A toy model of the brain

B. Hoeneisen and F. Pasmay

Universidad San Francisco de Quito
30 March 2004

Abstract

We have designed a toy brain and have written computer code that simulates it. This toy brain is flexible, modular, has hierarchical learning and recognition, has short and long term memory, is distributed (i.e. has no central control), is asynchronous, and includes parallel and series processing. We have simulated the neurons calculating their internal voltages as a function of time. We include in the simulation the ion pumps of the neurons, the synapses with glutamate or GABA neurotransmitters, and the delays of the action pulses in axons and dendrites. We have used known or plausible circuits of real brains. The toy brain reads books and learns languages using the Hebb mechanism. Finally, we have related the toy brain with what might be occurring in a real brain.

1 Introduction

We have designed a toy brain with the model described in [1], and have simulated it on the computer in C++ language. The purpose of this exercise is to simulate neurons by calculating their internal voltage, including their ion pumps, synapses with neurotransmitters, electrochemical action pulses that propagate with finite speed along the axons and dendrites, and the “Hebb mechanism”[2] that alters the strengths of the synapses so that the brain can learn. We have simulated excitatory synapses with glutamate neurotransmitter, and inhibitory synapses with GABA neurotransmitter.[2] These synapses can release neurotransmitters fast or slow. We have used known circuits of the brain wherever possible,[2] or at least circuits that the brain may plausibly use. The toy brain can learn languages, e.g. English and Spanish, without mixing them into “Spanglish”. We have designed a
plausible structure of the brain, including parallel and series hierarchical learning and recognition, with long and short term memory at the higher levels of the hierarchy. The toy brain is flexible, modular, asynchronous, has distributed processing (i.e. no central control), and its neurons have critical learning periods. This toy brain has a little over 12 thousand neurons and 70 million synapses.

The block diagram of the toy brain is described in Section 2. Then follow descriptions of the blocks, neurons, results, and the possible relation of the toy brain with a real brain. Conclusions are collected at the end.

2 Block diagram

To be specific we will describe the particular toy brain shown in Figure 1. This toy brain can learn up to 36 letters of 8 bits, 500 words of 4 letters, and 10,000 phrases of 4 words. This brain reads a book in English, or Spanish, or whatever. The text is parsed into phrases of 4 words. Each word is truncated to the first 4 letters (if the word is shorter than 4 letters it is padded with spaces). Each letter is coded into 8 bits with 4 ones and 4 zeroes. The toy brain has 4 hierarchical levels called “bits”, “letters”, “words” and “phrases”. The “letter” neurons learn patterns of 8 bits, the “word” neurons learn patterns of 4 letters, and the “phrase” neurons learn patterns of 4 words.

“Phrases” and “words” are accessible to short term memory, i.e. if a “phrase” neuron fires it causes the corresponding four “word” neurons to fire after a delay, which, in turn, cause the “phrase” neuron to fire again. Note the double arrows in Figure 1. These synchronized firings cease after about ten seconds (the duration of short term memory which is settable) because each of these neurons has an auxiliary neuron that integrates (counts) pulses until it reaches its threshold, and then inhibits the main neuron with a slow inhibiting (GABA) synapsis. Thus, according to the model of Figure 1, the “phrase” acquires the composite “meaning” of its 4 “words.” “Letters” and “bits” are not accessible to short term memory, i.e. they do not have feedback circuits to sustain repeated firings of the neurons. Note the single arrows in Figure 1.

The brain reads the book one word at a time. The 4 letters of the word are learned and recognized in parallel. To recognize a phrase of 4 words, the toy brain learns and recognizes the 4 words in series (i.e. one at a time).

1The numbers in Figure 1 are constants of the c++ program and can be set at will. We have tried other brain topologies, but limit the discussion to the particular one shown in the figure.
Figure 1: Model of a toy brain with four hierarchical levels: bits, letters, words and phrases. The number of principal neurons in each block are shown. The neurons in the upper hierarchies (words and phrases) have auxiliary neurons with slow negative feedback to turn off oscillations after a delay. Each block of word neurons is activated sequentially by one auxiliary neuron (shown only for the first and last word blocks). The arrows represent several axon, synapse and dendrite. A double arrow represents axons going up and axons coming down.
Each block of word neurons is activated sequentially by one auxiliary neuron that counts the words (shown only for the first and last word blocks in Figure 1). These auxiliary neurons are reset due to the lapse of time between one phrase and the next.

3 Blocks

All blocks in Figure 1 are similar. Let us describe the first block with 36 “letter” neurons. Four of these neurons are shown in Figure 2. Each “letter” neuron has (initially) 8 inputs corresponding to the 8 bits defining the first letter of a word, and one output connected to 2000 word neurons.

The neurons can be in one of three modes: inactive mode, learning mode, or recognition mode. Initially, all neurons in the block are in inactive mode, except for neuron “1” which is in learning mode. A “letter” with 4 ones and 4 zeroes is presented to the first block of 36 “letter” neurons. Neuron “1” fires and learns this letter by strengthening the corresponding 4 synapses and breaking the other 4. This is the Hebb mechanism. Neuron “1” passes to recognition mode, and tells neuron “2” to pass to learning mode. This signal is shown with a dashed arrow in Figure 2. Note that neuron “2” has reached its critical period for learning. Before learning, a “letter” neuron has 8 inputs. After learning, only 4 inputs survive (with synapses with strengthened couplings).
Figure 3: One “word” neuron with associated circuitry.

The output of each neuron has an inhibitory (GABA) connection to an input of each succeeding neuron of the block. These fast inhibiting connections (shown only for neuron “1” in Figure 2, see dotted lines) prevent several neurons in the block from learning the same letter, and also make the design of the brain more robust, since, for blocks with short term memory, only one neuron per block can fire repeatedly at any time.

Let us now consider the \( n \)th “word” neuron in a block of 500 words, see Figure 1. This neuron and associated circuitry is shown in Figure 3. Before learning, a “word” neuron has \( 36 \cdot 4 = 144 \) input connection from “letter” neurons. After learning, only 4 of these connections are left (with synapses with strengthened coupling). A “word” neuron has the same circuits of a “letter” neuron, plus one added circuit. To turn off the repeated firings of neuron “\( n \)” (due to the feedback loops between “phrase” neurons and “word” neurons) there is a connection from the output of neuron “\( n \)” to one of its inputs via an auxiliary neuron. This auxiliary neuron has a long time constant to return to its resting voltage, so it integrates (counts) its input pulses until it reaches its threshold voltage. The output synapse of the auxiliary neuron is inhibitory and releases GABA neurotransmitter slowly, so it turns off the repeated firings of neuron “\( n \)” after about 10 seconds (settable). Such positive and negative feedback circuits have been observed in real brains.[2]

The other difference between “letter” blocks and “word” blocks is that the former learn in parallel, while the latter learn in series. To implement the
series learning of words we need a control that activates one word block after another. This is accomplished with one auxiliary neuron per block. This auxiliary neuron has a long time constant and integrates (counts) the words of the phrase and fires to synchronize these words. The first “word” block learns the first word of a phrase, the second block learns the second word of the phrase, and so on. The words are synchronized by the lapse of time between one phrase and the next.

4 Neurons

The simulated neurons have a resting voltage -0.06 Volt. Ion pumps make the voltage of the neuron approach the resting voltage with a time constant \( \tau \), which is a settable parameter. The neurons have a threshold voltage -0.04 Volt. When the internal voltage of the neuron surpasses this threshold, an action pulse is produced (due to fast sodium and slow potassium voltage activated ion channels) with a time distribution taken from [2].

Synapses are defined by the following parameters: voltage step \( \Delta V \) into the target neuron with a settable time distribution (the injection of charge into the target neuron can be faster or slower), and delay \( \Delta t \) of associated dentrite and axon. If \( \Delta V > 0 \), the synapse is excitatory. If \( \Delta V < 0 \), the synapse is inhibitory.

Finally, if the neuron is in the learning state, then the \( \Delta V \) of all inputs that cause the neuron to fire are increases by \( \delta V \), and the \( \Delta V \) of all other inputs are set to zero (effectively disconnecting these synapses).

Real neurons must have adjusted these parameters (by learning from experience and/or by evolution).

5 Results

The toy brain has learned (in the sense described in this note) Spanish by reading “Vivir para contarla” by Gabriel García Marquez. To show the level of detail of the simulation, we present in Figure 4 the internal voltage of three neurons: the neuron that counts the fourth word in a phrase, a phrase neuron that recognizes four words, and the auxiliary neuron that turns this word neuron off after a delay. Note that the neurons have a resting voltage of -0.06 Volt, and a threshold voltage of -0.04 Volt. Note that when the phrase neuron fires, the feedback loops cause it to fire repeatedly, until the auxiliary shut-off neurons turn this oscillation off. Note, in the top and middle graphs, the four steps (corresponding to the four words) required to
Figure 4: Internal voltage of three neurons as a function of time. From top to bottom: auxiliary neuron that counts four words to enable the fourth word block; a “phrase” neuron that recognizes a phrase of four words; and the auxiliary neuron that turns off this “phrase” neuron after a delay.
reach the threshold voltage of these neurons.

6 Thoughts on thoughts

Let us put our toy brain in a more familiar setting. We will add one more hierarchical level: call it “paragraph”. For the sake of brevity we will consider only the nine neurons shown in Figure 5: one “paragraph” neuron called “my world”, two “phrase” neurons called “her face” and “me”, five “word” neurons called “eyes”, “mouth”, “voice”, “hands” and “tooth ache”, and one “letter” neuron called “pain”. The toy brain has many other neurons and another hierarchical level (“bits”) that we will not consider. The connections shown in Figure 5 have been learned by prior experience of the toy brain.

Now suppose I am discussing consciousness with a friend. My eyes see her and my ears hear her, and my brain recognizes her eyes, her mouth and her voice (meaning that the “eyes”, “mouth” and “voice” neurons fire). The firing of these neurons cause the “her face” neuron to fire, so I have recognized her face. Feedback loops cause repeated firings of these neurons, binding together those eyes, that mouth and that voice to form her face.

In a real brain, the neurons in the upper hierarchies are associated with awareness. We assume that “bits” neurons have no awareness, “letter” neurons have awareness and are not accessible from short term memory (see the single ended arrow in Figure 5), and “word”, “phrase” and “paragraph” neurons have awareness and are accessible from short term memory. So now, in a real brain, I am aware of that face with those eyes, that mouth and that
My eyes also see my hands. My brain recognizes these hands, meaning that the “hands” neuron fires. Also, a neuron in my tooth causes the “pain” neuron to fire, which in turn causes the “tooth ache” neuron to fire. The firing of the “hands” neuron and the “tooth ache” neuron cause the “me” neuron to fire, so I have recognized my self. Feedback loops cause repeated firings of these neurons, tying me together, so now I am aware of my self with these hands and this tooth ache with that pain.

The firing of the “her face” and “me” neurons in turn cause the firing of the “my world” neuron. Feedback loops now cause eight neurons to fire synchronously, tying my world together, so now I become aware of my world with her face (with those eyes, that mouth and that voice) and me (with these hands and this tooth ache with that pain). The “pain” neuron is not part of the feedback loops, so the pain goes away as soon as the dentist lifts that awful hook.

Of course this model and description are over simplified, but they give a general idea of what might be going on in a real brain. Lacking an understanding of the three difficult phenomena: awareness, attention and free will (if indeed we have free will!), we present the following speculations as a working hypothesis to help guide experiments.

**Hypothesis:** From a certain hierarchical level on upwards:

1. Awareness is the dynamic set of firing neurons.
2. Somehow, I can excite a neuron (by free will?).
3. Somehow, I can inhibit all neurons belonging to a hierarchical level (by free will?).

If (by Hypothesis 2) I excite, for example, the neuron “her face”, then feedback loops make “eyes”, “mouth”, “voice” and “her face” to fire repeatedly in synchronism. In this way I have brought the image of that face (with those eyes, that mouth and that voice) from long term memory and have re-lived it in short term memory. Note that if I excite the “me” neuron I can remember myself with these hands and this tooth ache, but I can (fortunately) not feel the pain of that tooth ache from memory (because the “pain” neuron is not within the feedback loops and can not be excited from memory).

To focus attention on, for example, her eyes, I must inhibit all “word” neurons except “eyes”. A way to do that is to inhibit all “word” neurons (Hypothesis 3) and excite the “eyes” neuron (Hypothesis 2).

René Descartes divided the world into *res extensa* (matter) and *res cogitans* (mind). The problem with this division is that it leaves out the interaction of matter on mind, and mind on matter. May we suggest identifying
“mind” with the “dynamic set of firing neurons” (in the upper hierarchical levels of processing). Then the interaction of matter on mind (via synapsis from sense cells to neurons), and mind on matter (via synapsis from neurons to muscles) becomes clear.

Let us repeat Hypothesis 1: Awareness is the dynamic set of firing neurons (in the upper hierarchical levels of processing). This set of firing neurons is determined by inputs from the senses and/or memory (Hypothesis 2), and/or attention (Hypothesis 2 and 3), and a lifelong learning process that programmed the strengths of the couplings at the synapses (and other parameters of neurons and synapses), and is partially \(^2\) sustained for a few seconds by feedback loops. According to Hypothesis 1, we have identified what I am aware of with the set of firing neurons. The pain of the tooth is a set of firing neurons. Who/what feels that pain: a grander set of firing neurons. The sight of her face is a pattern of firing neurons. Who/what sees her face: a grander set of firing neurons. The awareness of my world is a set of firing neurons. What/who has that awareness: that same pattern of firing neurons. If we define “I” as what I am aware of, then “I” am a dynamic set of firing neurons, sustained by the organization of my brain, the organization of my body, and by the world.

Our toy brain does not understand what it reads, for the same reason I do not understand a book in Polish (I would have understood the book if my mother would have been Polish). For the toy brain to understand, it is necessary (but hardly sufficient) to equip it with sensors and hands so it can explore the world, and give it a “mother” to teach it the names of the things in the world. Would the toy brain then wake up to awareness?

7 Conclusions

We have designed and developed a toy brain that runs on a personal computer. This toy brain is flexible, modular, has hierarchical learning and recognition, has short and long term memory, is distributed (i.e. has no central control), is asynchronous, and includes parallel and series processing. We have simulated the neurons calculating their internal voltages as a function of time. We include in the simulation the ion pumps of the neurons, the synapses with glutamate or GABA neurotransmitters, and the delays of the action pulses in axons and dendrites. We have used known or plausible circuits of real brains. The toy brain reads books and learns languages (in the limited sense described in the article) using the Hebb mechanism. We have identified parameters that real neurons must be able to adjust (by

\(^2\) In our example, the “pain” neuron is outside of the feedback loops.
learning from experience and/or evolution). We have related the toy brain with what might be occurring in a real brain, and have obtained some insight on our minds. We propose that neurons in a real brain can be in inactive mode, learning mode or recognition mode. Finally we have presented working hypothesis related to the difficult questions: awareness, attention and free will.

References

[1] B. Hoeneisen, “A model of memory, learning and recognition” http://arxiv.org/abs/physics/0210093 (2002)

[2] “Neuroscience”, Dale Purves et.al., editors, Sinauer Associates, Inc., Publishers (2001).