CCN Lab 2: Models of Spiking Neurons

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Introduction

The aim of this lab is to learn some of the basic tools of computational neuroscience: models of spiking neurons and synapses.

1 Poisson Spike Trains

- Generate spikes for 10 seconds using a Poisson spike generator with a constant rate of 100Hz.
- One way to assess the variability of spike trains is to study the statistics of the time intervals between spikes. The coefficient of variation, which is the ratio of the standard deviation of the inter-spikes intervals (isi) to the mean isi:

$$C_V = \frac{\mathrm{std}(isi)}{< isi >} \quad (1)$$

  is then often used as a quantitative measure for the variability (the higher it is the more variable the spike train). Compute the C_V and plot the interspike interval histogram.
- Are the C_V and ISI histogram as expected?

2 Integrate-and-Fire Neuron

The integrate-and-fire neuron is the model that is classically used to describe spiking neurons.

Build a model integrate-and-fire neuron defined by:

$$\tau_m \frac{dV}{dt} = E_L - V + R_m I_e \quad (2)$$

Use $E_L = -65$ mV, $R_m = 90M\Omega$, $\tau_M = 30$ msec. When the membrane potential reaches $V_{th} = -50$ mV, make the neuron fire a spike and reset the potential to $V_{reset} = -65$ mV .

- Show sample voltage traces (with spikes) for a 300-ms-long current pulse (choose a reasonable current I_e) centered in a 500-ms-long simulation.
- Determine the firing rate of the model for various magnitudes of constant I_e and compare with figure 1 (Figure 5.6 of [1]) .
- Include an extra current in the integrate-and-fire model to introduce spike-rate adaptation:

  $$\tau_m \frac{dV}{dt} = E_L - V - r_m g_{sra}(V - E_K) + R_m I_e \tag{3}$$

  This conductance relaxes to 0 exponentially with time constant τ_{sra} through the equation

  $$\tau_{sra} \frac{dg_{sra}}{dt} = -g_{sra} \tag{4}$$

  Whenever the neuron fires a spike, g_{sra} is increased by an amount Δg_{sra} : $g_{sra} \rightarrow g_{sra} + \Delta g_{sra}$. Use the parameters of Figure 1 (C).
- Check how things change and compare with Figure 1.

(from exercises 5.3 and 5.4 of [1])

3 Synaptic inputs

In realistic conditions, neurons are activated not by injected currents, but by a bombardment of synaptic inputs.

- Add an excitatory synaptic conductance to the integrate-and fire model by adding the extra synaptic conductance term

  $$\tau_m \frac{dV}{dt} = E_L - V - r_m g_s P_s(V - E_s) + R_m I_e \tag{5}$$

  with $E_s = 0$. Set the external curent to zero, $I_e = 0$. Use $r_m g_s = 0.35$ and describe P_s using the following equations:

  $$\tau_s \frac{dP_s}{dt} = -P_s \tag{6}$$

  making the replacement $P_s \rightarrow 1$ immediately after each presynaptic action potential.

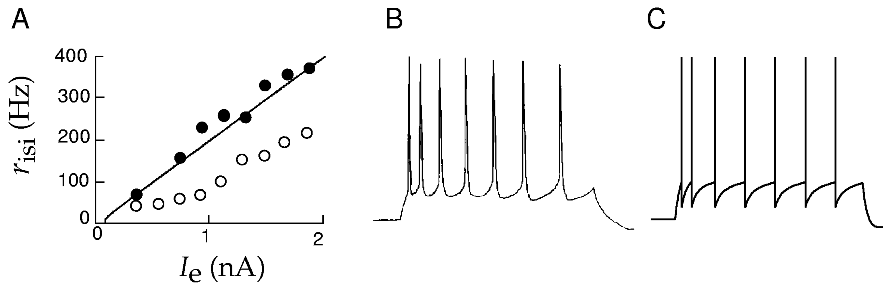

Figure 1: A) Comparison of interspike interval firing rates as a function of injected current for an integrate and fire model and a cortical neuron measure in vivo. The line gives r_{isi} for a model neuron with $\tau_m = 30$ msec, $E_L = V_{reset} = -65$ mV, $V_{th} = -50$ mV and $R_m = 90M\Omega$. The data points are from a pyramidal cell in primary visual cortex of a cat. The filled circles show the inverse of the inter-spike interval for the first two spikes fired, while the open circles show the steady- state interspike-interval firing rate after spike-rate adaptation. B) A recording of the firing of a cortical neuron under constant current injection showing spike-rate adaptation. C) Membrane voltage trajectory and spikes for an integrate and fire model with an added current with $r_m \Delta g_{sra} = 0.06$, $\tau_{sra} = 100$ ms and $E_K = -70$ mV. (Figure 5.6 of [1])

- Visualize the membrane potential of this neuron for a constant rate presynaptic Poisson spike train with frequency 10 Hz. Use τ_s =10 msec.
- Increase the frequency of the presynaptic spike train so as to make the cell fire (the presynaptic spike train might in fact represent the combined spiking of multiple neurons synapsing on the recorded cell).
- Make the conductance inhibitory by setting $E_s = -70$ mV. Use $r_m g_s = 0.5$. Visualize the membrane potential of this neuron for a presynaptic Poisson spike train with frequency 10 Hz. Comment.
- Now set I_e to 0.15 and observe again the effect of the hyperpolarizing conductance when the neuron is depolarized.

4 Model of Izhikevich (2003)

A popular model nowadays is the model of Izhikevich [2, 3]. The Izhikevich model neuron was developed as an efficient, powerful alternative to the integrate and fire model. The model uses two variables, a variable representing voltage potential and another representing membrane recovery (activation of potassium currents and inactivation of sodium currents). It has 4 parameters. According to Izhikivech, "The model can exhibit firing patterns of all known types of cortical neurons with [a suitable] choice of parameters".

- Using [2], implement the model (one neuron).
- Can you find all the dynamic modes that he describes in part III?
- Download the code describing the population of Izhikevich neurons [1]. Run it and study how it works. Change the thalamic input and recurrent weights. Can you find new dynamic modes for the population of neurons?

References

[1] Peter Dayan and Larry F Abbott. *Theoretical Neuroscience*. MIT Press, 2001.

[2] Eugene M Izhikevich. Simple model of spiking neurons. *IEEE Trans Neural Netw*, 14(5):1569–1572, Sep 2003.

[3] Eugene M Izhikevich. Which model to use for cortical spiking neurons? *IEEE Trans Neural Netw*, 15(5):1063–1070, Sep 2004.

[1]

– http://nsi.edu/users/izhikevich/publications/spikes.htm