Sensory and Motor Systems — Problem Set 1

1. Define equilibrium for an ion (within the context of the neuronal membrane). Your answer should mention forces.

   - Equilibrium for an ion is reached when its diffusion gradient is equal to the electrical gradient. The net flow through any open channel would be zero at equilibrium.
   - E_{ion} can be calucated with the Nernst equation:

$$E_{ion} = \frac{RT}{ZF} \ln \frac{[ion]_{out}}{[ion]_{in}}$$

     - E_{ion} is the equilibrium potential for a given ion, measured in volts (V).
     - R is the universal gas constant, equal to 8.314 $J{\cdot}mol^{-1}{\cdot}K^{-1}$
     - T is the absolute temperature, measured in kelvins (= K = degrees Celsius + 273.15)
     - z is the number of elementary charges (valence) of the ion involved in the reaction
     - F is the Faraday constant, equal to 96,485 coulombs/mol

2. What is the membrane potential at steady state in a cell with a membrane that is only permeable to calcium (Calcium out = 1.9mM, Calcium in= 0.0002mM)?

$$E_{eq,Ca^{+}} = \frac{RT}{ZF} \ln \frac{[Ca]_o}{[Ca]_i} \qquad \text{Nernst equation using calcium}$$

$$\frac{61\,\text{mV}}{2} \cdot \log \frac{1.9\,\text{mM}}{2 \times 10^{-4}\,\text{mM}} = 121.3\,\text{mV} \qquad \text{Simplified at } 37\,^{\circ}\text{C}$$

$$\boxed{E_{eq,Ca^{+}} = 121.3\,\text{mV}}$$

3. If Vm is -70mV and external sodium is 145mM and internal is 10 mM. Calculate the driving force for sodium ions after Nav channels open.

$$V_{DF} = V_m - V_{eq} \qquad \text{Electrochemical driving force}$$

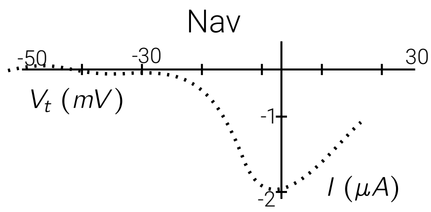
$$V_{eq} = \frac{RT}{F} \ln \frac{[Na]_o}{[Na]_i} \qquad \text{equilibrium potential when Nav channels open}$$

$$61\,\text{mV} \cdot \log \frac{145\,\text{mM}}{10\,\text{mM}} = 71.4\,\text{mV} \qquad \text{Simplified}$$

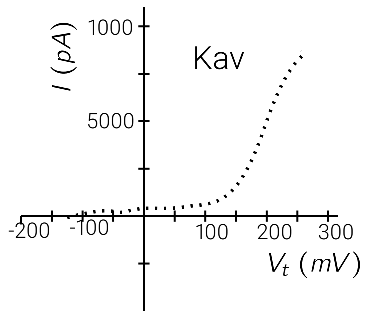
$$= -70\,\text{mV} - 71.4\,\text{mV} \qquad \text{Plug in } V_m \,\&\, V_{eq}$$

$$\boxed{V_{DF} = -144\,\text{mV}}$$

4. Please explain the shape of the current voltage relationship for both voltage gated sodium and potassium ion channels.

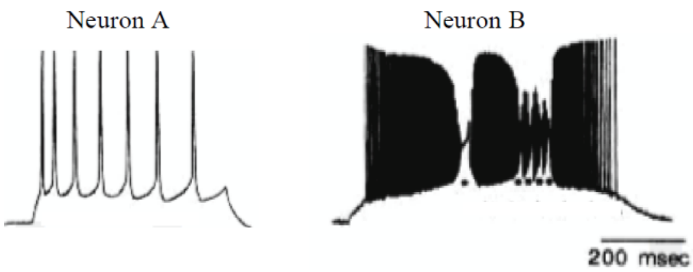


- **Voltage gated** sodium channels **open** at $-30\,\text{mV}$, at which point Na^+ starts coming **into** the cell resulting in a **negative** current. The current peaks then starts decreasing due to weakening driving force induced by incoming Na^+ as nears its equilibrium potential.



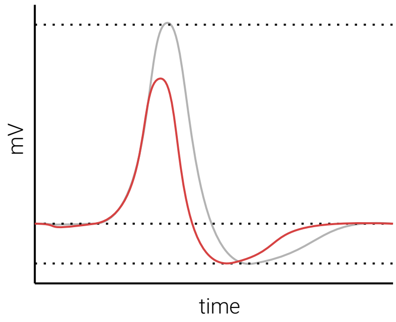
- **Voltage gated** potassium channels begin to open at approximately $10\,\text{mV}$, at which point K^+ begins to **leave** the cell resulting in a **positive** current. The driving force continues to increase until the relationship becomes linear due to OHM's law ($V = IR$) and the fact that the driving force continues to increase as potassium leaves the cell.

5. Neurons A and B are able to fire at different frequencies. Neuron A's maximum firing rate is shown below at left; Neuron B's maximum firing rate is shown at right. Note that in both cases, the vertical lines represent spikes, or individual action potentials. Suggest one specific difference in Na+ or K+ channel properties between these 2 neurons that could explain the different firing rates. Be as specific as you can.



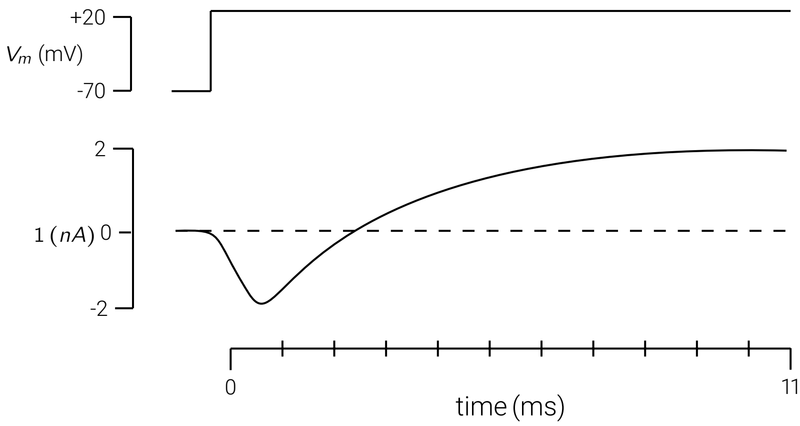
- Faster transition of voltage gated sodium channels from their inactivated state back to a closed (and now ready to open) state would allow for an increased firing rate.
- Potassium channels that close more quickly would allow for cells to return to their resting membrane potential faster than those that remain open for longer, thus increasing potential firing rate.

6. Imagine that a mutation causes faster inactivation of sodium channels compared to those that help produced the APs bellow. Draw and explain how the AP shape would change.



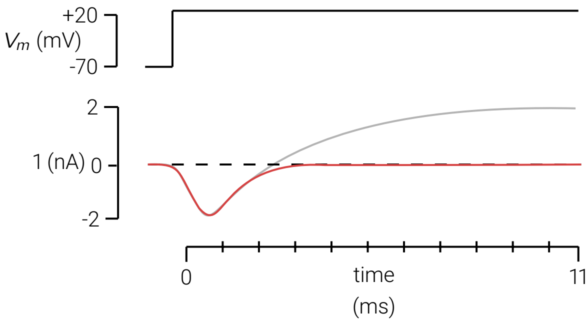
- Faster inactivation would cause the action potential to peak sooner and potentially allow for increased firing rates.

7. When a normal, healthy squid axon is voltage-clamped in artificial seawater, one obtains the following current (I) record in response to a step change in V_m from –70 mV to 20 mV.



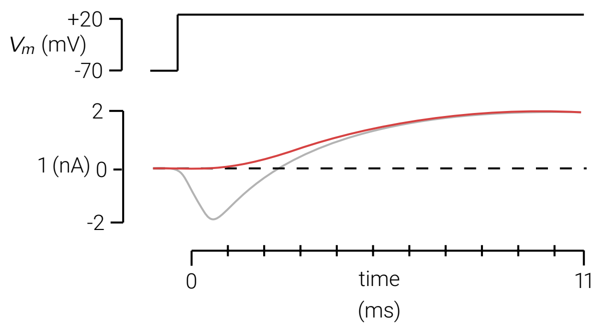
Draw plots of current vs. time when the recordings are made under each of the following experimental conditions. Overlay the new response on the control plot for each of the following situations. Briefly explain your reasoning next to each plot. Note that a dashed line is provided at 0 nA.

a. TEA, a voltage gated K+ channel blocker is added:



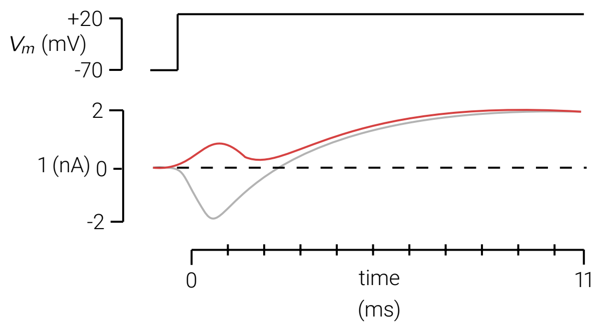
- TEA blocks potassium channels; only sodium flows in, then back out of the cell, until it returns to equilibrium.

b. TTX, a voltage gated Na+ channel blocker is added:



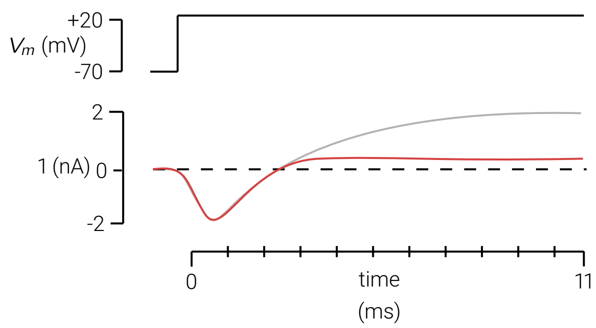
- TTX blocks sodium channels, so only the potassium channels open, which continue to flow out of the cell while the voltage is applied.

c. Na concentration out= Na concentration in:



- When $[Na^{+}]_{out} = [Na^{+}]_{in}$, then E_{Na} becomes 0 mV.
- A driving force is generated is thus generated when the cell voltage is stepped to 20 mV, since 20 mv > 0 mV. This is results in sodium flowing **out** of the cell, which produces a **positive** current.
- Additionally, the amplitude of the sodium current should be less than the control, where sodium is flowing into the cell. A greater driving force is present in the control (when the sodium flows into the cell; 40 mV) than the weaker driving force generated from the manual application of voltage (20 mV).
- No change to potassium, so it would continue to flow out as long as voltage is applied, just as it does in the control.

d. K^{+} concentration out= K concentration in:



- When $[K^+]_{out} = [K^+]_{in}$, then E_K becomes $0\,\text{mV}$.
- Potassium has a driving for of $100\,\text{mV}$ in the control and wants to bring the Vm down to $-80\,\text{mV}$, but when E_K becomes $0\,\text{mV}$, then it has a much weaker driving force of only $20\,\text{mV}$ and wants to bring Vm down to only $0\,\text{mV}$ due to new E_K. Thus, there will still be a small outward current of potassium, but it will be much smaller than the control.
- Sodium is unaffected, so there the initial current mimics the control.