CS 182 Spring 2004. Assignment 1 Solution.

The basics of the brain: the numbers, the basics of the visual system, etc.

The solutions here are model answers only. There are a number of equally good answers to these questions.

Question 1. [20 points]

a. What is the minimum time interval between firings of cortical neurons? [5 points]

> On the order of 1 to 5 ms.

b. What is the minimum time for a person to give a forced choice response to a simple stimulus? [5 points]

> On the order of 100 to 500 ms.

c. What do these facts suggest about the number of steps in a minimal neural computation? [5 points]

> On the order of 100 to 500 steps.

d. What is the speed of neural signal transmission? Does this change the intuition on the computing speed of the brain? [5 points]

> The speed of neural signal transmission in the non-myelinated cortical neurons is about 1 m/s. For myelinated neurons the speed is about 100 m/s.
>
> All in all, it takes on the order of 1ms for neural firing, 1ms for transmission down the axon, and 1ms for transmitters to drift across the synaptic cleft. The computing speed of the brain is approximately a few ms per cycle, which is dramatically slower than a modern-day CPU. It must therefore rely on massive parallelism to do the computation.

Question 2. [30 points]

a. About how many neurons are in the human brain? [5 points]

> 10-100 billion

b. What is the fan-out of cortical neurons (on the average, to how many other neurons is each neuron directly connected)? [5 points]

> 1000-10,000

c. From these two numbers, estimate the minimum number of links to reach all cortical neurons from some starting cell? (Note: [fan-out] ^ [# of links] should be greater than or equal to the [# of neurons].) [5 points]

> $10{,}000^n \geq 100$ billion
> $n = \log(10^{11}) / \log(10^4) = 11/4 = 2.75$
> Rounding up to get complete links, it should take a minimum of 3 links to reach all cortical neurons from one starting cell.

d. About how many synapses are there in the brain? [5 points]

> [number of synapses] = [number of neurons] x [average fan-out of neurons]
> [number of synapses] = $10^{11} \times 10^4 = 10^{15}$

e. At about what age is the number of synapses at its maximum. [5 points]

> 2.5 - 3 years old

f. About how many synapses per second are generated to this point. [5 points]

Assuming we start from the initial development of the fetus in the womb, the 10^15 synapses are generated over the course of 9 months prenatal development plus 36 months after birth.

[average rate of synapse generation] = 10^15 / 45 months = 8573388 synapses per second
Average rate is on the order of 8 million to 11 million synapse per second.

Question 3. [25 points]

a. About how many genes are in the human genome? Why is this controversial? [5 points]

The Human Genome Project currently puts the number of genes at around 30,000. Previous estimates go as high as 100,000 genes, and the number is still disputed by many scientists.

The controversy arises from the process used to analyze the genome, which contains some 3 billion DNA letters. Genes comprise only about 2% of the human genome, and are segments buried within this long string of DNA letters.

Genomics 101: A Primer
http://www.ornl.gov/sci/techresources/Human_Genome/publicat/primer2001/1.shtml

Helen Briggs. "Dispute Over Number of Human Genes." BBC News Online (2001).
http://news.bbc.co.uk/2/hi/sci/tech/1426702.stm

b. Since there are vastly more neural connections than genes, it has been claimed that very little of our brain is pre-specified. Show that this argument fails if one takes into account the fact that much of cortex is laid out in systematic maps with regular connection patterns. [5 points]

The wiring of neural connections can be grouped into sections with regular connection patterns. For example, the retinal ganglion extends from the eye to the brain in the same general direction. Since each group now requires only one piece of information specified in the gene, it is feasible to specify the connections for all the groups with the 30,000 or so genes.

c. How many bits would it take to specify a map of the retina (1000*1000) to a brain area of the same size? [5 points]

There are 1000*1000 = 1 million "pixels" in the retina that needs to connect to 1 milllion neurons in the brain. Each pixel needs to know which neuron it connects to, so each one needs an address among the 1 million neurons. It would take $\log_2[1{,}000{,}000] = 20$ bits to specify the "address", so it takes 20 million bits total.

d. Can you think of a biologically plausible way for precise neural wiring to be done during development? Describe how neural connectivity is not fully specified in the genetic code, although it could be in principle. Recall that a newborn colt or calf functions almost immediately. [10 points]

From part a and part c, it is clear that there are more bits of information than the gene can encode if neural wiring is done in a brute force way of specifying addresses. Systematic maps for neural wiring (part b) resolves the encoding issue by guiding groups of axons to grow to a general part of the brain. This is done by using chemical markers and chemical gradients to attract / repulse axons to certain directions.

However, the systematic map does not ecode the precise wiring of each connection. Once the axons reach their destination, they basically compete to form synapses wherever they land. The fine-tuning of the precise neural connection requires activity (stimulants). There are two types of activity-dependent tuning, pre-natal and post-natal. In pre-natal tuning, as in the case of a calf, the brain generates activity patterns while the calf is still in the womb to allow the visual and other system to fine-tune its connections. In post-natal tuning, as in the case of a cat, the visual input to its eyes causes certain connections to strengthen and others to die off.

Question 4. [25 points]

a. How many neurons are there in the main cable (retinal ganglion) from the eye to the brain? [5 points]

> around 800,000 to 1 million

b. About how many eye fixations do we make per second. [5 points]

> about 2 to 4

c. Using 4a and 4b, compute how many pieces of information get transferred from the eye to the brain each year. [5 points]

> Assuming that each bit of information in the retina is either “on” or “off” (which is clearly not the case), each second there are 2 million bits of information. In a year, 6.15E13 bits of information gets transferred to the brain, ignoring sleep for the moment.
>
> If we take into account colors, assuming we have 24-bit color depth, 7.38E14 bits of information are transferred to the brain.

d. Compare this number to the answer to question 2a - what dies this tell you about visual memory? [10 points]

> There are on the order of 10^11 neurons total and on the order of 10^14 bits of information from the visual system in just one year. The visual memory therefore must not be encoding information bit by bit. A large amount of information is basically just lost (forgotten), and other information is abstracted.