

## Week 5 Lecture Notes

### Points of clarification and fun facts re: video lectures

#### L1: Modeling Neurons

- Slide: Computing in carbon
  - o One of the big goals in neuroscience is to take a very complex cell model (based on physics and circuit components) and figure out what computation it's actually doing. Once we know what it's computing, then in many applications we can forget about the details of exactly how it does the computation. As an analogy, once you know how logic gates work, then you don't have to worry about how transistors work; you can figure out everything a computer does based on logic gates.
- Slide: RC circuits
  - o If you're new to circuits, think of voltage as an electrical pressure, and current as the movement of electrical charge. Essentially, positive electrical charge moves from areas of high electrical pressure (high voltage) to areas of low electrical pressure (low voltage), and the various circuit components govern the dynamics of that flow.
    - Remember that in circuits it only makes sense to talk about voltage differences. A single voltage has no meaning. Usually when people talk about the voltage at one particular spot in the circuit, they are speaking with reference to some "ground", a place in the circuit that we have labeled as having zero voltage.
  - o It is conventional to refer to the cell's membrane potential as the intracellular potential minus the extracellular potential.
  - o We think of both the extracellular and intracellular solutions as infinite conductors (not a bad approximation, as they are essentially saltwater).
- Slide: The passive membrane
  - o When you play with circuit diagrams, there is a certain arbitrariness regarding which directions mean positive current. You can pick whatever you like and still get the same physical description of the system, but it's often helpful to draw arrows on the diagram representing directions associated with positive current, just so you don't lose track.
- Slide: The cell has a battery
  - o The equation for the Nernst potential can be derived using statistical mechanics
- Slide: How does such a membrane behave?
  - o Friendly reminder: when dealing with physical quantities, always check to make sure your units line up!
  - o If  $I_{\text{ext}}$  is constant, this equation can be solved by simple integration. If  $I_{\text{ext}}$  varies with time, one can use Laplace transforms to get the solution for  $V(t)$  as a function of  $I_{\text{ext}}(t)$ .

- Slide: Currents flow through ion channels
  - o One doesn't normally worry about things like this in electronic circuits, because there is only one charge carrier, the electron. However, in biology there are multiple charge carriers, and one must take into account the properties of each.

## L2: Spikes

- Slide: The ion channel is a cool molecular machine
  - o In a very basic sense, voltage-gating in an ion channel arises because something attached to the gate has a certain charge configuration. When the membrane potential changes, the charged piece of the channel will move, and either open or close the gate as it does so.
- Slide: Dynamics of activation: persistent conductance
  - o Never trust anything you see on the internet! Plug in the equations for  $\tau$  and  $n_{\infty}$  to make sure it's correct.
- Slide: Dynamics of activation and inactivation
  - o The expression for the sodium channel conductance ( $m^3h$ ) doesn't mean that 3 subunits have the gate and one has the ball and chain. It just happens to be a good mathematical model. When Hodgkin and Huxley proposed their famous equations, they didn't know anything about the tetrameric nature of sodium channels.
- Slide: Hodgkin and Huxley's Nobel equation
  - o The Hodgkin-Huxley equations are a set of four coupled ordinary differential equations (they all depend on time). The four variables that change with time are  $V$ ,  $n$ ,  $m$ , and  $h$ .
- Slide: Dynamics of activation and inactivation
  - o Remember that we can write each of the equations for  $n$ ,  $m$ , and  $h$ , in terms of  $n_{\infty}$ ,  $\tau_n$ ,  $m_{\infty}$ ,  $\tau_m$ , ... , each of which is a function of voltage. Thus, it makes sense to plot each of these variables against voltage.

Dynamical systems 101: A point represents the state of your variable. The state determines the derivative (the "push" in each dimension), and so each point will have a certain push in a certain direction. At a fixed point, the push (derivative in each dimension) is zero. States move towards stable fixed points and away from unstable fixed points.

## L3: Simplified Model Neurons

- Slide: The electric personalities of neurons
  - o On these plots, the y-axis represents voltage, and the x-axis represents time. This shows what individual action potentials (spikes) look like when you see the raw voltage data.
- Slide: Capturing the basic dynamics of neurons

- o On this slide we are seeing what a reasonable  $f(V)$  might look like. In this case,  $V$  is the independent variable, and is plotted on the x-axis.  $f(V)$  is plotted on the y-axis.
- o The units of this equation appear incorrect, but remember that we still have terms like capacitance in the equation (which correct the units), but they have all been set equal to 1.
- Slide: The theta neuron
  - o This is kind of a new way of thinking about things. Before, the state of our neuron was represented by the voltage. And if you knew the voltage, you'd know the derivative of the voltage. Oftentimes the quantity *phase* is used, when talking about waves, to denote what section of the wave you're in (for example, the crest and the trough have opposite phases). We can do the same sort of thing with our neuron, but now phase represents where you are in the "spiking cycle." Certain phases will correspond to being at the top of the spike and other phases at different voltages above or below threshold. This single variable theta serves as a stand-in for the voltage.
  - o The importance of the theta neuron is that since  $\cos(\theta) = \cos(\theta + 2\pi)$ , the "resetting function" gets built into the model (i.e., when it gets to the end of a cycle/spike, it naturally goes back to its starting point, because the dynamic variable of interest is moving not just on a line, but on a circle), and you don't have to explicitly add it in.
- Slide: Two dimensional-model
  - o Null cline: the line in the phase plane at which the derivative in a certain dimension is zero. At the intersection of two null-clines, the derivatives in both dimensions are zero, there is no "push" on the state. It is a fixed point.
  - o Simple model: sorry for the change in notation –  $V'$  means the time derivative of  $V$ , and  $u'$  means the time derivative of  $u$
- Slide: The simple model
  - o Despite this model being so simple, it's remarkably robust!

#### L4: A forest of dendrites

- Slide: Dendrite picture
  - o Action potentials are canonically generated at the initial segment of the axon. I.e., the initial segment is where the ion channels "check" whether the voltage is above threshold and decide whether or not to fire an action potential. However, because of the complexity of the dendritic trees, there is an immense amount of computation that takes place to generate the voltage at the initial segment.
- Slide: The cable equation
  - o This just another differential equation. Now, however, instead of having several variables all depend on time, we have one variable depend on both time and space. This makes it a partial differential equation. It's a bit tricky to solve, but this equation says that whatever  $V(x,t)$  may be, it has

to have the property that its space and time derivatives are related according to the differential equation.

- Slide: General solution: filter and impulse response
  - o Remember that the goal is essentially to find the voltage at the initial segment so the ion channels there can check whether its above threshold or not. However, we would like to find this voltage in terms of the voltages at different locations in the dendritic arbor. If we know the times and locations of each voltage pulse in the arbor, then we can more or less figure out what the voltage is at the initial segment.
- Slide: Direction selectivity
  - o Dendrites of nonzero length (i.e., real dendrites) do a good job of predicting direction selectivity for fast moving stimuli. However, direction selectivity (and general computations on the relative timing of inputs) that happens on a slower scale often involves the use of multiple neurons (i.e., rather than just traveling along a longer portion of dendrite, the signal must travel through several entire neurons).