Decrease}} = \int_{-1}^{0} (-x)/x$
- Control of REM index
  1. Increase: $R_{\text{Increase}} = \int_{0}^{1} (x)/x$
  2. Maintain: $R_{\text{Maintain}} = \int_{-0.5}^{0} (2x+1)/x + \int_{0}^{0.5} ((-2)x+1)/x$
  3. Decrease: $R_{\text{Decrease}} = \int_{-1}^{-0.5} 1/x + \int_{-0.5}^{0} (-(\frac{8}{5}x)+0.2)/x$

After finishing defining the membership functions of all inputs and controlling operations, the fuzzy set can be used in the fuzzy reasoning system.

- **Rule-Based Fuzzy Logic System:** Fuzzy system must provide rules for reasoning. The general format of rule is "IF A THEN B". The A is called "premise" (or condition) and the B is called "consequence" of the rule. If the rule is composed by multiple premise, we can combine premises with operators

such as AND, OR or XOR, etc. For example, we define activity of wake-promoting neurons as input $x_1$, sleep-promoting neurons as input $x_2$ and REM-on neurons as input $x_3$. And then we use the fuzzy sets from the fuzzifier to define rules as follow:

*Rule1:* ***IF*** *[(*Wake-Promoting Nucleus ***is*** Rapid) ***AND*** *(*Sleep-Promoting Nucleus ***is*** *(*Low **OR** Stop)) ***AND*** *(*REM-Promoting Nucleus ***is*** Stop)] ***THEN*** **Decrease** Sleepy Index

*Rule2:* ***IF*** [(Wake-Promoting Nucleus ***is*** *(*Low ***OR*** Stop) ***AND*** *(*Sleep-Promoting Nucleus ***is*** Rapid) ***AND*** *(*REM-Promoting Nucleus ***is*** Stop)] ***THEN*** **Increase** Sleepy Index

*Rule3:* ***IF*** [(Wake-Promoting Nucleus ***is*** Stop) ***AND*** *(*Sleep-Promoting Nucleus ***is*** Low) ***AND*** *(*REM-Promoting Nucleus ***is*** Rapid)] ***THEN*** **Increase** REM Index

*Rule4:* ***IF*** [(Wake-Promoting Nucleus ***is*** Stop) ***AND*** *(*Sleep-Promoting Nucleus ***is*** Low) ***AND*** *(*REM-Promoting Nucleus ***is*** *(*Low **OR** Stop))] ***THEN*** **Decrease** REM Index

After defining rules, the system can start reasoning following these rules. During each iteration, the fuzzy system receives inputs (that is, activity of each nucleus) from the homeostatic regulating system and applies received inputs into each rule to calculate the membership functions of the consequence. The system will get several bounded membership functions from each rule, and then combine these functions with union operation. Finally, we can get a new function from the fuzzy reasoning system.

- **Defuzzifier:** After getting the combinational membership function of controlling operations, we must convert the fuzzy set into a single explicit output (or called "crisp value") so that the system can process the follow-up control. In this study we use the most common used method to get the output value: calculating the central area of the membership function.

The output value from the fuzzy reasoning system will be used to control the sleepy index. The workflow can be described as Figure.2:

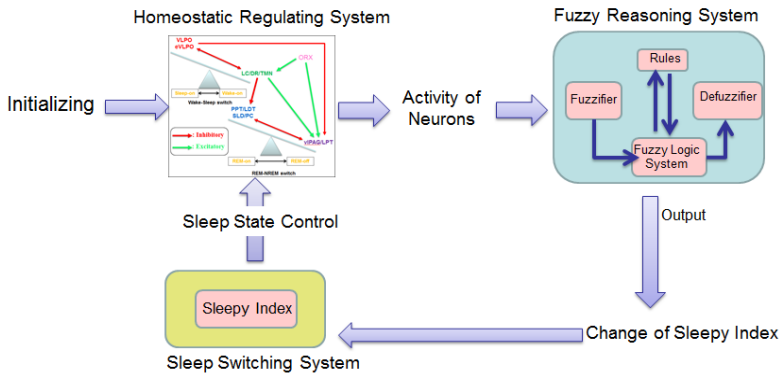


**Fig. 2.**The Workflow of Sleep Switches and Fuzzy Reasoning System

The homeostatic regulating system processes the mutual inhibitory interactions of each nucleus. After calculating activity values of nucleus, these values will be sent to the fuzzy reasoning system as inputs. The fuzzy system receives the inputs and starts the rule-based fuzzy reasoning. When the fuzzy reasoning is completed, there will be a single output from the reasoning system. That is, the change of sleepy index. This value increases, maintains or decreases the sleepy index of the switching system. When the sleepy index exceeds a certain threshold, the switching system will change the sleep state of the simulated brain. The sleep simulating algorithm can be described with pseudo code as follow:

```
SIMULATE_SLEEP_DYNAMICS(time t, sleepNetwork $s ,list $allNucleus[])
1  while time(t) < t_end
2      do sleepyIndex ← GET-CURRENT-SLEEPY-INDEX(s);
3          REMIndex ← GET-CURRENT-REM-INDEX(s);
4          for each nucleus n ∈ allNucleus[]
5                          do  changedList[] ← CALCULATE-INHIBITION-
EXCITATION(t,n);
6          changedSleepyIndex ← FUZZY-REASONING-SLEEP(changedList[]);
7          changedREMIndex ← FUZZY-REASONING-REM(changedList[]);
8        nextState     ←     CALCULATE-NEXT-STATES(changedSleepyIndex,
                                                   changedREMIndex);
9          update SLEEPY-INDEX(s,changedSleepyIndex);
10         update REM-INDEX(s,changedREMIndex);
11         update STATE(s, nextState);
12         update Nucleus-List(changedList[],allNucleus[]);
13 end while
```

Given a networks, which contains value of sleepy index, REM index and sleep state at time *t*. List allNucleus[] contains value of nucleus' activity and projecting amount of neurotransmitters at time *t* (see Table 1). Firstly, the brain simulator calculates the inhibition/excitation results of each nucleus. Next, the changed values will be sent to the fuzzy reasoning system; then the fuzzy system produces outputs, which represents changes of the sleepy and REM index. Finally, the simulator will check changed values of sleepy/REM index and determine whether the sleep switches will change or not. If the switches change, the sleep state of brain simulator will also be modified.

## 5 Brain Simulator Based Implementation

To complete the simulation, implementation of above systems into a simulator is required. In this paper, we use a brain network simulator suggested by Tseng, Lu, and Mei [17]. The brain simulator is an open-sourced project, which adopts object-oriented (OO) methodologies to design and implement brain components, brain regions, neurotransmitters and brain networks. In addition to anatomical structure, the brain simulator also integrates functional structures and operational models of the brain. This simulator adopted of case-based incremental delivery developmental process to increase the elasticity and flexibility of the brain simulator framework itself. With the case-based method, developers can add new functions or behavior models into the brain simulator according to their requirements. Besides providing Back-end integration, the simulator also supports front-end rendering of the brain network, including 3D-rendering functions and interactive visualization. With supports of the 3D graphics, presenting the

sleep behavioral models will be more intuitive and easier to understand. Currently, this simulator has integrated models of Alzheimer's disease and has basic structure of brain networks; in this study, we integrate sleep behavior models and the fuzzy system into the brain simulator and show the sleep physiological changes of the brain with user interfaces and the 3D-rendering system. Figure.3 shows a snapshot of the simulation. After initializing, the user interface will present the sleep states, activity of each nucleus, and projecting pathways of neurotransmitters. The activity changes of Wake/Sleep/REM Promoting Neurons are shown in Figure. 4.

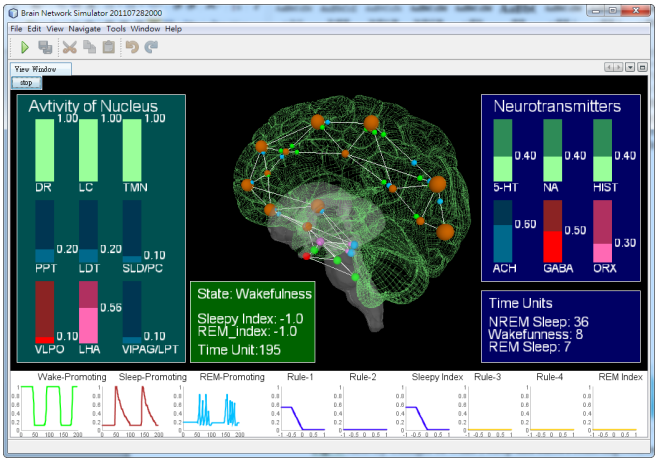


**Fig. 3.** Screenshot of the Brain Simulator

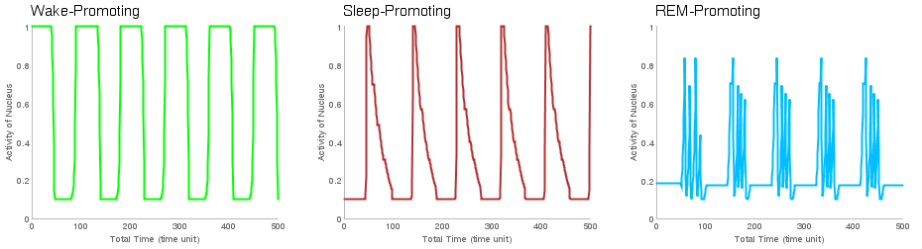


**Fig. 4.** Activity Changes of Wake-, Sleep and REM Promoting Neurons

## 6 Conclusion and Future Work

In this study, we focus on combining the sleep switch model and fuzzy theory to provide a possible methodology for resolving problems to formulate the sleep switch and mutual inhibition mechanism among nucleus of the human brain. Moreover, we implement these models and methodology with techniques of computer science, and then present changes of the brain network with 3D-rendering system to make these models more intuitive and easier to understand. However, currently we can only simulate general cases of sleep behaviors by gradually regulating fuzzy sets of nucleus status and controlling strategies. Thus, some training methods are required, such as pattern recognition from input data, and machine learning technologies. With

input data and appropriate training methodologies, it may be possible to generate various fuzzy sets, and finally achieve personalization. In summary, this study is still ongoing; more in-depth studies and improvement are required, such as rationality of theoretical models of sleep, more appropriate fuzzy sets and controlling strategies, and take other behavior models into account (i.e. Alzheimer's disease, cognitive or memory). Each improvement will enhance our works and make our methodology more reasonable and comprehensive. Finally, we hope that this study can inspire more related research and encourage people joining the development making more contributions for discovering the secrets of the sleep physiology.

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