Lecture 12: Type I and Type II neurons.

Objective

- Understand the firing pattern and differences between Type I and Type II neurons

Type I and Type II neuron models

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- Type I neurons exhibit continuous spiking in response to a sustained stimulus (input current).
- In contrast, Type II neurons display an initial burst of spikes followed by a quiescent period, even in the presence of a constant stimulus.
- Some neuron models are of Type I only, some of Type II only, and some can be of Type I or II, depending on the model's parameter values.

Type I and Type II neuron models

- Type I neurons exhibit continuous firing as long as the input current remains above a specific threshold value. They respond to stimuli in a more graded manner, with the membrane potential and firing rate changing proportionally to the intensity or duration of the input stimulus. Unlike Type II neurons, Type I neurons do not display the characteristic spikes-and-quiescent pattern. Instead, their responses are continuous and graded, with the response's magnitude and shape dependent on the stimulus's strength.

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- Type II neurons demonstrate a threshold-based firing behavior. They generate action potentials (spikes) only when the membrane potential surpasses a specific threshold, resulting in all-or-nothing responses with a distinct shape and magnitude. In an all-or-nothing response, the generated action potential is of the same magnitude and shape, regardless of the stimulus intensity that caused the threshold crossing. This binary response generates either an action potential (spike) or no action potential (no spike).

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- Note that the classifications of Type I and Type II neurons serve as simplified categorizations to describe firing behaviors. It can be more complex in real neurons, exhibiting characteristics that may fall between the strict definitions of Type I or Type II.

Type I and Type II neuron models

- The Leaky Integrate-and-Fire (LIF) neuron model, given in Eq.(1) below, is an example of a Type I that cannot be a Type II. LIF considers the incoming input current and spikes when a certain threshold is reached. The LIF neuron model includes a leak term, accounting for the passive charge leakage across the neuron's membrane. The equation governing the membrane potential (V, measured in mV) is:

$$\begin{cases} \tau_m \frac{dV}{dt} = -(V - V_{\text{rest}}) + R_m I(t) \\ \text{if} \quad V(t) \geq V_{threshold}, \text{then} \quad V \longleftarrow V_{reset} \end{cases} \tag{1}$$

  - τ_m represents the membrane time constant that determines the leakiness of the neuron. Typical values range from 10 ms to 30 ms. However, it can be adjusted based on the desired timescale of the neuron's dynamics.
  - V_{rest} is the resting potential of the neuron and is set at -70 mV.
  - R_m is the membrane resistance. The typical values range from 1 $M\Omega$ (megaohm) to 10 $M\Omega$.

Type I and Type II neuron models

- $V_{threshold}$ is the membrane threshold potential, typically set at -55.0 mV.
- V_{reset} is the reset membrane potential, typically set at -75.0 mV.
- $I(t)$ is the input current as a function of time t and measured in nA
- Examples of Type II neuron models (that we have studied in previous lectures and exercises) include
    - The Hodgkin-Huxley (HH) neuron model
    - Hindmarsh-Rose (HR) neuron model
    - FitzHugh-Nagumo (FHN) neuron model

Type I and Type II neuron models

- The Morris-Lecar (ML) neuron model describes the dynamics of a neuron's membrane potential based on ion channel conductances. Adjusting the model's parameters, such as the conductance values, can simulate different firing behaviors, making it possible for ML to exhibit characteristics of both Type I and Type II neurons.

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- On the other hand, by adjusting the parameters to generate a threshold-based firing behavior, where action potentials occur in an all-or-nothing manner, the ML neuron can exhibit characteristics similar to Type II behavior. This results in a binary response, where the generated action potential is of the same magnitude and shape regardless of the stimulus intensity.

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- Therefore, the Morris-Lecar neuron model is a versatile mathematical framework that can represent both Type I and Type II firing behaviors by appropriately adjusting its parameters, making it a valuable tool for studying different aspects of neural dynamics.

Type I and Type II neuron models

- The Morris-Lecar (ML) neuron model is given by

$$\begin{cases} C\dfrac{dV}{dt} &= -g_{\mathrm{Ca}}M_{ss}(V)(V-V_{\mathrm{Ca}})-g_{\mathrm{K}}W(V-V_{\mathrm{k}}) \\ &- \; g_{\mathrm{L}}(V-V_{\mathrm{L}})+I_{\mathrm{ext}} \\ \dfrac{dW}{dt} &= \dfrac{W_{ss}(V)-W}{\tau_W(V)} \end{cases} \tag{2}$$

where:

$$\begin{cases} M_{ss}(V) &= \Big(1+\tanh[(V-V_1)/V_2)]\Big)/2 \\ W_{ss}(V) &= \Big(1+\tanh[(V-V_3)/V_4)]\Big)/2 \\ \tau_W(V) &= 1/\Big(\phi\cosh[(V-V_3)/2V_4]\Big) \end{cases} \tag{3}$$

Type I and Type II neuron models

Where:

- V is the membrane potential, W is the recovery variable, $M_{ss}(V)$ is the steady-state activation variable for the calcium conductance, V_{Ca} is the ca equilibrium potential, g_{Ca} is the maximum calcium conductance, w is the potassium activation variable, V_{K} is the potassium equilibrium potential, g_{K} is the maximum potassium conductance, V_{L} is the leak equilibrium potential, g_{L} is the leak conductance, I_{ext} is the external current, C is the membrane capacitance, $W_{SS}(V)$ is the steady-state activation variable for the potassium conductance, and $\tau_W(V)$ is the time constant for the potassium activation variable. Parameters and constants. $\{V_1, V_2, V_3, V_4\}$ are tuning parameters for steady state and time constant, and ϕ is the rate scaling parameter.
- Note that there is more than one mathematical version of the ML neuron model. The one given above is the most used version.

Type I and Type II neuron models

Where the standard parameter values are:

- $V_1 = -1.2$ mV
- $V_2 = 18$ mV
- $V_3 = 2$ mV
- $V_4 = 30$ mV
- $g_{Ca} = 4.4\,\mu\text{S/cm}^2$
- $g_K = 8\,\mu\text{S/cm}^2$
- $g_L = 2\,\mu\text{S/cm}^2$
- $V_{Ca} = 120$ mV
- $V_K = -84$ mV
- $V_L = -60$ mV
- $C = 20\,\mu\text{F/cm}^2$
- $\phi = 0.041\ \text{ms}^{-1}$
- $I_{ext} \in [0, 100]\,\mu\text{A/cm}^2$

Type I and Type II neuron models

- Bifurcation in the Morris–Lecar model can be analyzed with the input current I_{ext}, as the main bifurcation parameter and ϕ, g_{Ca}, g_K, g_L, V_3, V_4 as secondary parameters for phase plane analysis.
- In the ML model, the conductance parameters that primarily affect the firing behavior are g_K, the g_{Ca}, and g_L.
- To create a type I neuron, you would generally have to reduce g_{Ca} or increase g_K.
- To create a type II neuron, the g_{Ca} should be high enough to allow for sustained repetitive firing.

Type I and Type II neuron models

- Exercise 4A: Simulate the LIF neuron model given in this lecture and show:
  1. The time series for the duration of $T = 200$ ms of both the membrane potential V and the input current $I(t) = Acos(\omega t)$, when for the first 50 ms the amplitude of the input current is $A = 0$, for the next 50 ms $A = 100$, the next 50 ms $A = 200$, and the last 50 ms $A = 0$. Assume that the frequency of the input current is $\omega = 0.25$ Hz or any other number that you should indicate in your figures.
  2. From the results of your simulations, explain why you think the LIF is a Type I and not Type II neuron model.

Type I and Type II neuron models

- Exercise 4B: Plot the v-nullcline and the w-nullcline of the Morris-Lecar neuron model and vary the input current and/or the maximum calcium conductance such that:
  1. The two nullclines intersect at only one fixed point.
  2. The two nullclines intersect at two fixed points.
  3. The two nullclines intersect at three fixed points.
- Exercise 4C: Show the time series and the corresponding phase portrait of the membrane potential and the recovery variables for a duration of $T = 1000$ ms when:
  1. The external current is $I_{ext} = 40$ nA
  2. The external current is $I_{ext} = 90$ nA

Please systematically organise your submission. For Exercises 4A1, 4B1, 4B2, 4B3, 4C1, and 4C2, I would like to see the outputs of your codes in one PDF and the corresponding Python codes (with the ".py" extension). For example, your Python code for exercise 7A1 should be called *Exercise_7A1.py*, and so on for the rest. Please ensure your codes can plot and show the figures required in the exercises, including all the necessary labeling and legends. I will NOT modify your code. So if your code does not run because of bugs and/or an omission, you get no points for the corresponding exercise. Your explanation in Exercise 4A2 should not exceed 10 sentences in the PDF that contains all the outputs of the codes.