Synapses

In the previous section we discussed action potentials, the voltage pulses that travel along axons and carry signals from neuron to neuron. What we didn't discuss was how the signals got from the axon of one neuron to the dendrite of the next. The answer is synapses.

In discussing the action potential we mentioned that it is a largely stereotypical signal, the action potentials from a neuron all have roughly the same amplitude and shape. The synapses, in contrast, are very variable; they have different strengths, the strengths can change over time. Beyond these variations in strength, synapses can have very different dynamics, with differences in the time course of how the synapse responds to a spike, or in how the synapse responds to spikes coming in quick succession.

The complicated and variable behaviours of synapses are possible because synapses do not simply connect the axon to the dendrite, they are not simply holes or pores through which ions flow. In fact, there are synapses, called *gap junctions* that are like that, these gap junctions are the only synapses in some simple creatures like jellyfish and are found in the mammalian brain. However, the synapses we usually have in mind are *chemical synapses* in which the signal transfer from *pre-synaptic* axon to *post-synaptic* dendrite involves a complex chemical cascade.

Chemical synapses

In Fig. 1 is a cartoon of a synapse. The first thing to note is that the dendrite and axon don't actually touch; there is a little gap, called the *synaptic cleft* between the two. Of course, the axon and dendrite are held together by glial cells, cells which also surround the cleft and keep everything in place. In important thing though, is that the charge doesn't flow directly from dendrite to axon.

When a spike arrives at the synapse it kicks off a chain of events. The sudden change in voltage opens channels in the membrane of the synapse which allow calcium to flow into the *terminal button*, the part of the synapse on the axon side of the cleft; it is an amazing property of neurons that they contain ion-specific channels. The calcium flows into the synapses and, by way of complicated chemical reactions, this causes some little spheres called *vesicles* to fuse with the wall of the cleft and burst releasing some very specialized molecules called *neurotransmitters* into the cleft. These

A diagram of a synapse. There are three parts, from top to bottom, the axon terminal, the synaptic cleft and the dendritic spine. The terminal looks like a round door knob, bulbous part facing down, the spine is like a flat hill and the gap between them is the cleft. In the axon terminal there are a number of circles labelled as synaptic vesiles, each filled with dots labelled as neurotransmitter, these vesicles are arranged in a circle with an arrow pointing around from one to the next, the bottom one has burst releasing its contents into the cleft. Spanning the edge of the axon terminal are some features that look like two tiny ovals lying parallel to each other, these are labelled as voltage-gated Ca^{2+} channels. On the edge of the dendritic spine facing the cleft there are some small T-shaped features spanning the edge, the top of the T in the cleft, there are labelled receptor. In the spine some wavy lines are labelled postsynaptic density.

Figure 1: **A diagram of a synapse**; this cartoon shows the main parts of the synapse; the axon of the pre-synaptic neuron is coming in from the top, the dendrite of the post-synaptic neuron is leaving through the bottom. Figure from `wikipedia`

neurotransmitters, in turn, bind with channels on the opposite face of the cleft, that is, with channels in the membrane of the post-synaptic dendrite.

These channels, in turn, in response to binding with the neurotransmitter, open and depending on the type of synapse, they either allow ions to flow into, or out of, the dendrite, either increasing its voltage, or decreasing it. In other words, before looking at all the other variations, there are two main types of chemical synapses, *excitatory* synapses, that increase the voltage of the post-synaptic neurons and *inhibitory* synapses that decrease it.

Each type of synapse has different channels in the dendritic face of the cleft and different neurotransmitter which binds to these channels. In an excitatory synapses these channels allow sodium ions into the cell; since sodium ions are positive ions this increases the charge inside the cell. Depending on exactly what type of inhibitory synapse it is, in an inhibitory synapse the channels either allow chlorine ions into the dendrite, chlorine ions are negative so this decreases the voltage, or they allow potassium ions out of the cell, potassium ions are positive, so again this decreases the voltage.

The channels open because they have bonded with the neurotransmitter; they are called *ligand-gated channels*; a ligand is a molecule that binds to things and so these are channels that act as gates, sometimes allowing ions

through and sometimes not and they do so depending on whether or not they are bound to a ligand. This is in contrast with the *voltage-gated channels* that open to let the calcium in, these open and close depending on voltage and, we will see, voltage gated channels are also important in understanding how spiking happens. The binding between ligand and ligand-gated channel is quite loose and the molecules are bathed in a warm fluid; random Brownian movements will unbind the ligand allowing the channel to close. The timescale for this unbinding is different for different channels; for typical excitatory synapses it is of the order of tens of milliseconds. The neurotransmitter in the cleft is also cleared away by little pumps; the reuptake pumps, and is repackaged into vesicles ready for the arrival of later spikes.

The final part of this story is the dendrite itself; consider first the situation with a excitatory neuron. The current flow into the neuron increases the voltage, this ramps up as more and more ligand-gated channels open before decaying away again as they close. The resulting positive pulse is called an *excitatory post-synaptic potential* or EPSP. For an inhibitory synapse the pulse is negative and is called an *inhibitory post-synaptic potential* or IPSP. Example PSPs are showing Fig. 2.

A graph, horizontal axis labelled time and running from zero to 100ms, the vertical axis labelled membrane potential and running from -4mV to 8mV. There are two sets of lines, in each case there is a red line in front of some very similar slightly noisier looking grey lines and blue line almost identical to the red one, but not returning quite as fast to zero. The two sets of curves look at lot like you might expect $\pm t \exp -t/\tau$ to look, one set of lines is positive, the other negative, the positive has a fairly rapid rise from zero at $t = 0$ and then a gradual fall, the negative is the mirror of this. The positive is labelled EPSP, the negative IPSP.

Figure 2: **Some PSPs**; the grey lines are recordings for individual PSPs with the red lines giving averages and blue lines demonstrate a model; we will look at simple models of PSPs later. Figure from [**?**]

In general dendrites lack the voltage-gated channels needed for action potentials and the PSPs in dendrites propagate passively towards the axon. In general dendrites are shorter than axons and thicker, so this conductance allows the change in voltage at the dendrite to propagate in to the soma. Even in the soma, where there are voltage gates channels an individual EPSP won't change the voltage enough to cause a spike. However, if lots of PSPs

arrive at around the same time, the voltage in the soma will increase until it reaches a tipping point, around -55 mV is typical value of where this tipping point is. At the tipping point the opening of voltage-gated channels will cause a spike, usually at the point the axon joins the soma, and this spike will head off down the axon.

1   Summary

Here we described synapses: this is a complicated story we will go through again. When the spike arrives at the synapse some of the vesicles, little bags of neurotransmitter, fuse to the membrane of the synapse closest to the dendrite and burst, emptying neurotransmitter into the synaptic cleft. This, in turn, causes channels to open in the dendrite, changing the potential there. This change in potential, a PSP, flows into the soma causing a small change in the potential in the soma. If these small changes add up to push the soma potential to a threshold, the neuron spikes, sending out an action potential along the axon.