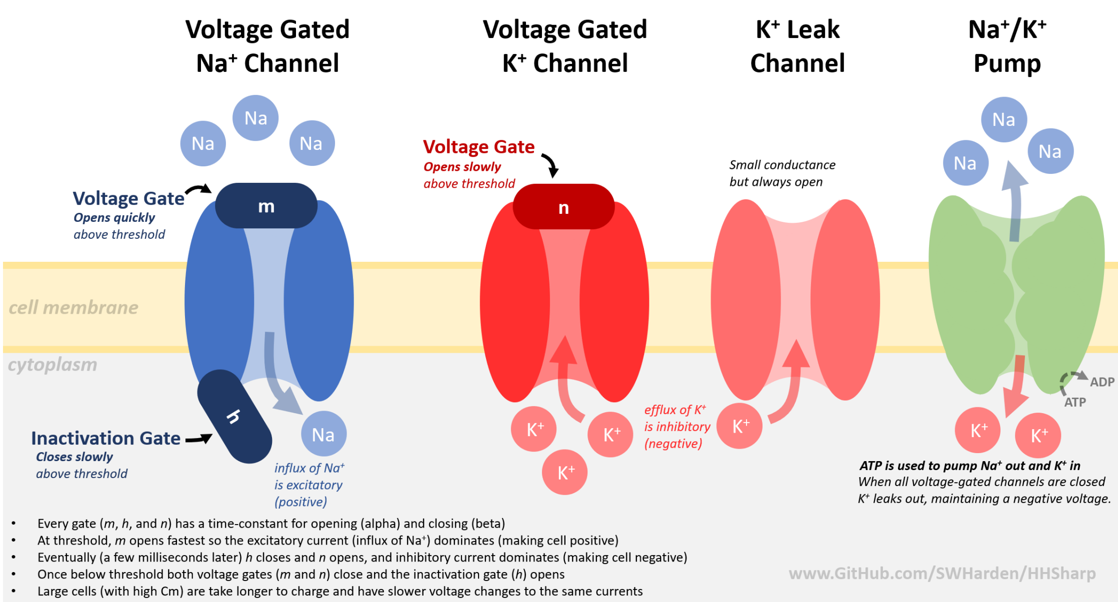
psy452-hodgkin-huxley-neuromorphic-model-dan-jang

February 11, 2024

1 PSY 452 - Advanced Neurophysiological Psychology

1.1 *Hodgkin-Huxley Neuromorphic Model Demonstration for Presentation* by Dan Jang

1.1.1 The Hodgkin-Huxley Model [1], Illustrated [2]



1.1.2 The Full Hodgkin-Huxley Model [1] Equations (in LaTeX [3])

"The Hodgkin-Huxley equations using modern conventions are given by:

$$\frac{dV}{dt} = \left[I_{inj} - \bar{g}_{Na}m^3h(V - V_{Na}) - \bar{g}_K n^4(V - V_K) - g_L(V - V_L)\right]/C \tag{1}$$

$$\frac{dn}{dt} = \alpha_n(V)(1-n) - \beta_n(V)n \tag{2}$$

$$\frac{dm}{dt} = \alpha_m(V)(1-m) - \beta_m(V)m \tag{3}$$

$$\frac{dh}{dt} = \alpha_h(V)(1-h) - \beta_h(V)h \tag{4}$$

where:

$$\alpha_n(V) = \frac{0.01(V+55)}{1-\exp[-(V+55)/10]} \tag{5}$$

$$\beta_n(V) = 0.125\exp[-(V+65)/80] \tag{6}$$

$$\alpha_m(V) = \frac{0.1(V+40)}{1-\exp[-(V+40)/10]} \tag{7}$$

$$\beta_m(V) = 4\exp[-(V+65)/18] \tag{8}$$

$$\alpha_h(V) = 0.07\exp[-(V+65)/20] \tag{9}$$

$$\beta_h(V) = \frac{1}{1+\exp[-(V+35)/10]} \tag{10}$$

The values of the constants are:

- $C = 1\mu F/cm^2$;
- $\bar{g}_{Na} = 120mS/cm^2$;
- $V_{Na} = 50mV$;
- $\bar{g}_K = 36mS/cm^2$;
- $V_K = -77mV$;
- $g_L = 0.3mS/cm^2$;
- $V_L = -54mV$;

In these equations, voltages are in mV, current densities in $\mu A/cm^2$, capacitance in $\mu F/cm^2$, and time in ms." [3]

1.1.3 Quick & Concise Variate & Verbose Variables List Made Easier-to-Understand [1]

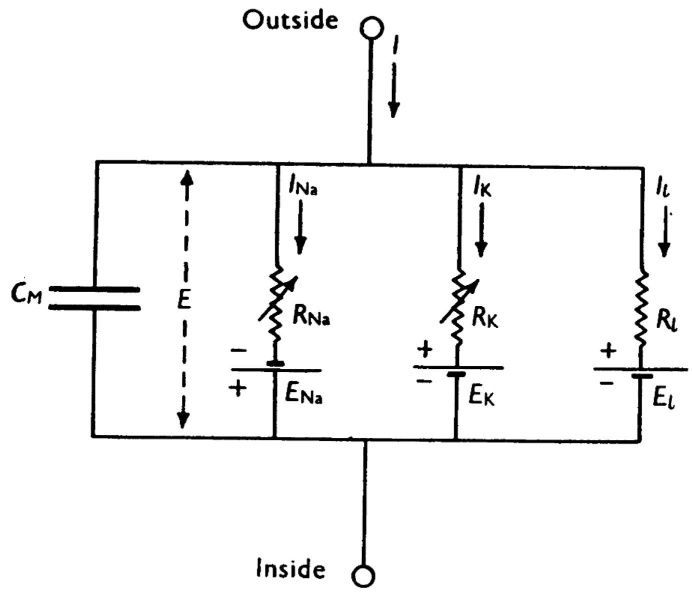


Fig. 1. Electrical circuit representing membrane. $R_{Na} = 1/g_{Na}$; $R_K = 1/g_K$; $R_l = 1/\bar{g}_l$. R_{Na} **and** R_K **vary with time and membrane potential; the other components are constant.**

1. **Vm**: Membrane Potential - Describes the electrochemical gradient across the neuron membrane. This variable is what the Hodgkin-Huxley model primarily focuses on to predict, etc!
2. **Cm**: Membrane Capacitance - Represents the ability of the neuron membrane to store charge as a constant variable!
3. **I**: External Current - The current, in our case, represents Squidward's impulse as output, applied to Rob, the Motor Neuron, to start positioning his clarinet!
4. **gNa, gK, gL**: Maximum Conductances for the Sodium (Na+) Cation, Potassium (K+) Cation, and Leak (L {e.g., Chlorine Cation (Cl)- or Calcium Anion (Ca2+)}) Channels!
5. **ENa, EK, EL**: Equilibrium Potentials for Sodium (Na+) Cation, Potassium (K+) Cation, and Leak (L {e.g., Chlorine Cation (Cl)- or Calcium Anion (Ca2+)}) Channels! These values represent the membrane potential, when reached, results / indicates no net flux in-between the membrane (intracellular space {e.g., axoplasm} or extracellular space)!
6. **m, h**: Sodium (Na+) channel activation and inactivation probability variables, they are also called & part of the gate variables!
7. **n**: Potassium (K+) channel activation probability variable, also one of the gate variables!
8. **alpha/beta + _ + n/m/h**: These represent rate constants. Alpha for opening & Beta for closing. Followed by either n, m, or h, representing the gate variables as described above!
9. **INa, IK, IL**: Currents that are folowing through the Sodium (Na+) Cation, Potassium (K+) Cation, and Leak (L {e.g., Chlorine Cation (Cl)- or Calcium Anion (Ca2+)}) Ionic Channels!

1.1.4 Part 0: *Initialization*

[1]:
```
#### PSY 452 (Winter 2024) - Advanced Neurophysiological Psychology: Part 0,␣
↪Initialization
### By Dan Jang

## I.) Installing necessary packages
# !pip install numpy
# !pip install matplotlib.pyplot
# !pip install scipy

# ## II.) Importing essential packages + pyHodgkin-Huxley package [1]

# import sys
# import os

# currpath = os.path.join(os.getcwd(), 'libraries', 'pyhh')

# if currpath not in sys.path:
#     sys.path.append(currpath)

## II.) Importing essential packages + pyHodgkin-Huxley package [1]

import numpy as np
import matplotlib.pyplot as plot
import scipy.integrate
from scipy.integrate import odeint

import pyhh as hodhux

## III.) Create full Hodgkin-Huxley model-based action potential stimulation

## III.A) Create Squidward's Rob Motor Neuron :^)
class Squidward:
    def __init__(self):
        self.robert, self.gNa, self.gK, self.gL, self.Cm, self.ENa, self.EK,␣
↪self.EL, self.I, self.Vm, self.m, self.h, self.n, self.t, self.pulse, self.
↪pulsex, self.pulsey, self.movement, self.playtime = None, 120.0, 36.0, 0.3,␣
↪1.0, 50.0, -77.0, -54.387, 10.0, -65.0, 0.052, 0.596, 0.317, 50, 7000,␣
↪13000, None, 0.01, np.zeros(20000)
        self.timestep = 0.01
        self.robert = Robert()

    # Essentially, a funny named new-custom constructor
    def tentacles(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h, n,␣
↪t, pulse, pulsex, pulsey, movement, timestep):
```

```
        if robert is None:
            if self.robert is None:
                self.robert = Robert()

        else:
            try:
                self.robert.activation(robert, gNa, gK, gL, Cm, ENa, EK, EL, I,␣
↪Vm, m, h, n, t, pulse, pulsex, pulsey)
            except:
                print("[E1<Squid-Init>] bruh u might have missed a neuronal␣
↪parameter for rob lol")

        self.playtime = np.zeros(t) #self.robert.t
        self.playtime[pulsex:pulsey] = pulse

        #if clarinet is None:
            #if self.clarinet is None:
        if timestep is None:
            timestep = 0.01
            self.timestep = timestep
        else:
            self.timestep = timestep
        if movement is None:
            self.movement = hodhux.Simulation(self.robert.model)
            self.clarinet(self.timestep, self.movement)
        else:
            self.clarinet(self.timestep, movement)
                #self.clarinet = clarinet(t, timestep, )

        #self.playtime = self.robert.t

    def clarinet(self, timestep, movement):
        # if playtime is None:
        #     playtime = np.zeros(20000)

        if timestep is None:
            timestep = 0.01

        if movement is None:
            self.movement = hodhux.Simulation(self.robert.model)
            self.movement.Run(stimulusWaveform=self.playtime,␣
↪stepSizeMs=timestep)
            self.movement = movement
            #print("[E4<Squid-Clarinet>] bruh u gotta pass a movement thingy so␣
↪u can actually graph the results u silly head lol")

        else:
```

```
        #    try:
            movement.Run(stimulusWaveform=self.playtime, stepSizeMs=timestep)
            self.movement = movement
        #    except:
        #        print("[E3<Squid-Clarinet>] bruh squidward's robert motor␣
↪neuron model might be misconfigured lol")

    def sheetmusic(self, figsizex, figsizey, color1, color2, color3, color4,␣
↪color5, color6, color7, color8, title, file):
        #try:
        if figsizex:
            if figsizey:
                plot.figure(figsize=(figsizex, figsizey))
        else:
            plot.figure(figsize=(10, 8))
        # except:
        #     print("[E4<Squid-SheetMusic>] bruh u might have missed the figure␣
↪sizes for the sheet music lol")

        if title is None:
            title = "PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic␣
↪Computational Graphical Model"

        else:
            title = "PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic␣
↪Computational Graphical Model: " + title

        if file is None:
            file = "PSY452-Hodgkin-Huxley-Model-Waveform-DanJ.png"

        if self.movement is None:
            print("[E4<Squid-SheetMusic>] bruh squidward apparently hasnt moved␣
↪his clarinet or if he did, it wasn't recorded u silly goose lol")

        if self.robert is None:
            print("[E5<Squid-SheetMusic>] bruh somehow at this stage, Robert␣
↪the Motor Neuron still has not been created yet, you are one silly goose dan␣
↪lmao")

        else:
            movement = self.movement # lazy but saves typing self. each time␣
↪lmao
            # Potential (mV) Color
            if color1 is None:
                color1 = 'r'
```

```python
        # Input Stimulation (µA/cm^2) Color
        if color2 is None:
            color2 = 'b'

        # Sodium Activation Gating Variable (m) Color
        if color3 is None:
            color3 = 'purple'

        # Sodium Inactivation Gating Variable (h) Color
        if color4 is None:
            color4 = 'orange'

        # Potassium Activation Gating Variable (n) Color
        if color5 is None:
            color5 = 'yellow' # BANANA

        # Sodium Current (INa) (µA/cm^2) Color
        if color6 is None:
            color6 = 'purple'

        # Potassium Current (IK) (µA/cm^2) Color
        if color7 is None:
            color7 = 'yellow'

        # Leak Current (IL) (µA/cm^2) Color
        if color8 is None:
            color8 = 'turquoise'

        ## Credits to [2] for parts from README.md Example Code

        # Potential (mV) Plot #1
        potentialplt = plot.subplot(411)
        potentialplt.set_title(title)
        potentialplt.set_ylabel("Rob's Membrane Potential (mV)")
        potentialplt.plot(movement.times, movement.Vm - 70, color=color1)

        # Input Stimulation (µA/cm^2) Plot #2
        stimulationplt = plot.subplot(412)
        stimulationplt.set_ylabel("Squidward Stimulation (µA/cm²)")
        playtime = self.playtime
        ## Sanity Debug Print Statement
        #print(movement.times, playtime, color2)
        stimulationplt.plot(movement.times, playtime, color=color2)

        # Gating Variable Activation (m/h/n) Plot #3
        activationplt = plot.subplot(413, sharex=potentialplt)
        activationplt.set_ylabel("Rob's Channel Activation (fractional)")
```

```
            activationplt.plot(movement.times, movement.StateM, label='m (Na+␣
↪Channel Open Prob.)', color=color3)
            activationplt.plot(movement.times, movement.StateH, label='h (Na+␣
↪Channel Close Prob.)', color=color4)
            activationplt.plot(movement.times, movement.StateN, label='n (K+␣
↪Channel Open Prob.)', color=color5)
            activationplt.legend()

            # Ionic Channel Current Plot (INa/IK/Ileak) Plot #4
            currentplt = plot.subplot(414, sharex=potentialplt)
            currentplt.set_xlabel("Clarinet Action Potential Time (in␣
↪milliseconds)")
            currentplt.set_ylabel("Rob Membrane Ionic Current (μA/cm²)")
            currentplt.plot(movement.times, movement.INa, label='INa (Sodium␣
↪Current)', color=color6)
            currentplt.plot(movement.times, movement.IK, label='IK (Potassium␣
↪Current)', color=color7)
            currentplt.plot(movement.times, movement.IKleak, label='IKLeak␣
↪(KLeakage Current)', color=color8)
            currentplt.legend()

            plot.tight_layout()
            plot.savefig(file)
            plot.show()

class Robert:
        def __init__(self):
            self.model = hodhux.HHModel()
            self.t = None

        def activation(self, model, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h,␣
↪n, t, pulse, pulsex, pulsey):

            if model is None:
                if self.model is None:
                    robert = hodhux.HHModel()

                    # Squidward's Rob Motor Neuron Parameter, gNa: Avg. Na+␣
↪(Sodium cation) conductance per unit area (mS/cm^2)
                    robert.gNa = 120

                    # Squidward's Rob Motor Neuron Parameter, gK: Avg. K+␣
↪(Potassium cation) conductance per unit area (mS/cm^2)
                    robert.gK = 36
```

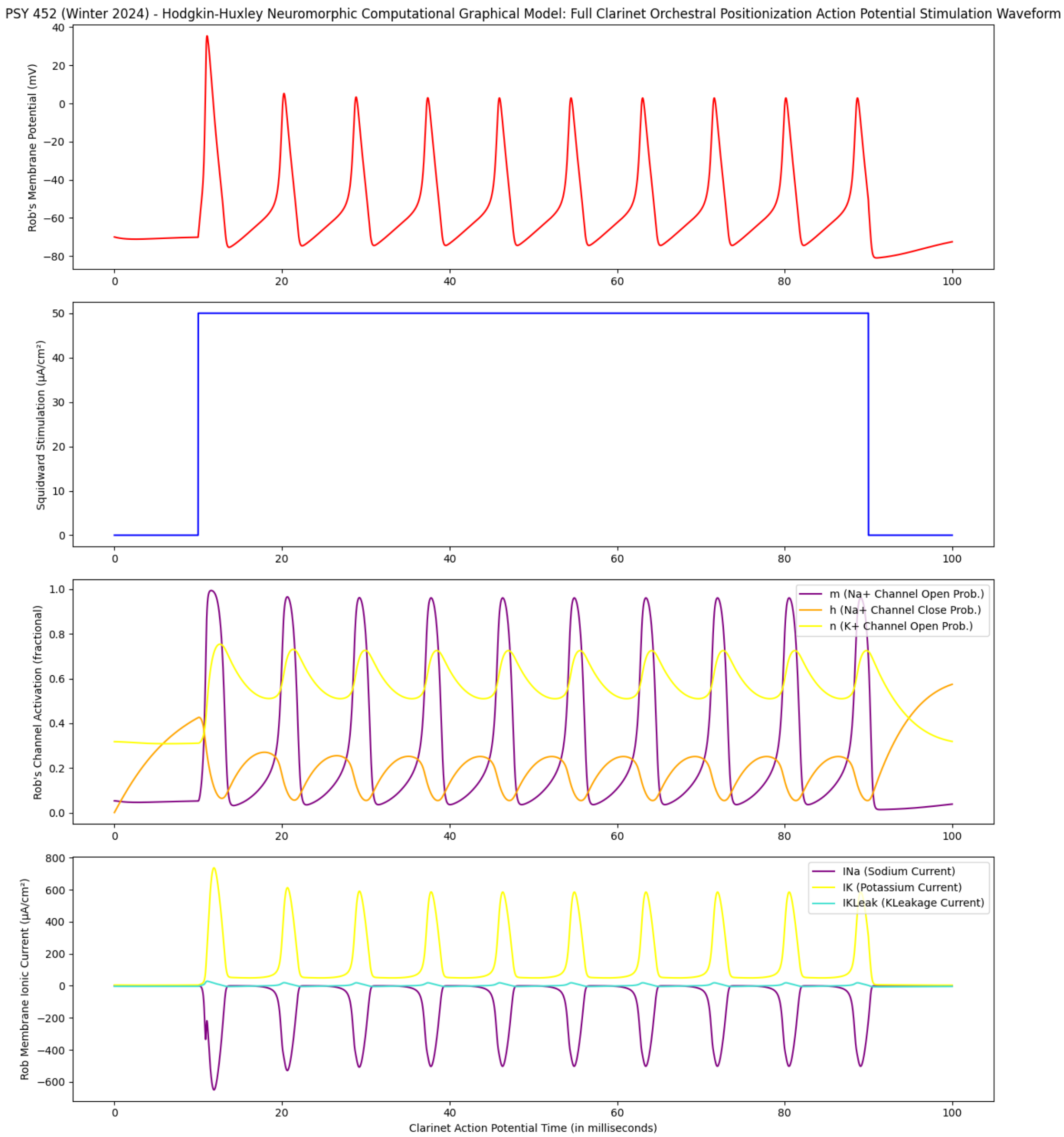
```
                    # Squidward's Rob Motor Neuron Parameter, gL: Avg. Leak (e.
↪g., Chlorine anions / Calcium {2+} cations) conductance per unit area (mS/
↪cm^2)
                    robert.gKleak = 0.3

                    # Squidward's Rob Motor Neuron Parameter, Cm: Membrane␣
↪capacitance per unit area (uF/cm^2)
                    robert.Cm = 1.0

                    # Squidward's Rob Motor Neuron Parameter, ENa: Sodium␣
↪cation Nernst reversal potential (mV)
                    robert.ENa = 115

                    # Squidward's Rob Motor Neuron Parameter, EK: Potassium␣
↪cation Nernst reversal potential (mV)
                    robert.EK = -12

                    # Squidward's Rob Motor Neuron Parameter, EL: Leak Nernst␣
↪reversal potential (mV)
                    robert.EKleak = 10.6

                    # Squidward's Rob Motor Neuron Parameter, I: External␣
↪current (uA/cm^2)
                    #robert.I = 10.0

                    # Squidward's Rob Motor Neuron Parameter, Vm: Membrane␣
↪potential (mV)
                    #robert.Vm = 0

                    # Squidward's Rob Motor Neuron Parameter, m: Sodium cation␣
↪activation gating variable
                    #robert.m = 0

                    # Squidward's Rob Motor Neuron Parameter, h: Sodium cation␣
↪inactivation gating variable
                    #robert.h = 0

                    # Squidward's Rob Motor Neuron Parameter, n: Potassium␣
↪cation activation gating variable
                    #robert.n = 0

                    # Stimulus Waveform thingy
                    self.t = np.zeros(20000)

                    # Stimulus Waveform <+ Square Pulse
                    self.t[7000:13000] = 50
```

```
            self.model = robert
    try:

        robert = self.model

        if gNa is not None:
            robert.gNa = gNa

        if gK is not None:
            robert.gK = gK

        if gL is not None:
            robert.gKleak = gL

        if Cm is not None:
            robert.Cm = Cm

        if ENa is not None:
            robert.ENa = ENa

        if EK is not None:
            robert.EK = EK

        if EL is not None:
            robert.EKleak = EL

        # if I is not None:
        #     robert.I = I

        # if Vm is not None:
        #     robert.Vm = Vm

        # if m is not None:
        #     robert.m = m

        # if h is not None:
        #     robert.h = h

        # if n is not None:
        #     robert.n = n

        if t is not None:
            # Stimulus Waveform thingy
            self.t = np.zeros(t)

        if pulse is not None:
```

```
                if pulsex is not None:
                    if pulsey is not None:
                        self.t[pulsex:pulsey] = pulse

            self.model = robert
        except:
            print("[E2<SubSquid-Rob-Init>] bruh u might have missed a␣
↪neuronal parameter for rob within squidward initialization thingy lol")

    def model(self):
        return self.model

### Finally, the grand test for class Squidward (main wrapper), with a subclass␣
↪Robert (le Motor Neuron model encompassing wrapper)

# Reference - Squidward(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m,␣
↪h, n, t, pulse, pulsex, pulsey, movement, timestep)
squidward = Squidward()

# Reference -
# Squidward's Rob Motor Neuron Parameter, gNa: Avg. Na+ (Sodium cation)␣
↪conductance per unit area (mS/cm^2)
# robert.gNa = 120.0
# # Squidward's Rob Motor Neuron Parameter, gK: Avg. K+ (Potassium cation)␣
↪conductance per unit area (mS/cm^2)
# robert.gK = 36.0
# # Squidward's Rob Motor Neuron Parameter, gL: Avg. Leak (e.g., Chlorine␣
↪anions / Calcium {2+} cations) conductance per unit area (mS/cm^2)
# robert.gKleak = 0.3
# # Squidward's Rob Motor Neuron Parameter, Cm: Membrane capacitance per unit␣
↪area (uF/cm^2)
# robert.Cm = 1.0
# # Squidward's Rob Motor Neuron Parameter, ENa: Sodium cation Nernst reversal␣
↪potential (mV)
# robert.ENa = 115.0
# # Squidward's Rob Motor Neuron Parameter, EK: Potassium cation Nernst␣
↪reversal potential (mV)
# robert.EK = -12.0
# # Squidward's Rob Motor Neuron Parameter, EL: Leak Nernst reversal potential␣
↪(mV)
# robert.EKleak = 10.6
# # Squidward's Rob Motor Neuron Parameter, I: External current (uA/cm^2)
# robert.I = 10.0
# # Squidward's Rob Motor Neuron Parameter, Vm: Membrane potential (mV)
# robert.Vm = -65.0
```

```python
# # Squidward's Rob Motor Neuron Parameter, m: Sodium cation activation gating variable
# robert.m = 0.052
# # Squidward's Rob Motor Neuron Parameter, h: Sodium cation inactivation gating variable
# robert.h = 0.596
# # Squidward's Rob Motor Neuron Parameter, n: Potassium cation activation gating variable
# robert.n = 0.317
# tentacles(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h, n, t, pulse, pulsex, pulsey, movement, timestep):

squidward.tentacles(None, 120.0, 36.0, 0.3, 1.0, 115, -12, 10.6, 0, 0, 0, 0, 0, 10000, 50, 1000, 9000, None, 0.01)

# Reference - sheetmusic(self, figsizex, figsizey, color1, color2, color3, color4, color5, color6, color7, color8, title)
#             movement = self.movement # lazy but saves typing self. each time lmao
# # Potential (mV) Color
#     color1 = 'r'
# # Input Stimulation (μA/cm^2) Color
#     color2 = 'b'
# # Sodium Activation Gating Variable (m) Color
#     color3 = 'purple'
# # Sodium Inactivation Gating Variable (h) Color
#     color4 = 'orange'
# # Potassium Activation Gating Variable (n) Color
#     color5 = 'yellow' # BANANA
# # Sodium Current (INa) (μA/cm^2) Color
#     color6 = 'purple'
# # Potassium Current (IK) (μA/cm^2) Color
#     color7 = 'yellow'
# # Leak Current (IL) (μA/cm^2) Color
#     color8 = 'turquoise'

squidward.sheetmusic(13, 15, 'r', 'b', 'purple', 'orange', 'yellow', 'purple', 'yellow', 'turquoise', "Full Clarinet Orchestral Positionization Action Potential Stimulation Waveform", "PSY452-FullSquidwardClarinetActionPotentialStimulationWave-DanJ.png")
```

```
Simulating 10000 time points…
Simulation complete!
```



1.1.5 Part 1: *Resting Membrane Potential (RMP)*

[2]:
```
#### PSY 452 (Winter 2024) - Advanced Neurophysiological Psychology: Part 1,␣
↪Initialization
### By Dan Jang
### Credits to Scott W. Harden for pyhh package [1]

class Squidward:
    def __init__(self):
```

```
        self.robert, self.gNa, self.gK, self.gL, self.Cm, self.ENa, self.EK,␣
↪self.EL, self.I, self.Vm, self.m, self.h, self.n, self.t, self.pulse, self.
↪pulsex, self.pulsey, self.movement, self.playtime = None, 120.0, 36.0, 0.3,␣
↪1.0, 50.0, -77.0, -54.387, 10.0, -65.0, 0.052, 0.596, 0.317, 50, 7000,␣
↪13000, None, 0.01, np.zeros(20000)
        self.timestep = 0.01
        self.robert = Robert()

    # Essentially, a funny named new-custom constructor
    def tentacles(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h, n,␣
↪t, pulse, pulsex, pulsey, movement, timestep):

        if robert is None:
            if self.robert is None:
                self.robert = Robert()

        else:
            try:
                self.robert.activation(robert, gNa, gK, gL, Cm, ENa, EK, EL, I,␣
↪Vm, m, h, n, t, pulse, pulsex, pulsey)
            except:
                print("[E1<Squid-Init>] bruh u might have missed a neuronal␣
↪parameter for rob lol")

        self.playtime = np.zeros(t) #self.robert.t
        self.playtime[pulsex:pulsey] = pulse

        #if clarinet is None:
            #if self.clarinet is None:
        if timestep is None:
            timestep = 0.01
            self.timestep = timestep
        else:
            self.timestep = timestep
        if movement is None:
            self.movement = hodhux.Simulation(self.robert.model)
            self.clarinet(self.timestep, self.movement)
        else:
            self.clarinet(self.timestep, movement)
                #self.clarinet = clarinet(t, timestep, )

        #self.playtime = self.robert.t

    def clarinet(self, timestep, movement):
        # if playtime is None:
        #     playtime = np.zeros(20000)
```

```
        if timestep is None:
            timestep = 0.01

        if movement is None:
            self.movement = hodhux.Simulation(self.robert.model)
            self.movement.Run(stimulusWaveform=self.playtime,␣
↪stepSizeMs=timestep)
            self.movement = movement
            #print("[E4<Squid-Clarinet>] bruh u gotta pass a movement thingy so␣
↪u can actually graph the results u silly head lol")

        else:
        #    try:
            movement.Run(stimulusWaveform=self.playtime, stepSizeMs=timestep)
            self.movement = movement
        #    except:
        #        print("[E3<Squid-Clarinet>] bruh squidward's robert motor␣
↪neuron model might be misconfigured lol")

    def sheetmusic(self, figsizex, figsizey, color1, color2, color3, color4,␣
↪color5, color6, color7, color8, title, file):
        #try:
        if figsizex:
            if figsizey:
                plot.figure(figsize=(figsizex, figsizey))
        else:
            plot.figure(figsize=(10, 8))
        # except:
        #     print("[E4<Squid-SheetMusic>] bruh u might have missed the figure␣
↪sizes for the sheet music lol")

        if title is None:
            title = "PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic␣
↪Graphical Model"

        else:
            title = "PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic␣
↪Graphical Model: " + title

        if self.movement is None:
            print("[E4<Squid-SheetMusic>] bruh squidward apparently hasnt moved␣
↪his clarinet or if he did, it wasn't recorded u silly goose lol")

        if self.robert is None:
```

```
            print("[E5<Squid-SheetMusic>] bruh somehow at this stage, Robert␣
↪the Motor Neuron still has not been created yet, you are one silly goose dan␣
↪lmao")

        else:
            movement = self.movement # lazy but saves typing self. each time␣
↪lmao
            # Potential (mV) Color
            if color1 is None:
                color1 = 'r'

            # Input Stimulation (μA/cm^2) Color
            if color2 is None:
                color2 = 'b'

            # Sodium Activation Gating Variable (m) Color
            if color3 is None:
                color3 = 'purple'

            # Sodium Inactivation Gating Variable (h) Color
            if color4 is None:
                color4 = 'orange'

            # Potassium Activation Gating Variable (n) Color
            if color5 is None:
                color5 = 'yellow' # BANANA

            # Sodium Current (INa) (μA/cm^2) Color
            if color6 is None:
                color6 = 'purple'

            # Potassium Current (IK) (μA/cm^2) Color
            if color7 is None:
                color7 = 'yellow'

            # Leak Current (IL) (μA/cm^2) Color
            if color8 is None:
                color8 = 'turquoise'

            ## Credits to [2] for parts from README.md Example Code

            # Potential (mV) Plot #1
            potentialplt = plot.subplot(411)
            potentialplt.set_title(title)
            potentialplt.set_ylabel("Rob's Membrane Potential (mV)")
            potentialplt.plot(movement.times, movement.Vm - 70, color=color1)
```

```
            # Input Stimulation (µA/cm^2) Plot #2
            stimulationplt = plot.subplot(412)
            stimulationplt.set_ylabel("Squidward Stimulation (µA/cm²)")
            playtime = self.playtime
            ## Sanity Debug Print Statement
            #print(movement.times, playtime, color2)
            stimulationplt.plot(movement.times, playtime, color=color2)

            # Gating Variable Activation (m/h/n) Plot #3
            activationplt = plot.subplot(413, sharex=potentialplt)
            activationplt.set_ylabel("Rob's Channel Activation (fractional)")
            activationplt.plot(movement.times, movement.StateM, label='m (Na+␣
↪Channel Open Prob.)', color=color3)
            activationplt.plot(movement.times, movement.StateH, label='h (Na+␣
↪Channel Close Prob.)', color=color4)
            activationplt.plot(movement.times, movement.StateN, label='n (K+␣
↪Channel Open Prob.)', color=color5)
            activationplt.legend()

            # Ionic Channel Current Plot (INa/IK/Ileak) Plot #4
            currentplt = plot.subplot(414, sharex=potentialplt)
            currentplt.set_xlabel("Clarinet Action Potential Time (in␣
↪milliseconds)")
            currentplt.set_ylabel("Rob Membrane Ionic Current (µA/cm²)")
            currentplt.plot(movement.times, movement.INa, label='INa (Sodium␣
↪Current)', color=color6)
            currentplt.plot(movement.times, movement.IK, label='IK (Potassium␣
↪Current)', color=color7)
            currentplt.plot(movement.times, movement.IKleak, label='IKLeak␣
↪(KLeakage Current)', color=color8)
            currentplt.legend()

            plot.tight_layout()
            plot.savefig(file)
            plot.show()

class Robert:
        def __init__(self):
            self.model = hodhux.HHModel()
            self.t = None

        def activation(self, model, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h,␣
↪n, t, pulse, pulsex, pulsey):

            if model is None:
                if self.model is None:
```

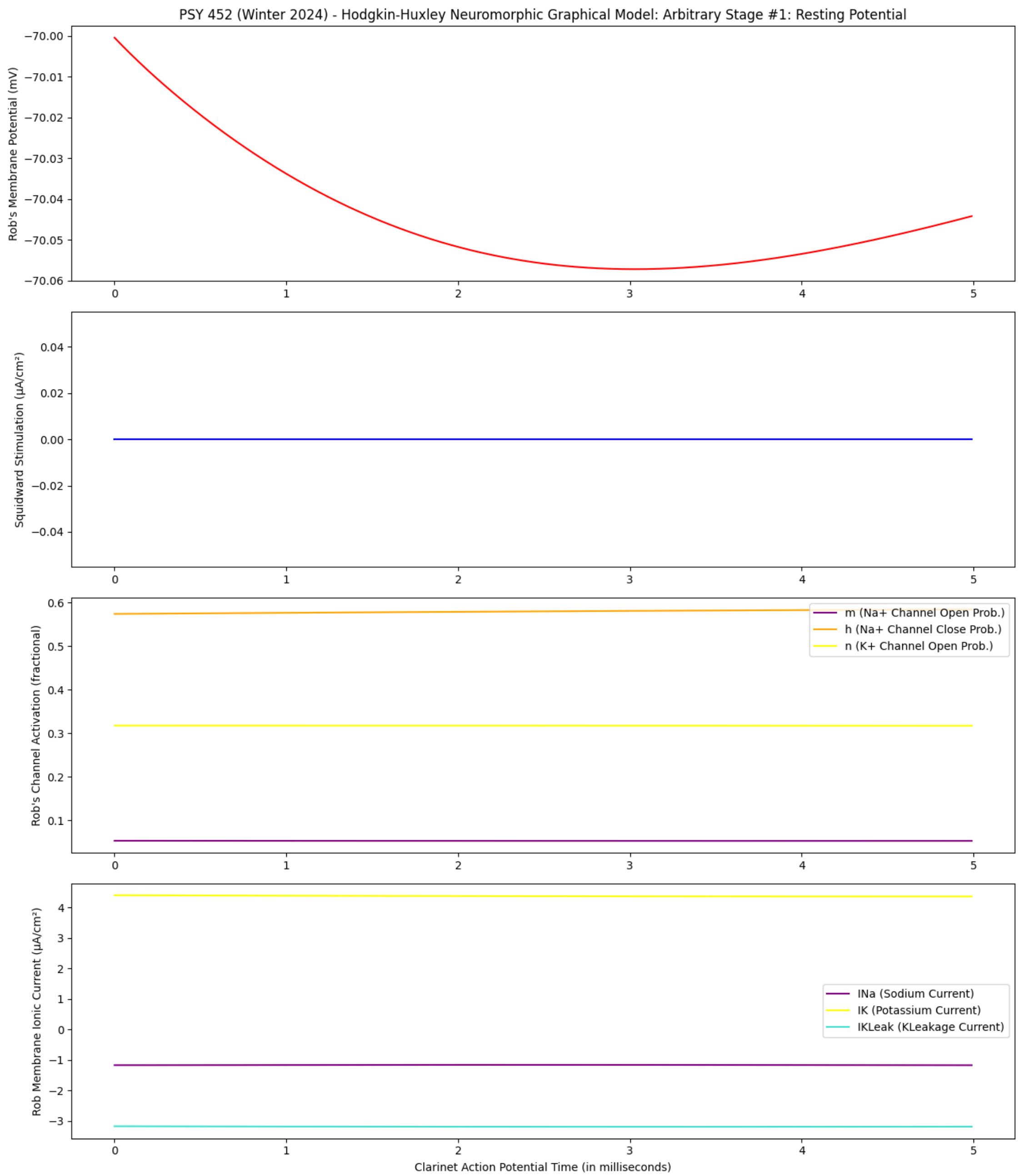
```python
                    robert = hodhux.HHModel()

                    # Squidward's Rob Motor Neuron Parameter, gNa: Avg. Na+␣
↪(Sodium cation) conductance per unit area (mS/cm^2)
                    robert.gNa = 120

                    # Squidward's Rob Motor Neuron Parameter, gK: Avg. K+␣
↪(Potassium cation) conductance per unit area (mS/cm^2)
                    robert.gK = 36

                    # Squidward's Rob Motor Neuron Parameter, gL: Avg. Leak (e.
↪g., Chlorine anions / Calcium {2+} cations) conductance per unit area (mS/
↪cm^2)
                    robert.gKleak = 0.3

                    # Squidward's Rob Motor Neuron Parameter, Cm: Membrane␣
↪capacitance per unit area (uF/cm^2)
                    robert.Cm = 1.0

                    # Squidward's Rob Motor Neuron Parameter, ENa: Sodium␣
↪cation Nernst reversal potential (mV)
                    robert.ENa = 115

                    # Squidward's Rob Motor Neuron Parameter, EK: Potassium␣
↪cation Nernst reversal potential (mV)
                    robert.EK = -12

                    # Squidward's Rob Motor Neuron Parameter, EL: Leak Nernst␣
↪reversal potential (mV)
                    robert.EKleak = 10.6

                    # Squidward's Rob Motor Neuron Parameter, I: External␣
↪current (uA/cm^2)
                    #robert.I = 10.0

                    # Squidward's Rob Motor Neuron Parameter, Vm: Membrane␣
↪potential (mV)
                    #robert.Vm = 0

                    # Squidward's Rob Motor Neuron Parameter, m: Sodium cation␣
↪activation gating variable
                    #robert.m = 0

                    # Squidward's Rob Motor Neuron Parameter, h: Sodium cation␣
↪inactivation gating variable
                    #robert.h = 0
```

```
                # Squidward's Rob Motor Neuron Parameter, n: Potassium␣
↪cation activation gating variable
                #robert.n = 0

                # Stimulus Waveform thingy
                self.t = np.zeros(20000)

                # Stimulus Waveform <+ Square Pulse
                self.t[7000:13000] = 50

                self.model = robert
        try:

            robert = self.model

            if gNa is not None:
                robert.gNa = gNa

            if gK is not None:
                robert.gK = gK

            if gL is not None:
                robert.gKleak = gL

            if Cm is not None:
                robert.Cm = Cm

            if ENa is not None:
                robert.ENa = ENa

            if EK is not None:
                robert.EK = EK

            if EL is not None:
                robert.EKleak = EL

            # if I is not None:
            #     robert.I = I

            # if Vm is not None:
            #     robert.Vm = Vm

            # if m is not None:
            #     robert.m = m

            # if h is not None:
```

```
            #     robert.h = h

            # if n is not None:
            #     robert.n = n

            if t is not None:
                # Stimulus Waveform thingy
                self.t = np.zeros(t)

            if pulse is not None:
                if pulsex is not None:
                    if pulsey is not None:
                        self.t[pulsex:pulsey] = pulse

            self.model = robert
        except:
            print("[E2<SubSquid-Rob-Init>] bruh u might have missed a␣
↪neuronal parameter for rob within squidward initialization thingy lol")

    def model(self):
        return self.model

### Finally, the grand test for class Squidward (main wrapper), with a subclass␣
↪Robert (le Motor Neuron model encompassing wrapper)

# Reference - Squidward(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m,␣
↪h, n, t, pulse, pulsex, pulsey, movement, timestep)
squidward = Squidward()

# tentacles(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h, n, t,␣
↪pulse, pulsex, pulsey, movement, timestep):

squidward.tentacles(None, 120.0, 36.0, 0.3, 1.0, 115, -12, 10.6, 0, 0, 0, 0, 0,␣
↪500, 0, 0, 0, None, 0.01)

# Reference - sheetmusic(self, figsizex, figsizey, color1, color2, color3,␣
↪color4, color5, color6, color7, color8, title)
#             movement = self.movement # lazy but saves typing self. each time␣
↪lmao
# # Potential (mV) Color
#     color1 = 'r'
# # Input Stimulation (μA/cm^2) Color
#     color2 = 'b'
# # Sodium Activation Gating Variable (m) Color
#     color3 = 'purple'
# # Sodium Inactivation Gating Variable (h) Color
```

```python
#     color4 = 'orange'
# # Potassium Activation Gating Variable (n) Color
#     color5 = 'yellow' # BANANA
# # Sodium Current (INa) (μA/cm^2) Color
#     color6 = 'purple'
# # Potassium Current (IK) (μA/cm^2) Color
#     color7 = 'yellow'
# # Leak Current (IL) (μA/cm^2) Color
#     color8 = 'turquoise'

squidward.sheetmusic(13, 15, 'r', 'b', 'purple', 'orange', 'yellow', 'purple',␣
↪'yellow', 'turquoise', "Arbitrary Stage #1: Resting Potential",␣
↪"PSY452-Phase1-SquidwardClarinetActionPotentialStimulationWaveform-DanJ.png")
```

```
Simulating 500 time points…
Simulation complete!
```



1.1.6 Part 2: *Depolarization / Beginning of Action Potential*

[3]:
```
#### PSY 452 (Winter 2024) - Advanced Neurophysiological Psychology: Part 2,␣
↪Depolarization / Beginning of Action Potential
### By Dan Jang
### Credits to Scott W. Harden for pyhh package [1]

class Squidward:
```

```
    def __init__(self):
        self.robert, self.gNa, self.gK, self.gL, self.Cm, self.ENa, self.EK,␣
↪self.EL, self.I, self.Vm, self.m, self.h, self.n, self.t, self.pulse, self.
↪pulsex, self.pulsey, self.movement, self.playtime = None, 120.0, 36.0, 0.3,␣
↪1.0, 50.0, -77.0, -54.387, 10.0, -65.0, 0.052, 0.596, 0.317, 50, 7000,␣
↪13000, None, 0.01, np.zeros(20000)
        self.timestep = 0.01
        self.robert = Robert()

    # Essentially, a funny named new-custom constructor
    def tentacles(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h, n,␣
↪t, pulse, pulsex, pulsey, movement, timestep):

        if robert is None:
            if self.robert is None:
                self.robert = Robert()

        else:
            try:
                self.robert.activation(robert, gNa, gK, gL, Cm, ENa, EK, EL, I,␣
↪Vm, m, h, n, t, pulse, pulsex, pulsey)
            except:
                print("[E1<Squid-Init>] bruh u might have missed a neuronal␣
↪parameter for rob lol")

        self.playtime = np.zeros(t) #self.robert.t
        self.playtime[pulsex:pulsey] = pulse

        #if clarinet is None:
            #if self.clarinet is None:
        if timestep is None:
            timestep = 0.01
            self.timestep = timestep
        else:
            self.timestep = timestep
        if movement is None:
            self.movement = hodhux.Simulation(self.robert.model)
            self.clarinet(self.timestep, self.movement)
        else:
            self.clarinet(self.timestep, movement)
                #self.clarinet = clarinet(t, timestep, )

        #self.playtime = self.robert.t

    def clarinet(self, timestep, movement):
        # if playtime is None:
        #     playtime = np.zeros(20000)
```

```
        if timestep is None:
            timestep = 0.01

        if movement is None:
            self.movement = hodhux.Simulation(self.robert.model)
            self.movement.Run(stimulusWaveform=self.playtime, stepSizeMs=timestep)
            self.movement = movement
            #print("[E4<Squid-Clarinet>] bruh u gotta pass a movement thingy so u can actually graph the results u silly head lol")

        else:
        #    try:
            movement.Run(stimulusWaveform=self.playtime, stepSizeMs=timestep)
            self.movement = movement
        #    except:
        #        print("[E3<Squid-Clarinet>] bruh squidward's robert motor neuron model might be misconfigured lol")

    def sheetmusic(self, figsizex, figsizey, color1, color2, color3, color4, color5, color6, color7, color8, title, file):
        #try:
        if figsizex:
            if figsizey:
                plot.figure(figsize=(figsizex, figsizey))
        else:
            plot.figure(figsize=(10, 8))
        # except:
        #     print("[E4<Squid-SheetMusic>] bruh u might have missed the figure sizes for the sheet music lol")

        if title is None:
            title = "PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic Graphical Model"

        else:
            title = "PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic Graphical Model: " + title

        if self.movement is None:
            print("[E4<Squid-SheetMusic>] bruh squidward apparently hasnt moved his clarinet or if he did, it wasn't recorded u silly goose lol")

        if self.robert is None:
```

```
            print("[E5<Squid-SheetMusic>] bruh somehow at this stage, Robert␣
↪the Motor Neuron still has not been created yet, you are one silly goose dan␣
↪lmao")

        else:
            movement = self.movement # lazy but saves typing self. each time␣
↪lmao
            # Potential (mV) Color
            if color1 is None:
                color1 = 'r'

            # Input Stimulation (μA/cm^2) Color
            if color2 is None:
                color2 = 'b'

            # Sodium Activation Gating Variable (m) Color
            if color3 is None:
                color3 = 'purple'

            # Sodium Inactivation Gating Variable (h) Color
            if color4 is None:
                color4 = 'orange'

            # Potassium Activation Gating Variable (n) Color
            if color5 is None:
                color5 = 'yellow' # BANANA

            # Sodium Current (INa) (μA/cm^2) Color
            if color6 is None:
                color6 = 'purple'

            # Potassium Current (IK) (μA/cm^2) Color
            if color7 is None:
                color7 = 'yellow'

            # Leak Current (IL) (μA/cm^2) Color
            if color8 is None:
                color8 = 'turquoise'

            ## Credits to [2] for parts from README.md Example Code

            # Potential (mV) Plot #1
            potentialplt = plot.subplot(411)
            potentialplt.set_title(title)
            potentialplt.set_ylabel("Rob's Membrane Potential (mV)")
            potentialplt.plot(movement.times, movement.Vm - 70, color=color1)
```

```
            # Input Stimulation (μA/cm^2) Plot #2
            stimulationplt = plot.subplot(412)
            stimulationplt.set_ylabel("Squidward Stimulation (µA/cm²)")
            playtime = self.playtime
            ## Sanity Debug Print Statement
            #print(movement.times, playtime, color2)
            stimulationplt.plot(movement.times, playtime, color=color2)

            # Gating Variable Activation (m/h/n) Plot #3
            activationplt = plot.subplot(413, sharex=potentialplt)
            activationplt.set_ylabel("Rob's Channel Activation (fractional)")
            activationplt.plot(movement.times, movement.StateM, label='m (Na+␣
↪Channel Open Prob.)', color=color3)
            activationplt.plot(movement.times, movement.StateH, label='h (Na+␣
↪Channel Close Prob.)', color=color4)
            activationplt.plot(movement.times, movement.StateN, label='n (K+␣
↪Channel Open Prob.)', color=color5)
            activationplt.legend()

            # Ionic Channel Current Plot (INa/IK/Ileak) Plot #4
            currentplt = plot.subplot(414, sharex=potentialplt)
            currentplt.set_xlabel("Clarinet Action Potential Time (in␣
↪milliseconds)")
            currentplt.set_ylabel("Rob Membrane Ionic Current (µA/cm²)")
            currentplt.plot(movement.times, movement.INa, label='INa (Sodium␣
↪Current)', color=color6)
            currentplt.plot(movement.times, movement.IK, label='IK (Potassium␣
↪Current)', color=color7)
            currentplt.plot(movement.times, movement.IKleak, label='IKLeak␣
↪(KLeakage Current)', color=color8)
            currentplt.legend()

            plot.tight_layout()
            plot.savefig(file)
            plot.show()

class Robert:
        def __init__(self):
            self.model = hodhux.HHModel()
            self.t = None

        def activation(self, model, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h,␣
↪n, t, pulse, pulsex, pulsey):

            if model is None:
                if self.model is None:
```

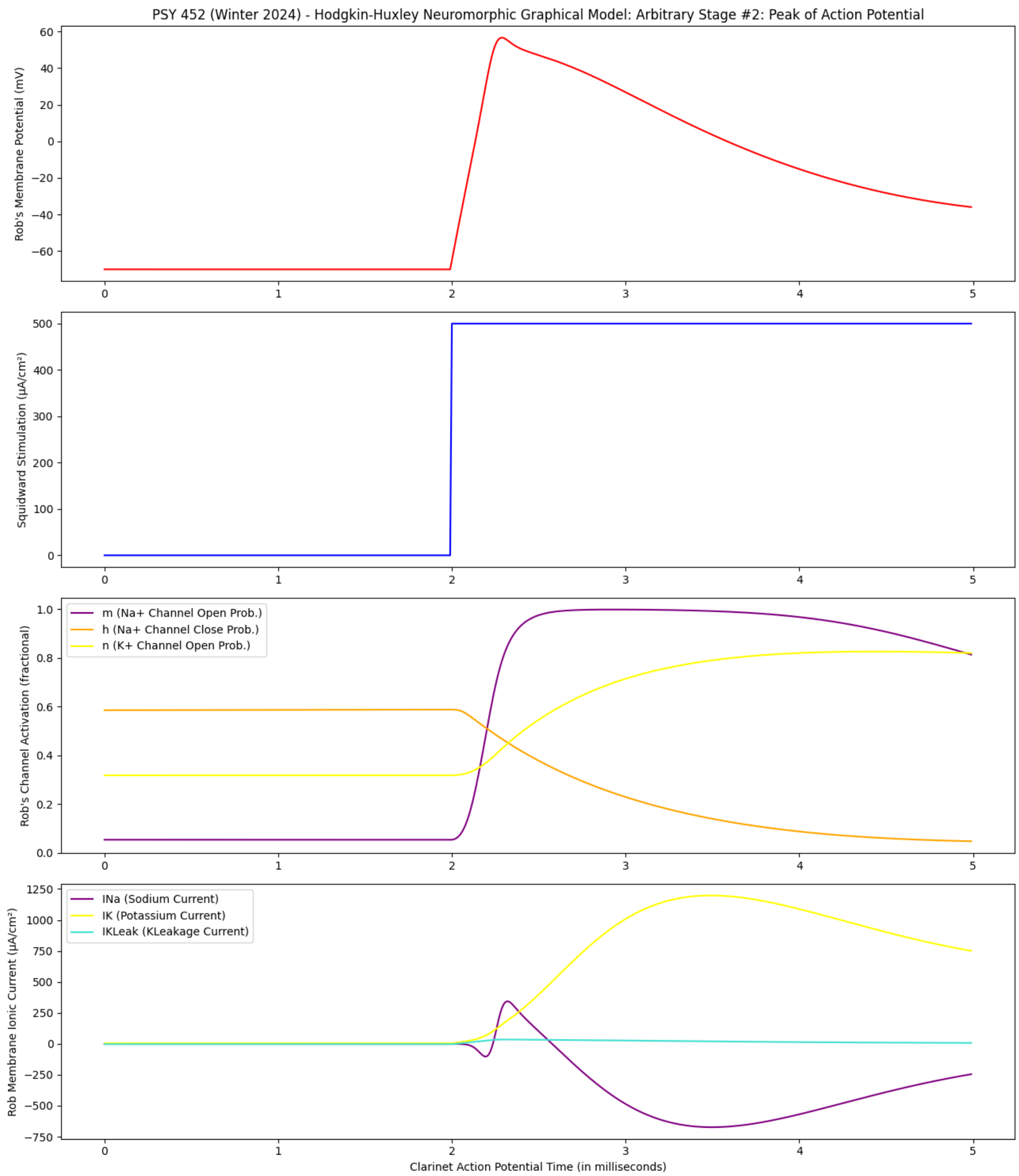
```python
                    robert = hodhux.HHModel()

                    # Squidward's Rob Motor Neuron Parameter, gNa: Avg. Na+␣
↪(Sodium cation) conductance per unit area (mS/cm^2)
                    robert.gNa = 120

                    # Squidward's Rob Motor Neuron Parameter, gK: Avg. K+␣
↪(Potassium cation) conductance per unit area (mS/cm^2)
                    robert.gK = 36

                    # Squidward's Rob Motor Neuron Parameter, gL: Avg. Leak (e.
↪g., Chlorine anions / Calcium {2+} cations) conductance per unit area (mS/
↪cm^2)
                    robert.gKleak = 0.3

                    # Squidward's Rob Motor Neuron Parameter, Cm: Membrane␣
↪capacitance per unit area (uF/cm^2)
                    robert.Cm = 1.0

                    # Squidward's Rob Motor Neuron Parameter, ENa: Sodium␣
↪cation Nernst reversal potential (mV)
                    robert.ENa = 115

                    # Squidward's Rob Motor Neuron Parameter, EK: Potassium␣
↪cation Nernst reversal potential (mV)
                    robert.EK = -12

                    # Squidward's Rob Motor Neuron Parameter, EL: Leak Nernst␣
↪reversal potential (mV)
                    robert.EKleak = 10.6

                    # Squidward's Rob Motor Neuron Parameter, I: External␣
↪current (uA/cm^2)
                    #robert.I = 10.0

                    # Squidward's Rob Motor Neuron Parameter, Vm: Membrane␣
↪potential (mV)
                    #robert.Vm = 0

                    # Squidward's Rob Motor Neuron Parameter, m: Sodium cation␣
↪activation gating variable
                    #robert.m = 0

                    # Squidward's Rob Motor Neuron Parameter, h: Sodium cation␣
↪inactivation gating variable
                    #robert.h = 0
```

```
                # Squidward's Rob Motor Neuron Parameter, n: Potassium␣
↪cation activation gating variable
                #robert.n = 0

                # Stimulus Waveform thingy
                self.t = np.zeros(20000)

                # Stimulus Waveform <+ Square Pulse
                self.t[7000:13000] = 50

                self.model = robert
        try:

            robert = self.model

            if gNa is not None:
                robert.gNa = gNa

            if gK is not None:
                robert.gK = gK

            if gL is not None:
                robert.gKleak = gL

            if Cm is not None:
                robert.Cm = Cm

            if ENa is not None:
                robert.ENa = ENa

            if EK is not None:
                robert.EK = EK

            if EL is not None:
                robert.EKleak = EL

            # if I is not None:
            #     robert.I = I

            # if Vm is not None:
            #     robert.Vm = Vm

            # if m is not None:
            #     robert.m = m

            # if h is not None:
```

```python
                #     robert.h = h

                # if n is not None:
                #     robert.n = n

                if t is not None:
                    # Stimulus Waveform thingy
                    self.t = np.zeros(t)

                if pulse is not None:
                    if pulsex is not None:
                        if pulsey is not None:
                            self.t[pulsex:pulsey] = pulse

                self.model = robert
            except:
                print("[E2<SubSquid-Rob-Init>] bruh u might have missed a␣
↪neuronal parameter for rob within squidward initialization thingy lol")

        def model(self):
            return self.model

### Finally, the grand test for class Squidward (main wrapper), with a subclass␣
↪Robert (le Motor Neuron model encompassing wrapper)

# Reference - Squidward(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m,␣
↪h, n, t, pulse, pulsex, pulsey, movement, timestep)
squidward = Squidward()

# tentacles(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h, n, t,␣
↪pulse, pulsex, pulsey, movement, timestep):

squidward.tentacles(None, 120.0, 36.0, 0.3, 1.0, 115, -12, 10.6, 0, 0, 0, 0, 0,␣
↪500, 500, 200, 1000, None, 0.01)

# Reference - sheetmusic(self, figsizex, figsizey, color1, color2, color3,␣
↪color4, color5, color6, color7, color8, title)
#             movement = self.movement # lazy but saves typing self. each time␣
↪lmao
# # Potential (mV) Color
#     color1 = 'r'
# # Input Stimulation (µA/cm^2) Color
#     color2 = 'b'
# # Sodium Activation Gating Variable (m) Color
#     color3 = 'purple'
# # Sodium Inactivation Gating Variable (h) Color
```

```python
#     color4 = 'orange'
# # Potassium Activation Gating Variable (n) Color
#     color5 = 'yellow' # BANANA
# # Sodium Current (INa) (μA/cm^2) Color
#     color6 = 'purple'
# # Potassium Current (IK) (μA/cm^2) Color
#     color7 = 'yellow'
# # Leak Current (IL) (μA/cm^2) Color
#     color8 = 'turquoise'

squidward.sheetmusic(13, 15, 'r', 'b', 'purple', 'orange', 'yellow', 'purple',␣
 ↪'yellow', 'turquoise', "Arbitrary Stage #2: Peak of Action Potential",␣
 ↪"PSY452-Phase2-SquidwardClarinetActionPotentialStimulationWaveform-DanJ.png")
```

```
Simulating 500 time points…
Simulation complete!
```



1.1.7 Part 3: *Re- / Hyperpolarization to Reach Resting Membrane Potential (RMP)*

[4]:
```
#### PSY 452 (Winter 2024) - Advanced Neurophysiological Psychology: Part 3,␣
↪Re- / Hyperpolarization to Reach Resting Membrane Potential (RMP)
### By Dan Jang
### Credits to Scott W. Harden for pyhh package [1]

class Squidward:
```

```
    def __init__(self):
        self.robert, self.gNa, self.gK, self.gL, self.Cm, self.ENa, self.EK,␣
↪self.EL, self.I, self.Vm, self.m, self.h, self.n, self.t, self.pulse, self.
↪pulsex, self.pulsey, self.movement, self.playtime = None, 120.0, 36.0, 0.3,␣
↪1.0, 50.0, -77.0, -54.387, 10.0, -65.0, 0.052, 0.596, 0.317, 50, 7000,␣
↪13000, None, 0.01, np.zeros(20000)
        self.timestep = 0.01
        self.robert = Robert()

    # Essentially, a funny named new-custom constructor
    def tentacles(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h, n,␣
↪t, pulse, pulsex, pulsey, movement, timestep):

        if robert is None:
            if self.robert is None:
                self.robert = Robert()

        else:
            try:
                self.robert.activation(robert, gNa, gK, gL, Cm, ENa, EK, EL, I,␣
↪Vm, m, h, n, t, pulse, pulsex, pulsey)
            except:
                print("[E1<Squid-Init>] bruh u might have missed a neuronal␣
↪parameter for rob lol")

        self.playtime = np.zeros(t) #self.robert.t
        self.playtime[pulsex:pulsey] = pulse

        #if clarinet is None:
            #if self.clarinet is None:
        if timestep is None:
            timestep = 0.01
            self.timestep = timestep
        else:
            self.timestep = timestep
        if movement is None:
            self.movement = hodhux.Simulation(self.robert.model)
            self.clarinet(self.timestep, self.movement)
        else:
            self.clarinet(self.timestep, movement)
                #self.clarinet = clarinet(t, timestep, )

        #self.playtime = self.robert.t

    def clarinet(self, timestep, movement):
        # if playtime is None:
        #     playtime = np.zeros(20000)
```

```
        if timestep is None:
            timestep = 0.01

        if movement is None:
            self.movement = hodhux.Simulation(self.robert.model)
            self.movement.Run(stimulusWaveform=self.playtime,␣
↪stepSizeMs=timestep)
            self.movement = movement
            #print("[E4<Squid-Clarinet>] bruh u gotta pass a movement thingy so␣
↪u can actually graph the results u silly head lol")

        else:
        #    try:
            movement.Run(stimulusWaveform=self.playtime, stepSizeMs=timestep)
            self.movement = movement
        #    except:
        #        print("[E3<Squid-Clarinet>] bruh squidward's robert motor␣
↪neuron model might be misconfigured lol")

    def sheetmusic(self, figsizex, figsizey, color1, color2, color3, color4,␣
↪color5, color6, color7, color8, title, file):
        #try:
        if figsizex:
            if figsizey:
                plot.figure(figsize=(figsizex, figsizey))
        else:
            plot.figure(figsize=(10, 8))
        # except:
        #     print("[E4<Squid-SheetMusic>] bruh u might have missed the figure␣
↪sizes for the sheet music lol")

        if title is None:
            title = "PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic␣
↪Graphical Model"

        else:
            title = "PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic␣
↪Graphical Model: " + title

        if self.movement is None:
            print("[E4<Squid-SheetMusic>] bruh squidward apparently hasnt moved␣
↪his clarinet or if he did, it wasn't recorded u silly goose lol")

        if self.robert is None:
```

```
            print("[E5<Squid-SheetMusic>] bruh somehow at this stage, Robert␣
↪the Motor Neuron still has not been created yet, you are one silly goose dan␣
↪lmao")

        else:
            movement = self.movement # lazy but saves typing self. each time␣
↪lmao
            # Potential (mV) Color
            if color1 is None:
                color1 = 'r'

            # Input Stimulation (μA/cm^2) Color
            if color2 is None:
                color2 = 'b'

            # Sodium Activation Gating Variable (m) Color
            if color3 is None:
                color3 = 'purple'

            # Sodium Inactivation Gating Variable (h) Color
            if color4 is None:
                color4 = 'orange'

            # Potassium Activation Gating Variable (n) Color
            if color5 is None:
                color5 = 'yellow' # BANANA

            # Sodium Current (INa) (μA/cm^2) Color
            if color6 is None:
                color6 = 'purple'

            # Potassium Current (IK) (μA/cm^2) Color
            if color7 is None:
                color7 = 'yellow'

            # Leak Current (IL) (μA/cm^2) Color
            if color8 is None:
                color8 = 'turquoise'

            ## Credits to [2] for parts from README.md Example Code

            # Potential (mV) Plot #1
            potentialplt = plot.subplot(411)
            potentialplt.set_title(title)
            potentialplt.set_ylabel("Rob's Membrane Potential (mV)")
            potentialplt.plot(movement.times, movement.Vm - 70, color=color1)
```

```
            # Input Stimulation (μA/cm^2) Plot #2
            stimulationplt = plot.subplot(412)
            stimulationplt.set_ylabel("Squidward Stimulation (μA/cm²)")
            playtime = self.playtime
            ## Sanity Debug Print Statement
            #print(movement.times, playtime, color2)
            stimulationplt.plot(movement.times, playtime, color=color2)

            # Gating Variable Activation (m/h/n) Plot #3
            activationplt = plot.subplot(413, sharex=potentialplt)
            activationplt.set_ylabel("Rob's Channel Activation (fractional)")
            activationplt.plot(movement.times, movement.StateM, label='m (Na+␣
↪Channel Open Prob.)', color=color3)
            activationplt.plot(movement.times, movement.StateH, label='h (Na+␣
↪Channel Close Prob.)', color=color4)
            activationplt.plot(movement.times, movement.StateN, label='n (K+␣
↪Channel Open Prob.)', color=color5)
            activationplt.legend()

            # Ionic Channel Current Plot (INa/IK/Ileak) Plot #4
            currentplt = plot.subplot(414, sharex=potentialplt)
            currentplt.set_xlabel("Clarinet Action Potential Time (in␣
↪milliseconds)")
            currentplt.set_ylabel("Rob Membrane Ionic Current (μA/cm²)")
            currentplt.plot(movement.times, movement.INa, label='INa (Sodium␣
↪Current)', color=color6)
            currentplt.plot(movement.times, movement.IK, label='IK (Potassium␣
↪Current)', color=color7)
            currentplt.plot(movement.times, movement.IKleak, label='IKLeak␣
↪(KLeakage Current)', color=color8)
            currentplt.legend()

            plot.tight_layout()
            plot.savefig(file)
            plot.show()

class Robert:
        def __init__(self):
            self.model = hodhux.HHModel()
            self.t = None

        def activation(self, model, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h,␣
↪n, t, pulse, pulsex, pulsey):

            if model is None:
                if self.model is None:
```

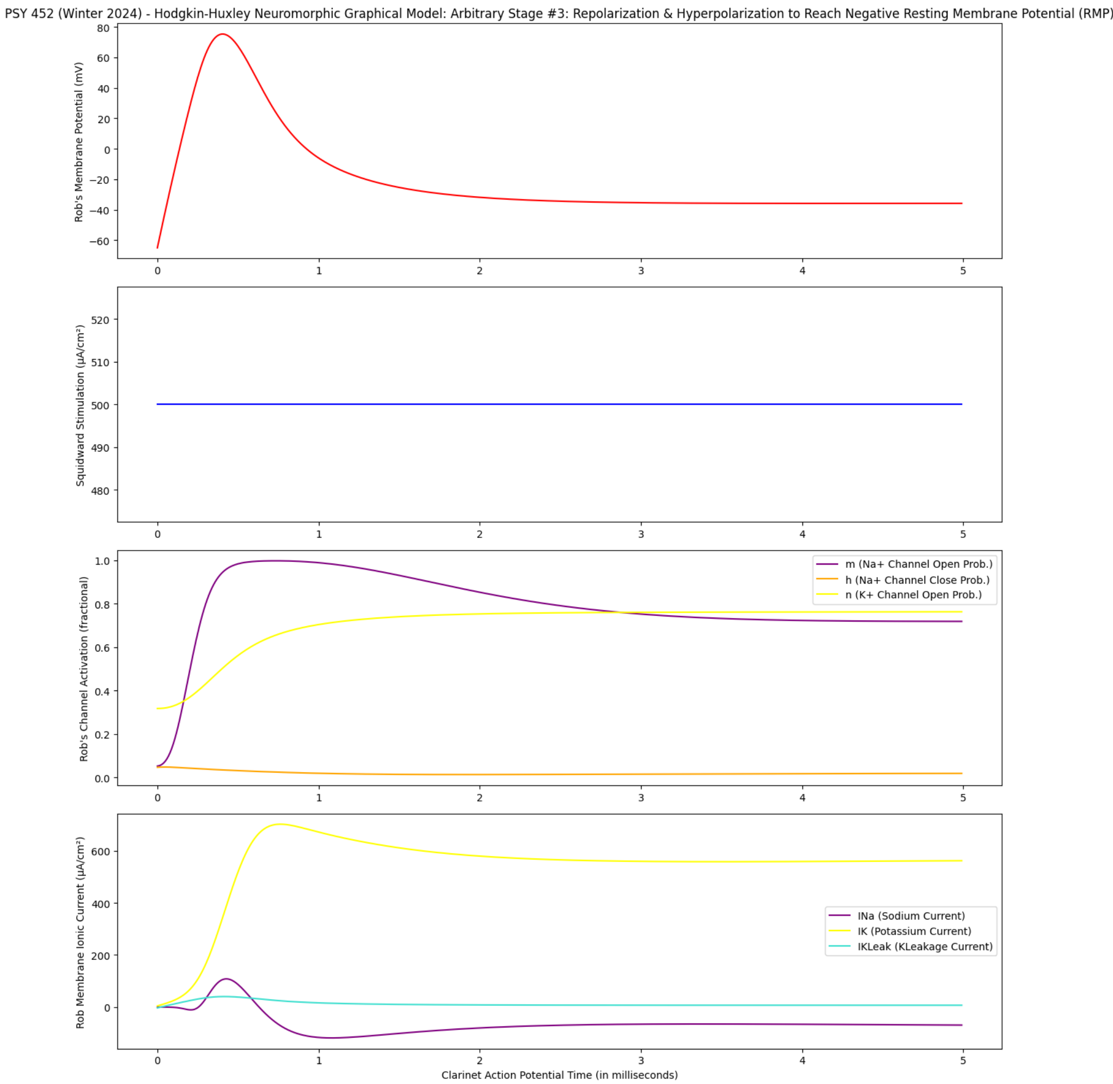
```
                robert = hodhux.HHModel()

                # Squidward's Rob Motor Neuron Parameter, gNa: Avg. Na+ (Sodium cation) conductance per unit area (mS/cm^2)
                robert.gNa = 120

                # Squidward's Rob Motor Neuron Parameter, gK: Avg. K+ (Potassium cation) conductance per unit area (mS/cm^2)
                robert.gK = 36

                # Squidward's Rob Motor Neuron Parameter, gL: Avg. Leak (e.g., Chlorine anions / Calcium {2+} cations) conductance per unit area (mS/cm^2)
                robert.gKleak = 0.3

                # Squidward's Rob Motor Neuron Parameter, Cm: Membrane capacitance per unit area (uF/cm^2)
                robert.Cm = 1.0

                # Squidward's Rob Motor Neuron Parameter, ENa: Sodium cation Nernst reversal potential (mV)
                robert.ENa = 115

                # Squidward's Rob Motor Neuron Parameter, EK: Potassium cation Nernst reversal potential (mV)
                robert.EK = -12

                # Squidward's Rob Motor Neuron Parameter, EL: Leak Nernst reversal potential (mV)
                robert.EKleak = 10.6

                # Squidward's Rob Motor Neuron Parameter, I: External current (uA/cm^2)
                #robert.I = 10.0

                # Squidward's Rob Motor Neuron Parameter, Vm: Membrane potential (mV)
                #robert.Vm = 0

                # Squidward's Rob Motor Neuron Parameter, m: Sodium cation activation gating variable
                #robert.m = 0

                # Squidward's Rob Motor Neuron Parameter, h: Sodium cation inactivation gating variable
                #robert.h = 0
```

```
                # Squidward's Rob Motor Neuron Parameter, n: Potassium␣
↪cation activation gating variable
                #robert.n = 0

                # Stimulus Waveform thingy
                self.t = np.zeros(20000)

                # Stimulus Waveform <+ Square Pulse
                self.t[7000:13000] = 50

                self.model = robert
        try:

            robert = self.model

            if gNa is not None:
                robert.gNa = gNa

            if gK is not None:
                robert.gK = gK

            if gL is not None:
                robert.gKleak = gL

            if Cm is not None:
                robert.Cm = Cm

            if ENa is not None:
                robert.ENa = ENa

            if EK is not None:
                robert.EK = EK

            if EL is not None:
                robert.EKleak = EL

            # if I is not None:
            #     robert.I = I

            # if Vm is not None:
            #     robert.Vm = Vm

            # if m is not None:
            #     robert.m = m

            # if h is not None:
```

```
                #     robert.h = h

                # if n is not None:
                #     robert.n = n

                if t is not None:
                    # Stimulus Waveform thingy
                    self.t = np.zeros(t)

                if pulse is not None:
                    if pulsex is not None:
                        if pulsey is not None:
                            self.t[pulsex:pulsey] = pulse

                self.model = robert
            except:
                print("[E2<SubSquid-Rob-Init>] bruh u might have missed a␣
↪neuronal parameter for rob within squidward initialization thingy lol")

        def model(self):
            return self.model

### Finally, the grand test for class Squidward (main wrapper), with a subclass␣
↪Robert (le Motor Neuron model encompassing wrapper)

# Reference - Squidward(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m,␣
↪h, n, t, pulse, pulsex, pulsey, movement, timestep)
squidward = Squidward()

# tentacles(self, robert, gNa, gK, gL, Cm, ENa, EK, EL, I, Vm, m, h, n, t,␣
↪pulse, pulsex, pulsey, movement, timestep):

squidward.tentacles(None, 120.0, 36.0, 0.3, 1.0, 115, -12, 10.6, 0, 0, 0, 0, 0,␣
↪500, 500, 0, 500, None, 0.01)

# Reference - sheetmusic(self, figsizex, figsizey, color1, color2, color3,␣
↪color4, color5, color6, color7, color8, title)
#             movement = self.movement # lazy but saves typing self. each time␣
↪lmao
# # Potential (mV) Color
#     color1 = 'r'
# # Input Stimulation (µA/cm^2) Color
#     color2 = 'b'
# # Sodium Activation Gating Variable (m) Color
#     color3 = 'purple'
# # Sodium Inactivation Gating Variable (h) Color
```

```
#     color4 = 'orange'
# # Potassium Activation Gating Variable (n) Color
#     color5 = 'yellow' # BANANA
# # Sodium Current (INa) (μA/cm^2) Color
#     color6 = 'purple'
# # Potassium Current (IK) (μA/cm^2) Color
#     color7 = 'yellow'
# # Leak Current (IL) (μA/cm^2) Color
#     color8 = 'turquoise'

squidward.sheetmusic(13, 15, 'r', 'b', 'purple', 'orange', 'yellow', 'purple',␣
 ↪'yellow', 'turquoise', "Arbitrary Stage #3: Repolarization &␣
 ↪Hyperpolarization to Reach Negative Resting Membrane Potential (RMP)",␣
 ↪"PSY452-Phase3-SquidwardClarinetActionPotentialStimulationWaveform-DanJ.png")
```

```
Simulating 500 time points…
Simulation complete!
```


PSY 452 (Winter 2024) - Hodgkin-Huxley Neuromorphic Graphical Model: Arbitrary Stage #3: Repolarization & Hyperpolarization to Reach Negative Resting Membrane Potential (RMP)
Rob's Membrane Potential (mV)
Squidward Stimulation (μA/cm²)
Rob's Channel Activation (fractional)
m (Na+ Channel Open Prob.)
h (Na+ Channel Close Prob.)
n (K+ Channel Open Prob.)
Rob Membrane Ionic Current (μA/cm²)
INa (Sodium Current)
IK (Potassium Current)
IKLeak (KLeakage Current)
Clarinet Action Potential Time (in milliseconds)

[4]

1.2 References

[1] S. W. Harden, “swharden/pyHH.” Feb. 11, 2024. [Online]. Available: https://github.com/swharden/pyHH

[2] A. L. Hodgkin and A. F. Huxley, “A quantitative description of membrane current and its application to conduction and excitation in nerve,” J Physiol, vol. 117, no. 4, pp. 500–544, Aug. 1952. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1392413/

[3] J. Żygierewicz, “Exercise 1: The Hodgkin Huxley model.” [Online]. Available: https://www.fuw.edu.pl/~jarekz/MODELOWANIE/Hh/HH_exercises.tex

[4] C. J. Schwiening, “A brief historical perspective: Hodgkin and Huxley,” J Physiol, vol. 590, no. Pt 11, pp. 2571–2575, Jun. 2012, doi: 10.1113/jphysiol.2012.230458.