What is this unit about?

This unit is about how the brain works. We don't know how the brain works, but this unit is about what we do know. Typically when you ask how the brain works, you expect one of two sorts of answers, one sort of answer describes the stuff the brain is made of, neurons, synapses, dendrites and axons, and explains what they do and how it might support computation in the brain. The other sort of answer talks about parts of the brain, the hippocampus, the basal ganglia, the cerebellum, and suggests which algorithm might be at work in each.

Of course, neither of these answers rely addresses the central mystery we all want answering: what am I doing when I am thinking, how can a computational device produce the sense that I am 'I'; what is going on? Nor does any answer you will get now answer the more modest, but still incredibly ambitious scientific programme that neuroscientists have decided is a reasonable substitute for answering these fundamental questions: what computations occur in the brain and how are these made possible by the action of the brain's constituents across different scales: the chemicals that build synapses, the synapses the connect neurons, the neuronal circuits these connections produce, the brain areas that contain the circuits.

This unit, therefore, describes a small part of a science in progress, a science with incredible ambitions and amazing potential which is still in its infancy. We believe that those things we do understand from neuroscience have something useful to tell us as computer scientists, roboticists and technologists.

Neurons and action potentials

What is the brain made of?

One answer to this question is that the brain is made of cells; there are other answers, the brain is made of atoms, the brain is made of circuits and so on, but in this introduction we will first concentrate on the cells.

Many of the cells in the brain serve a sort of support role, they hold things in place, help with metabolic processes and maintain the brain as a living organ. These cells, many of which are *glial cells* may well play some role in neuronal computation; but here we will focus on the *neurons*, the cells which are directly involved in the cell-to-cell signaling we believe is responsible for computation in the brain.

We will be looking in detail at how neurons signal; our aim here, however, is to get an overview of how the story fits together to make it easier to understand the more detailed discussion when we get to it. In Fig. 1 there is a diagram giving the main parts of a neuron. In the center there is the *soma*, the neuron is a cell and the soma is the cell body; here many of the metabolic processes, the life-supporting, functions of the neuron occur, it contains, for example, the nucleus where the genetic material is found and which controls the synthesis of proteins.

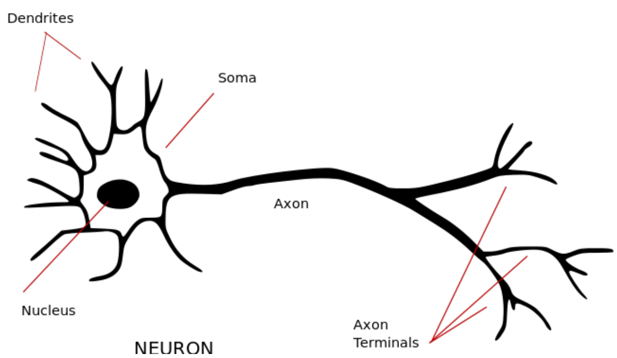

Figure 1: **A diagram of a neuron**; this cartoon shows the main parts of the neuron, very very roughly, the dendrites, where the signals come in, the soma where they get added together and the axon, which carries signals on to other neurons. Figure from `wikimedia`

There are two sorts of tubes extending from the soma, the *dendrites* and the *axon*. These really are tubes, though it is tempting to think of them as wires: the neuron has an inside and an outside separated by a membrane. Both inside and outside the neuron there is fluid, basically water with dissolved salts, but the fluid inside and out have different concentrations of the ions that make up the salts. There can be a potential difference, that is a voltage difference, across the membrane and, as we will discuss, the signals we are will be talking about are changes in voltage.

Roughly speaking, and this is a very rough claim, the signals to the neuron come in along the dendrite whereas the signals the neuron sends go out along the axon. The axon of other neurons will transmit signals to this neuron's dendrites at points where they, the other neuron's axon and this neuron's dendrite, nearly touch: the nearly-touching place is called a synapses and synapses contains complicated bio-mechanical machinery to allow the signals to be communicated from axon to dendrite. We will discuss this further soon.

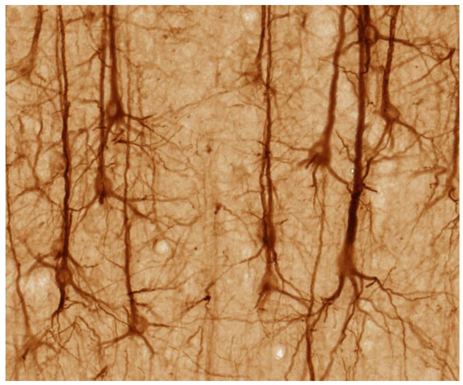

Figure 2: **A picture of some neurons**; these show the pyramidal neurons found in the cortex, part of the brain; they are called pyramidal because of the shape of the soma; you can also see the large number of dendrites. Figure from `wikipedia`

In Fig. 2 is a picture of some neurons; it would be a mistake to think that all neurons are similar to each other. There is a huge diversity of different neurons, they differ in their shape, in their size, in how connected they are and in their voltage dynamics. As an extreme example, the Purkinje cells, as in Fig. 3 has a huge number of dendrites and receives connections from as many as 100_000 other neurons, however, many of those other neurons are cerebellum granule cells, very small neurons that receive inputs from only three or four other neurons.

It is tempting, as a computer scientist, to think of neurons as a sort of universal circuit component; this is a mistake. However, there are, nonetheless, aspect to the description of neurons that are reasonably general.The first of these reasonably general aspects we have already covered: signals come in the dendrites, accumulate in the soma and go out the axon. There is a more general aspect we have already alluded to: the signals correspond to changes in voltage.

Figure 3: **Drawing of a Purkinje cell**; this is a drawing of a Purkinje cell, by Santiago Ramón y Cajal, an important neuroanatomist active in the late nineteenth and early twentieth century. The Purkinje cells are found in the cerebellum. Figure from `wikipedia`

0.1 Action potentials

There is a potential difference between the inside and outside of a neuron. For convenience we usually regard the fluid in the brain as being at a zero voltage; relative to that the fluid inside a neuron has a negative voltage; -70 mV at rest would be a typical value. You might think this makes no sense, if there is a voltage difference between the inside and outside of the neuron, surely a current would flow between the two equalizing the voltage difference? There are a number of reasons that doesn't happen, firstly the membrane is an insulator, largely preventing the flow of current, secondly, the situation is, as we will see, more subtle, not only is there a difference in voltage across the membrane, there is a difference in the concentration of ions with, for example, an excess of sodium ions outside the cell relative to inside and an excess of potassium ions inside relative to out. Along with the voltage differences, these concentration differences also have the potential to cause ions to flow into or out of the neuron. Finally, there are pumps, minuscule molecular machines, which pump ions in and out of the neuron to help maintain the voltage difference. It is, all-in-all, a complicated story, for now, what we need to know is that there is a voltage difference across the cell membrane.

Why is this important: well it is important because the signaling dynamics of a neuron is voltage dynamics: signals are carried by what are called *action potentials* or *spikes*: these are spikes in the voltage that travel along the axon. A picture of an action potential is shown in Fig. 4. During a spike the voltage shoots up by about 80 mV and then falls back to near the resting value, all during 1-2 ms. The dynamics that allow this to happen come from ions traveling through the membrane, in a sense the energy for the spike has been stored up by the all ion pumping that has created the concentration differences across the membrane. The spike will travel along the axon. The axon will usually have many branches and when this happens a spike will travel down each branch: the spike doesn't split in the sense that the spike traveling down each branch will be the same size as the original spike. Similarly, broadly speaking, the spike does not change amplitude or shape as it propagates along the axon. I think a useful analogy here is to a train of dominoes fall over; the energy in that case comes from the energy stored in the domino when it was set upright, the collision from the other domino hitting it is what causes it to fall over but isn't the source of most of the energy involved in its own fall; when a train of dominoes splits, the wave of falling-over is just as fast along each branch.

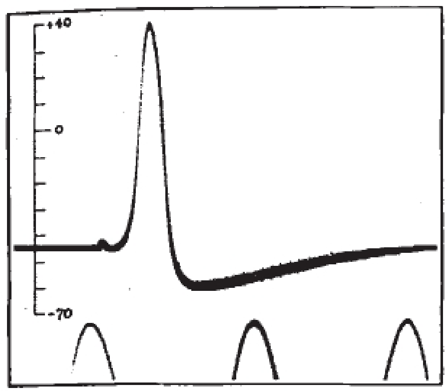

Figure 4: **An action potential**; this is an action potential recorded from an axon, it is actually a very early recording performed by Hodgkin and Huxley, pioneers in recording and modeling action potentials; this picture is actually a photograph of an oscilloscope trace.

1 Summary

So far we have begun a broad overview of neurons and what they do; this is all going to be revisited in more detail later. In particular we have described the division of neurons into dendrites, soma and axons and have seen that signals propagate along the axon in the form of voltage spikes.