Neuro B2: Excitatory Inhibitory Pair

PHASE 2: CIRCUIT DEVELOPMENT AND SIMULATION

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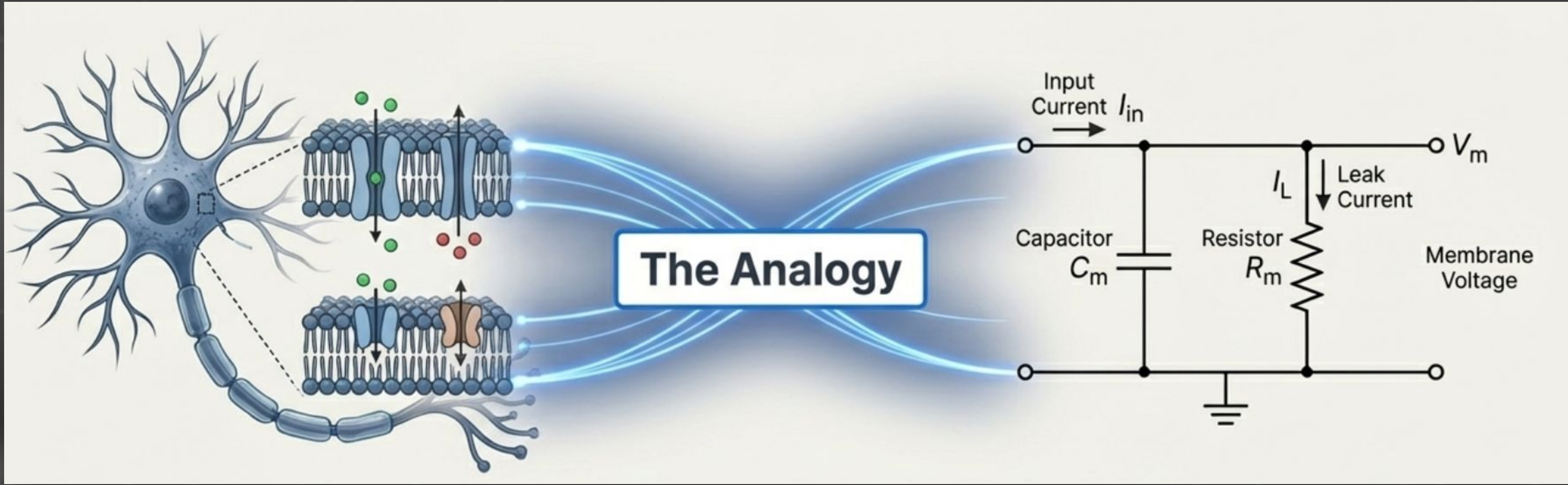
Model 1:

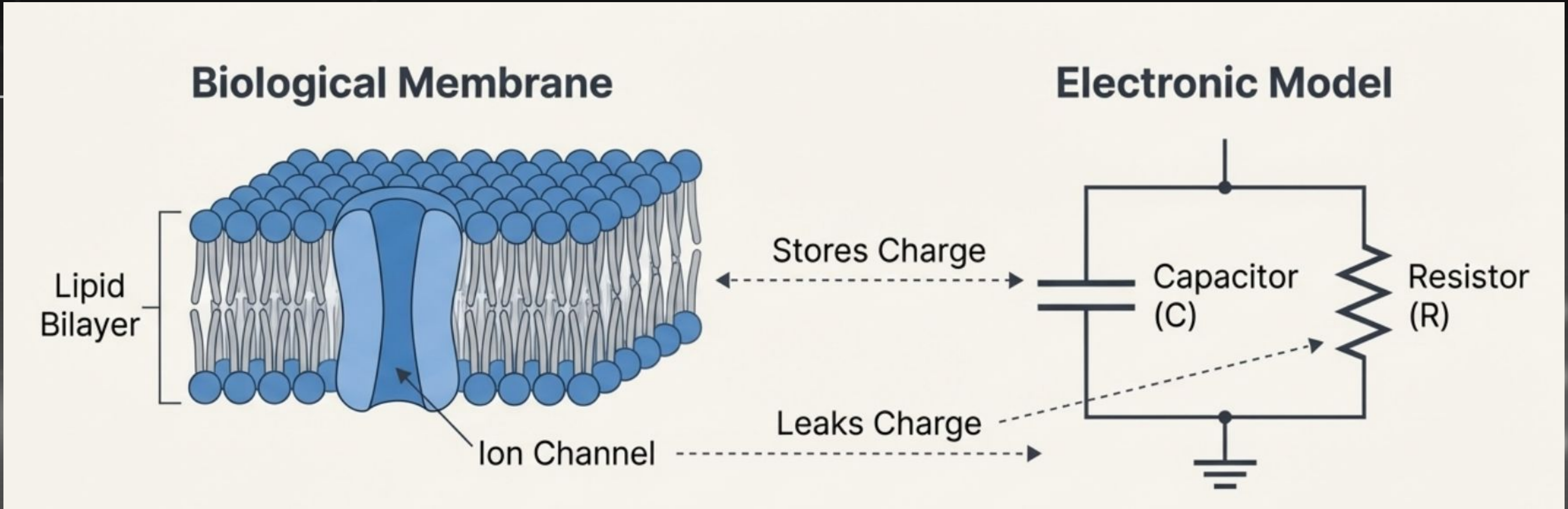
RC CIRCUIT AS A *LEAKY INTEGRATOR*

The Neuron: A Leaky, Integrating Device

The process of integrating thousands of excitatory and inhibitory signals can be emulated by a very basic passive circuit:



THE RC INTEGRATOR

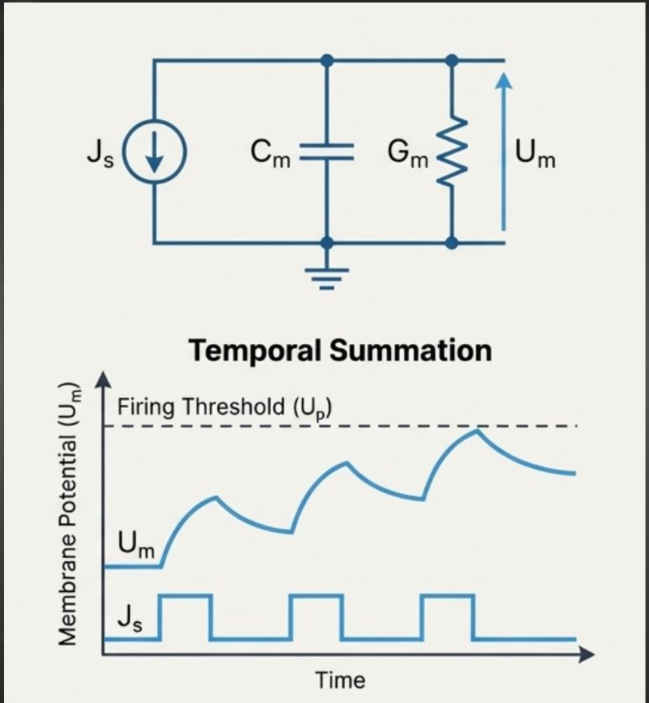


We can model the post-synaptic membrane using a parallel RC circuit.

- ★ **Inside cell:** K+ ion solution (conducting)
- ★ **Cell membrane:** Lipid bilayer (insulating)
- ★ **Outside cell:** Na+ ion solution (conducting)

Insulator sandwiched b/w 2 conductors is a **CAPACITOR**

Voltage across capacitor is a direct analog of the neuron's membrane potential. An incoming EPSP or IPSP is modelled as a voltage pulse.



This 'leaky integrate-and-fire' model can be represented by a simple RC circuit.

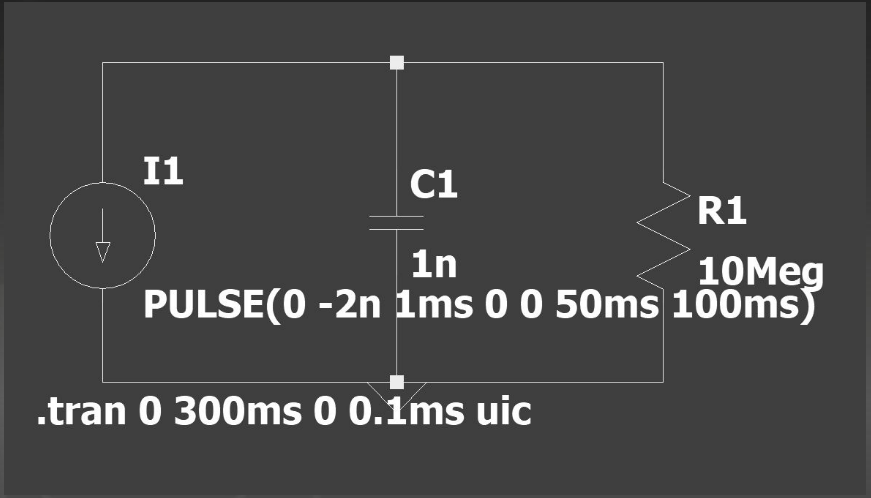
The circuit's behaviour over time is defined by its time constant.

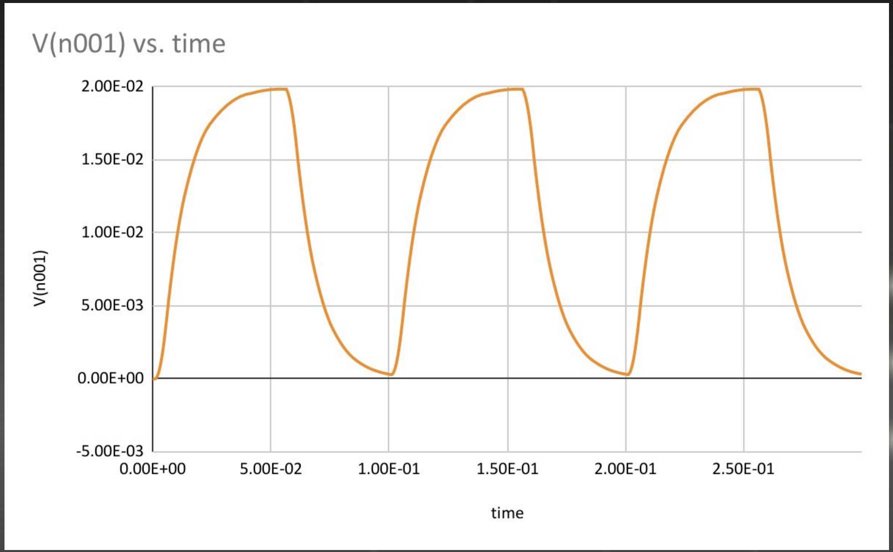
$$\tau = RC$$

This represents the neuron's 'memory' of recent pulses.

- high $\tau \rightarrow$ slow leakage, allows pulses to sum effectively
- low $\tau \rightarrow$ the neuron 'forgets' previous inputs quickly.

Leaky Integrate & Fire Model



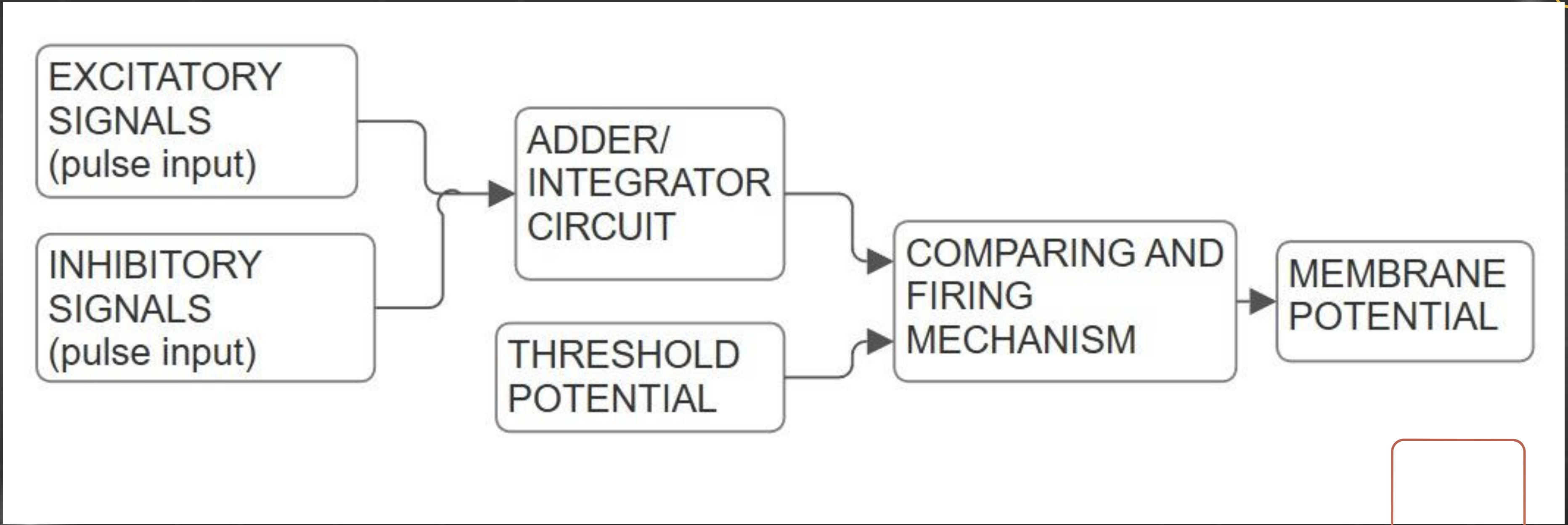


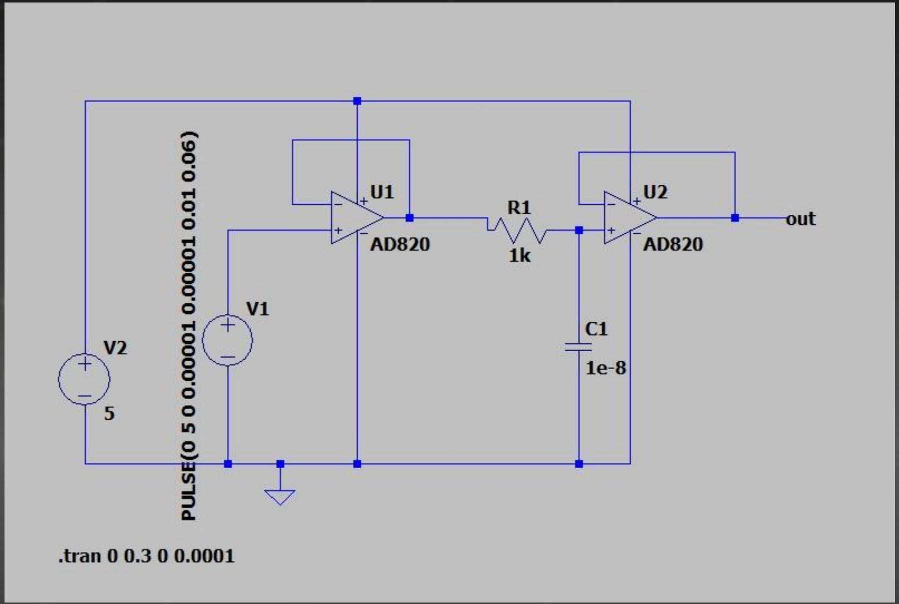
Simulation Results

Of the Leaky Integrate and Fire Circuit

USING ACTIVE ELEMENTS

Block Diagram





Each neuron is configured as an op-amp.

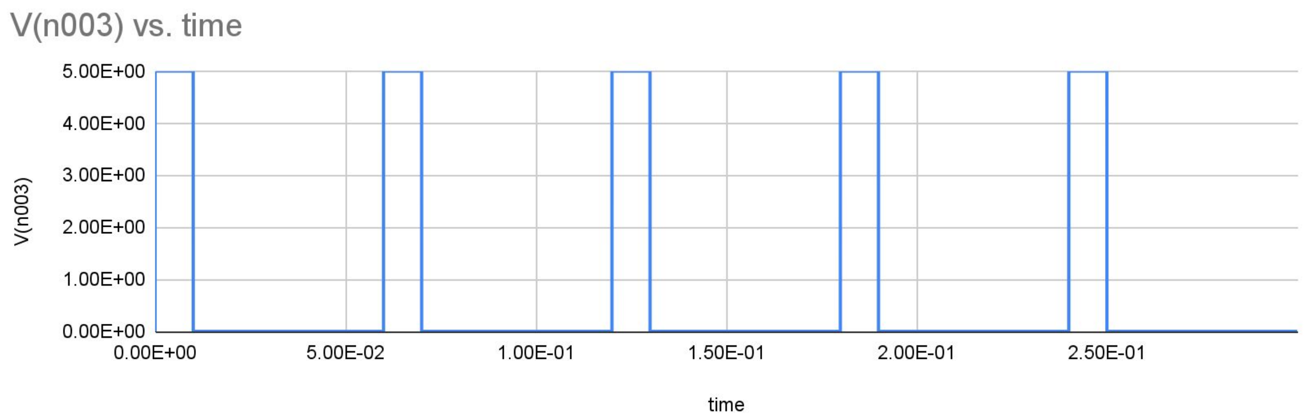
- **U1:** Voltage Follower
- **R1 + C1:** RC network representing *synapse* and *post-synaptic membrane*
  - R1: resistance of ion channels
  - C1: cell membrane capacitance
- **U2:** Voltage Follower

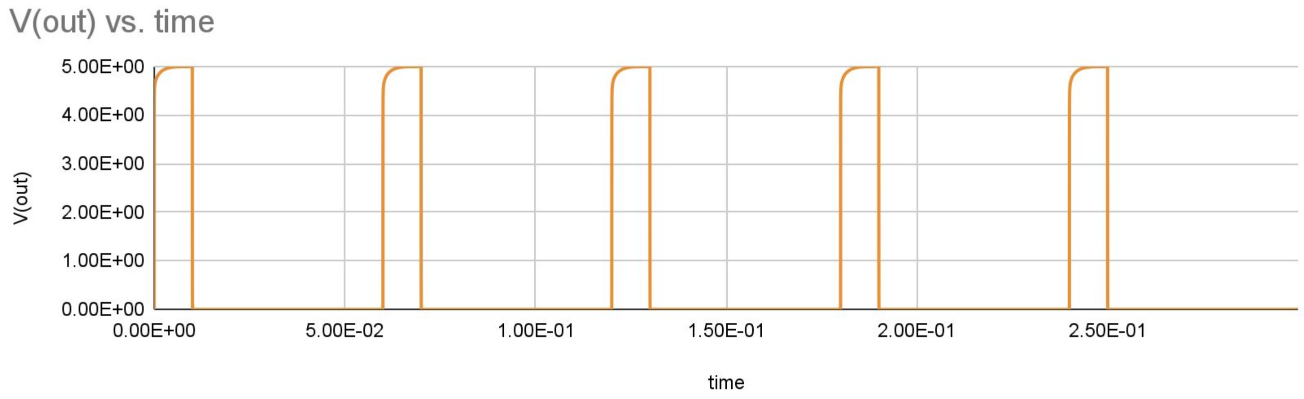
V2 is the supply voltage, V1 is the pulse voltage source.

When U1 goes high, it cannot instantly raise the voltage at U2. It must charge capacitor C1 through resistor R1. This creates the biological Time Constant (τ).

EXCITATORY SIGNALS (pulse input)

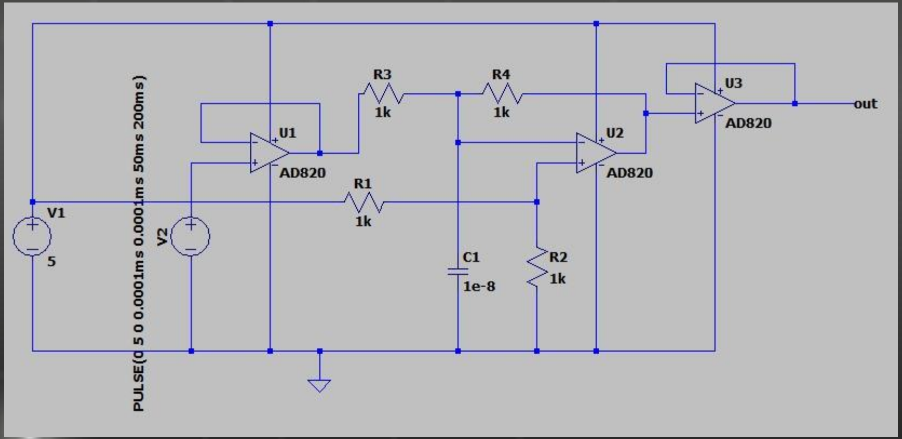
Feedforward Excitation


V(n003) vs. time
V(n003)
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
0.00E+00
5.00E-02
1.00E-01
1.50E-01
2.00E-01
2.50E-01
time


V(out) vs. time
V(out)
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
0.00E+00
5.00E-02
1.00E-01
1.50E-01
2.00E-01
2.50E-01
time

Feedforward Inhibition

INHIBITORY SIGNALS (pulse input)

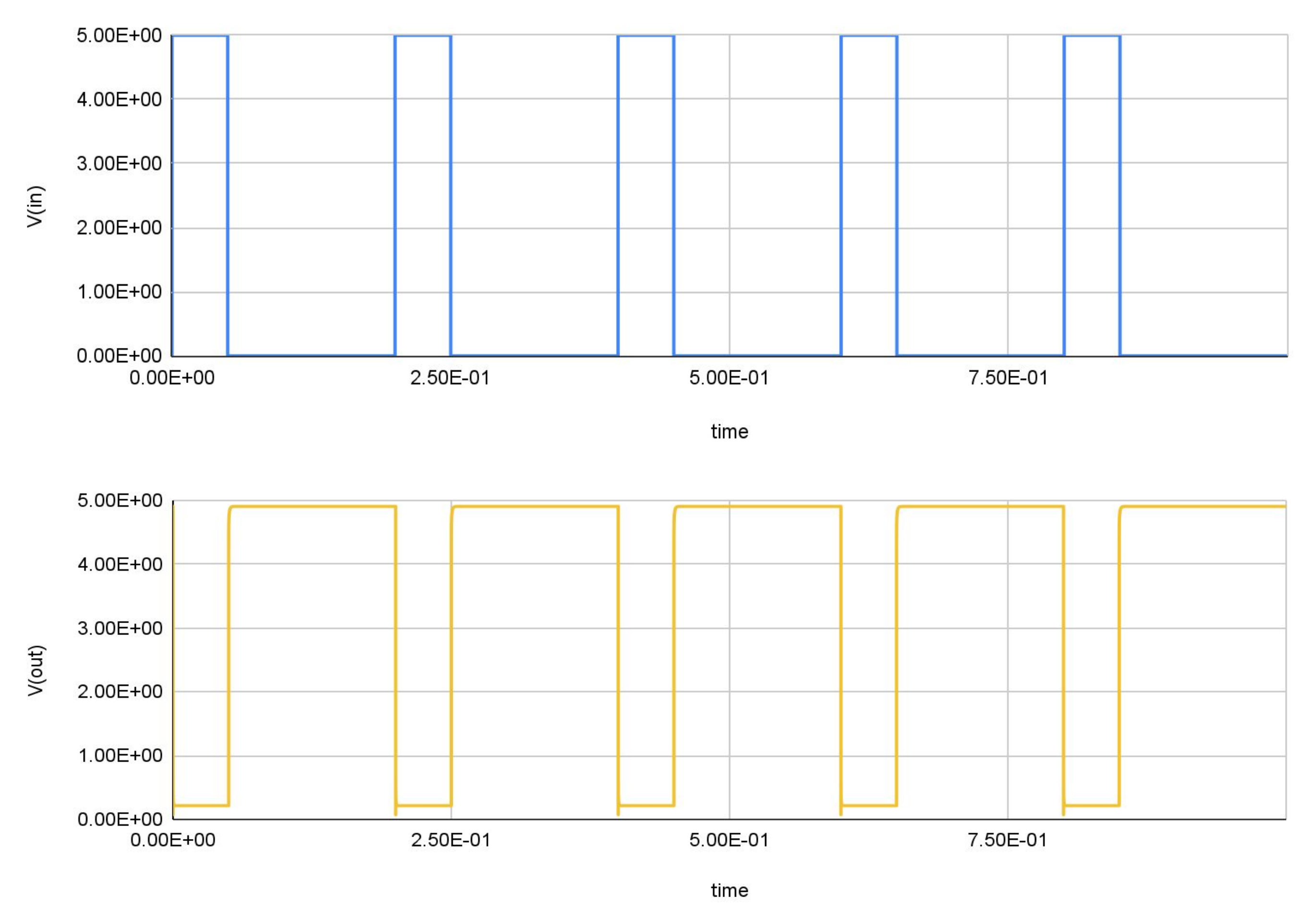


Each neuron is configured as an op-amp.

- **U1:** Voltage Follower
- **U2:** Inverting Amplifier
- **R1 + C1:** RC network representing *synapse* and *post-synaptic membrane*
  - R1: resistance of ion channels
  - C1: cell membrane capacitance
- **U3:** Summing Amplifier

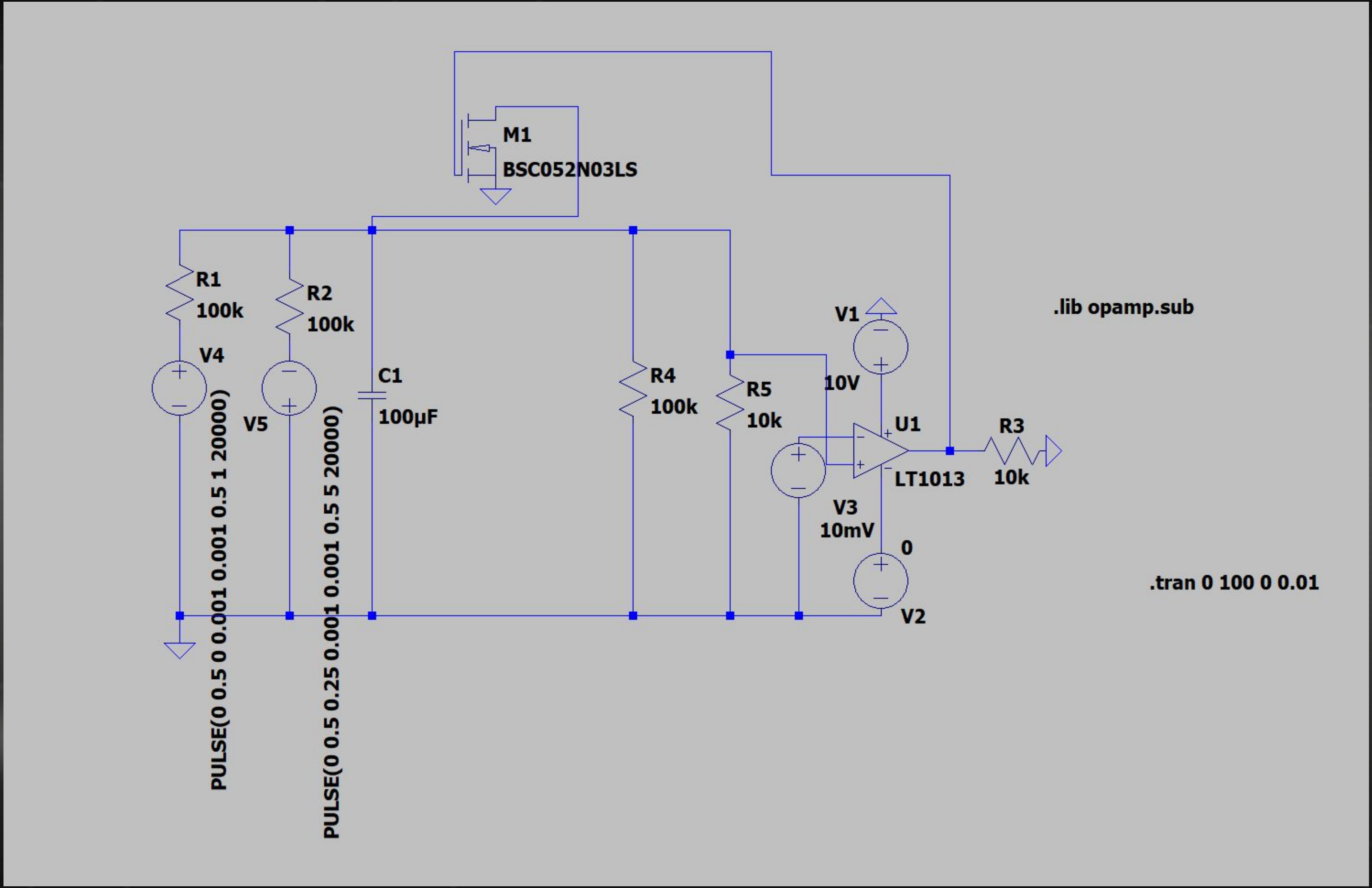
V2 is the supply voltage, V1 is the pulse voltage source.

The input neuron (U1) excites the interneuron (U2), which then releases inhibitory neurotransmitters (like GABA) onto the target (U3), which effectively cuts off/limits the signal.

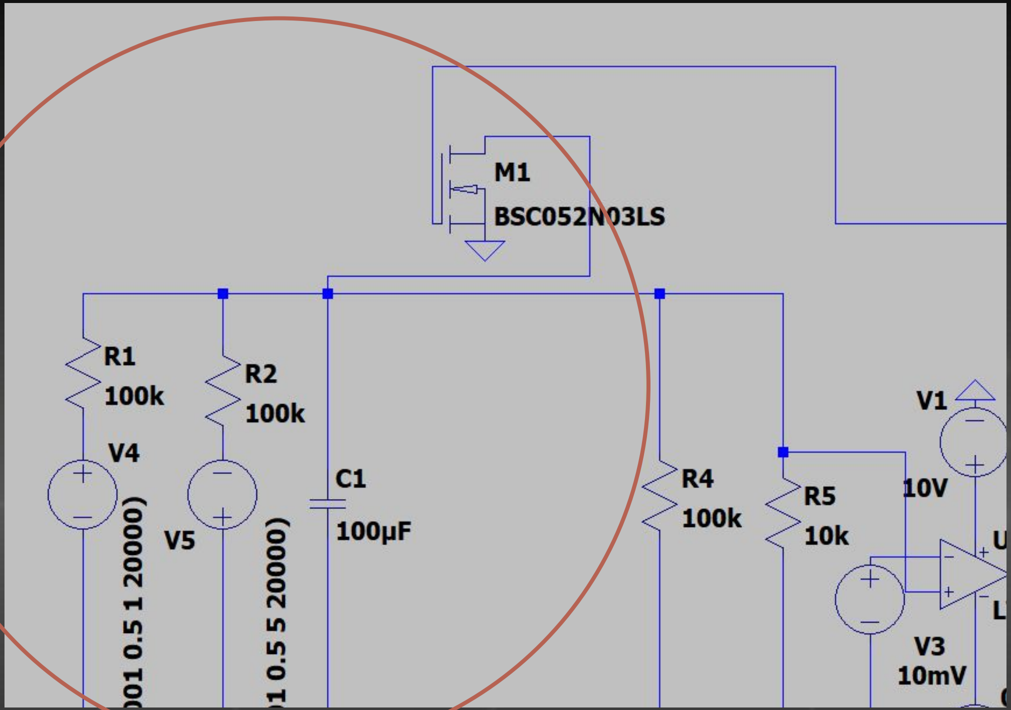


V(in)
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
0.00E+00
2.50E-01
5.00E-01
7.50E-01
time
V(out)
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
0.00E+00
2.50E-01
5.00E-01
7.50E-01
time

Model 2:


M1
BSC052N03LS
R1
100k
R2
100k
V4
V5
C1
100µF
R4
100k
R5
10k
V1
10V
U1
LT1013
R3
10k
V3
10mV
0
V2
PULSE(0 0.5 0 0.001 0.001 0.5 1 20000)
PULSE(0 0.5 0.25 0.001 0.001 0.5 5 20000)
.lib opamp.sub
.tran 0 100 0 0.01

M1: BSC052N03LS	N-channel MOSFET
R1, R2	100k
C1	100 µF
V4 and V5	Two pulse voltage sources



Generates a slowly varying control voltage using **pulse inputs** and **RC filtering**, with **MOSFET-based reset**.

$$Req = R1 \mid\mid R2 = \frac{100k + 100k}{(100k \cdot 100k)} = 50k\Omega$$

$$\tau = Req \cdot C1 = 50k \cdot 100\mu F = 5s$$

Charging: $$VC(t) = V_{FINAL}(1 - e^{-\frac{t}{\tau}})$$

Discharging: $$VC(t) = V_{INITIAL}(e^{-\frac{t}{\tau}})$$

MOSFET function:

- ON: Discharges C1 rapidly
- OFF: Allows smooth RC charge buildup

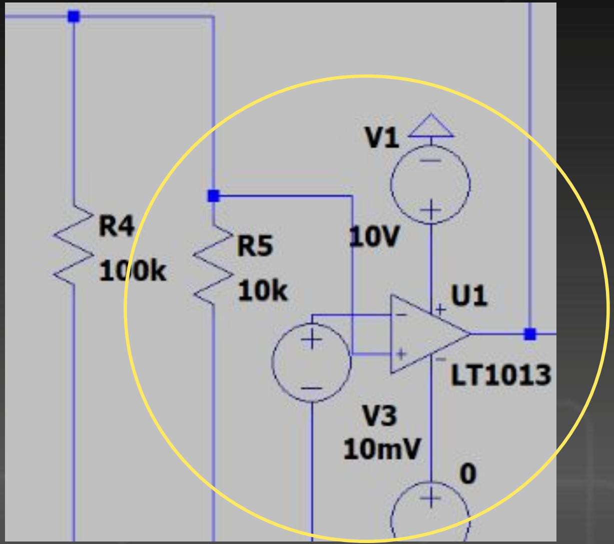
MOSFET + RC network

This block produces a resettable ramp voltage.

R4	100k
R5	10k
V3	10mV

$$V_{div} = V_C \cdot \frac{R4 + R5}{R5}$$

$$= V_C \cdot \frac{110k}{10k} \approx 0.091V$$



Comparator switches when:

$$V_C = \frac{Vref(R4 + R5)}{R5}$$

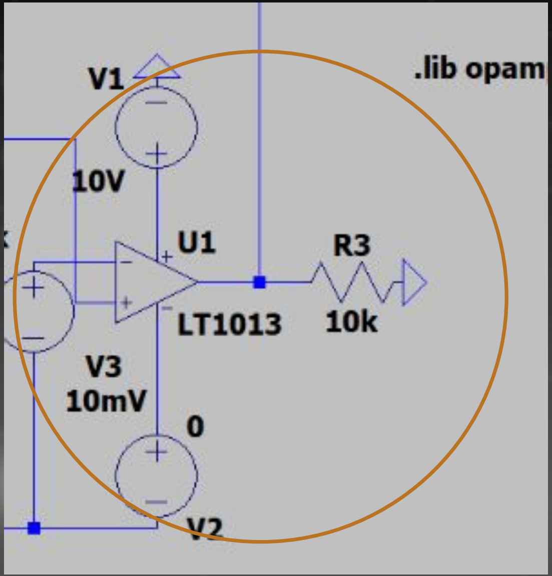
$$= \frac{10mV\,(10k + 100k)}{10k}$$

$$= 110mV$$

Divider + Reference Network:

Scales down the RC output voltage and defines the comparator reference level = 110 mV.

Op-Amp Comparator



Converts analog ramp into sharp switching signal.

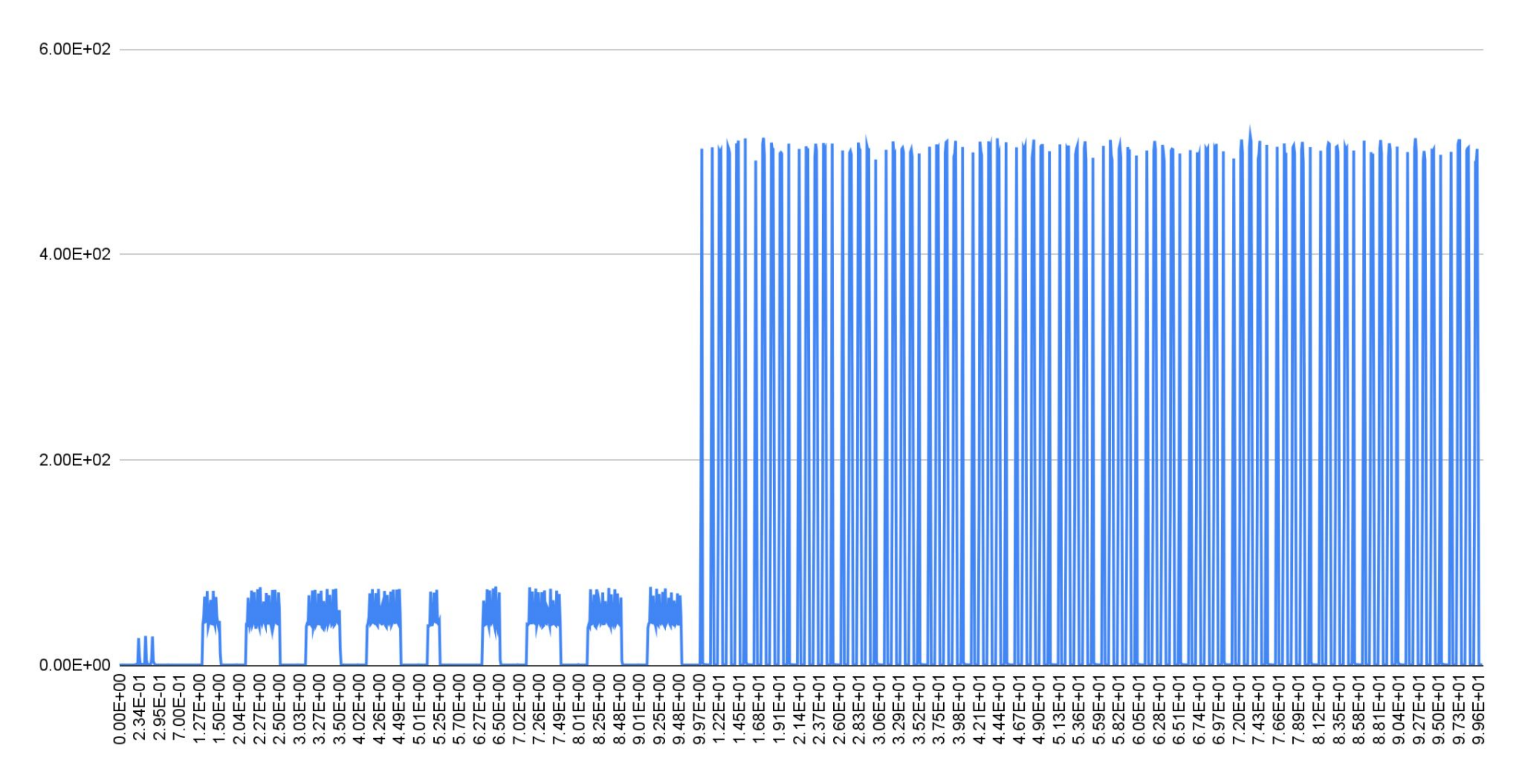
$$V_{out} = +V_{sat},\ if\ V_+ > V_-$$

$$V_{out} = -V_{sat},\ if\ V_+ < V_-$$

$$+V_{sat} = 10mV = HIGH$$

$$-V_{sat} = 0.091V_c = LOW$$

U1: LT013	Op Amp
V1	10V supply
V2	Ground
Inverting Input	Divider Output
Non-Inverting Input	10mV Reference



Simulation Results

Model 3:

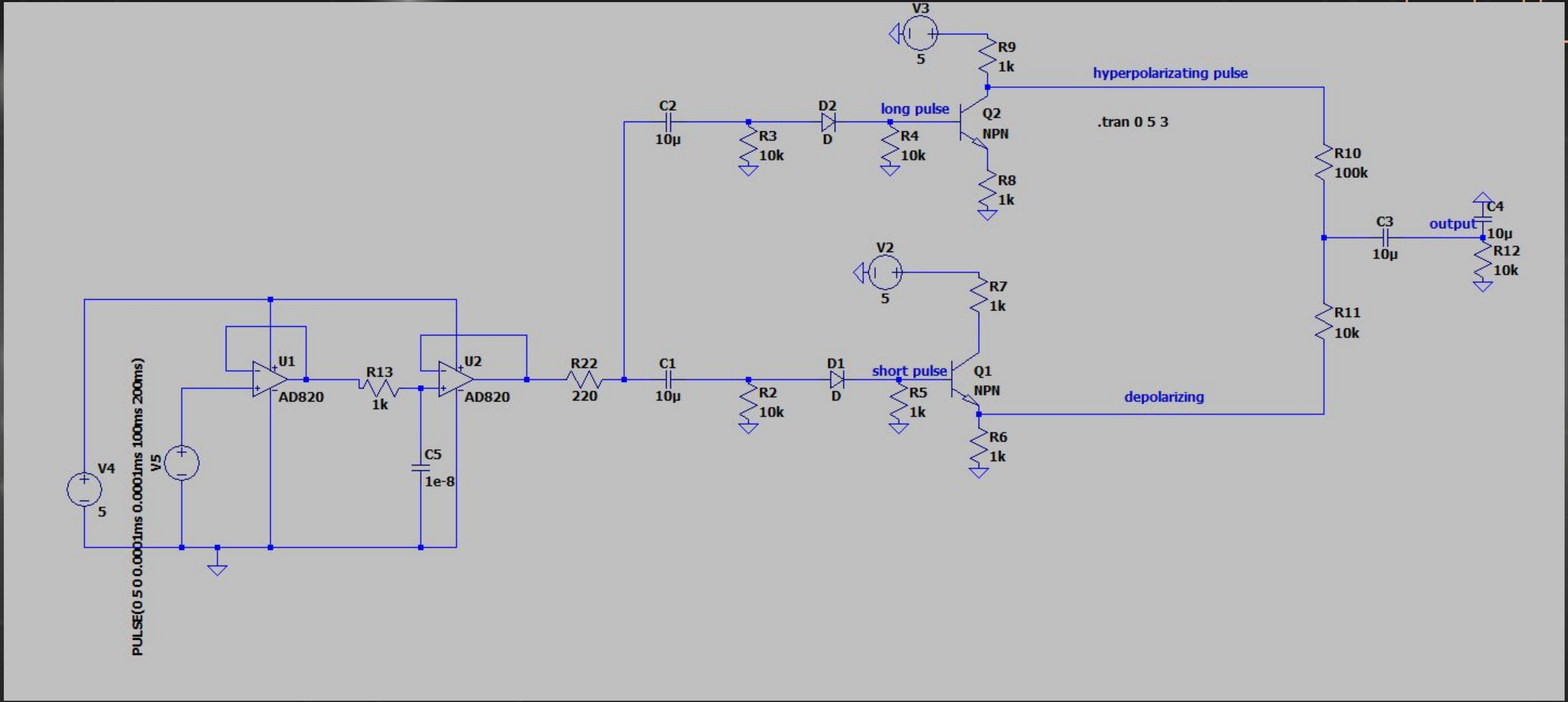
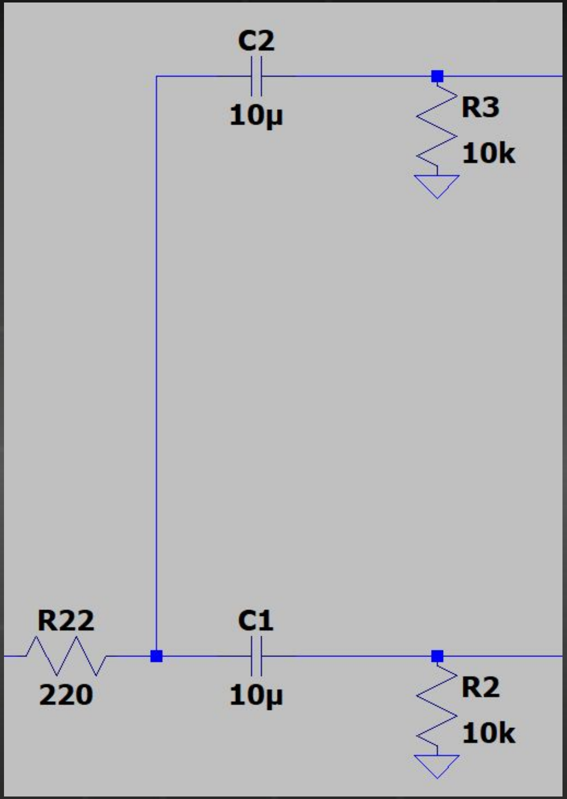
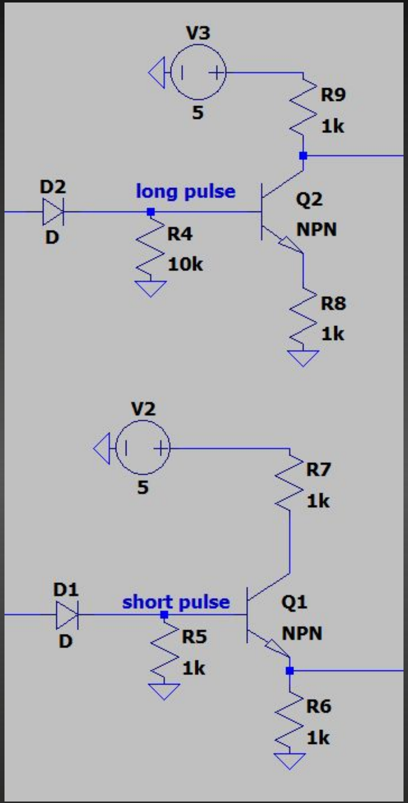


Fig. Excitatory action potential simulation





Short Pulse

Time Constant (very short):

$$\tau_{short} = R_5 C_1$$

Depolarizing spike amplitude:

$$V_{dep} \approx I_C R_7$$

Long Pulse

Time Constant (long):

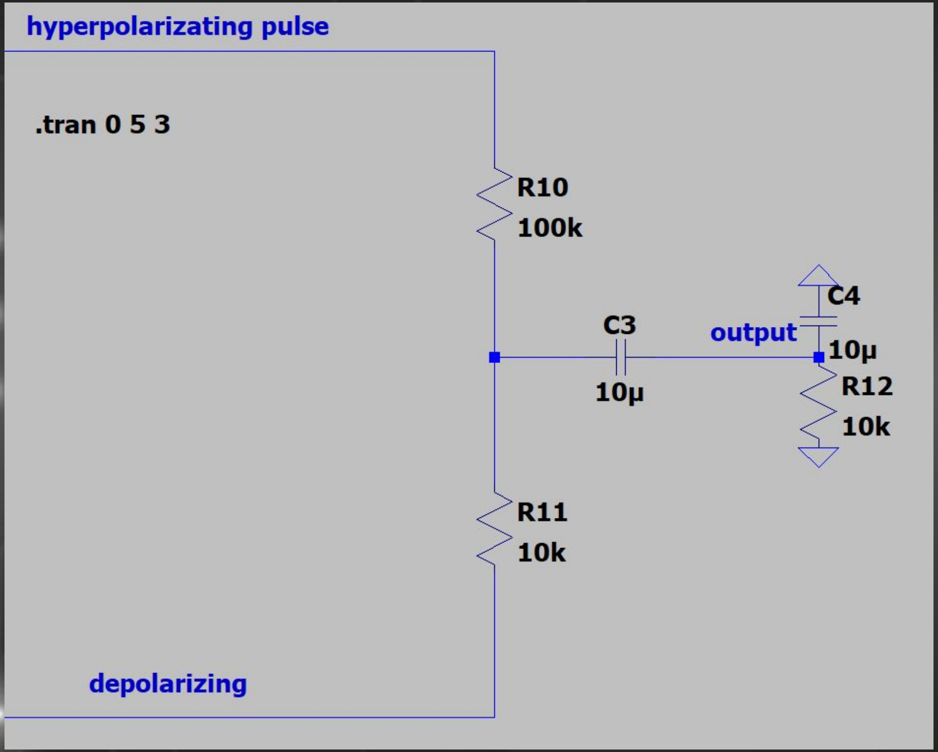
$$\tau_{long} = R_4 C_2$$

Hyperpolarization tail:

$$V_{hyp}(t) = V_{C0} e^{-t/\tau_{long}}$$

For a step ΔV at input: $I_C(t) = C\frac{dV}{dt} \approx \frac{\Delta V}{\Delta t}$

Voltage at the node after the capacitor: $V(t) = \Delta V e^{-t/(RC)}$



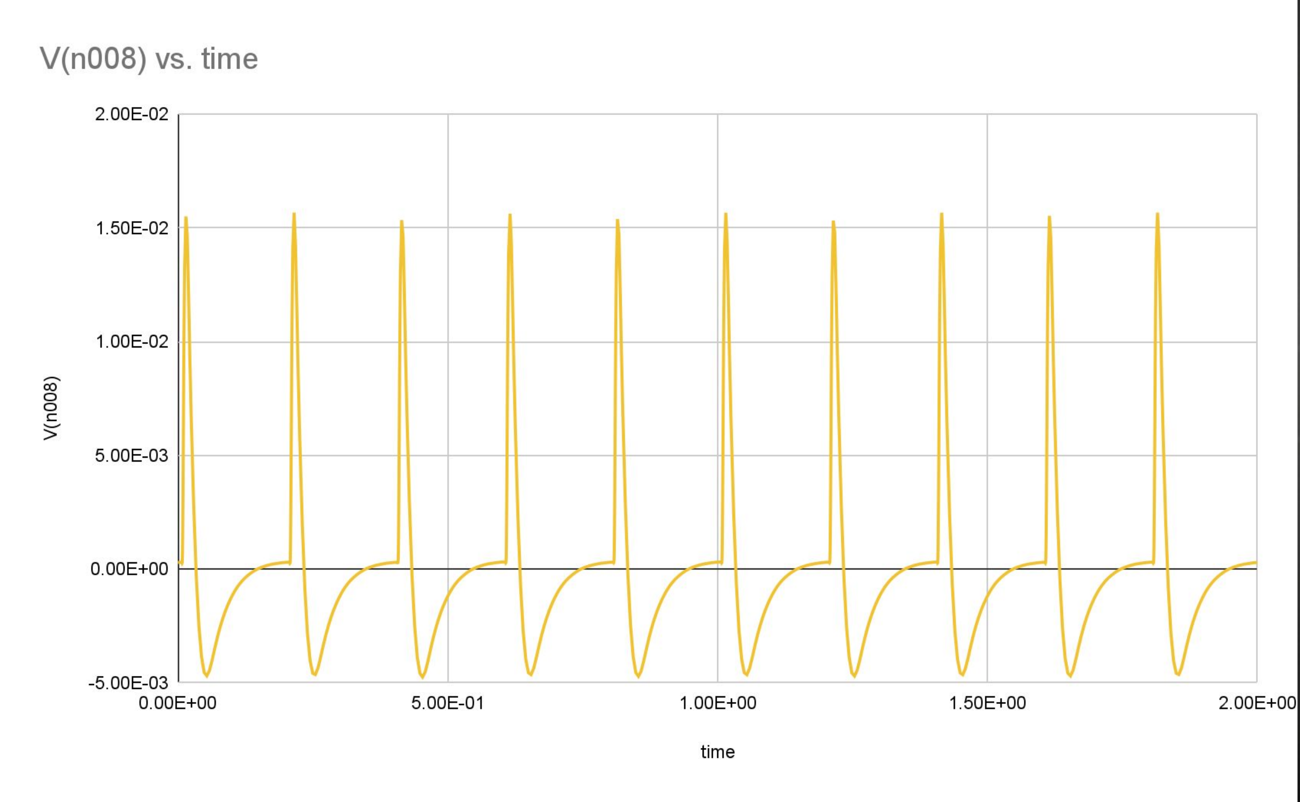
Superposition at summing node:

$$V_{sum}(t) = \frac{R_{10}}{R_{10}+R_{11}} V_{hyp}(t) + \frac{R_{11}}{R_{10}+R_{11}} V_{dep}(t)$$

Final output (after C3-C4 high pass effect):

$$V_{out}(t) = V_{sum}(t) * e^{-t/(R_{12}C_4)}$$

Simulation Results.

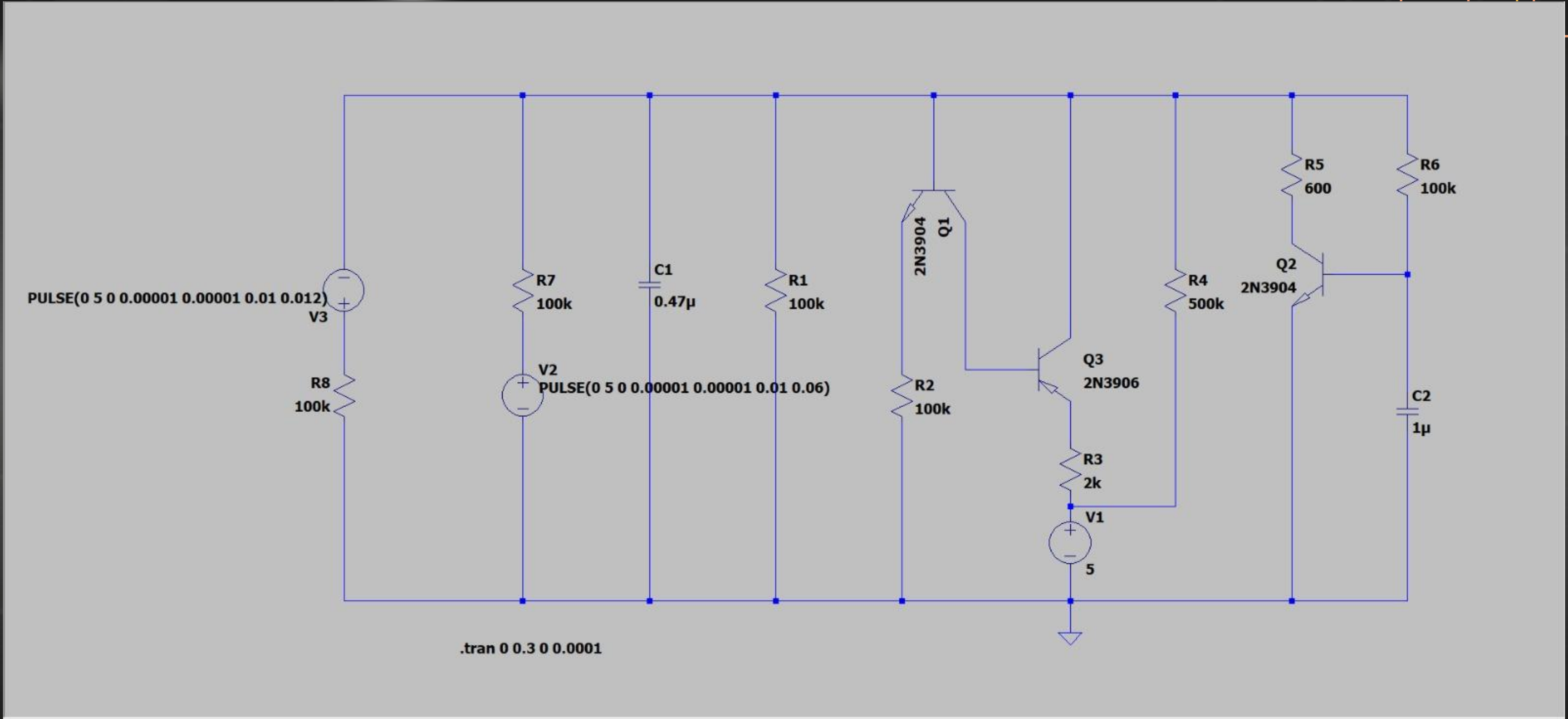


Model 4:

LTSpice Circuit for Spiking Neuron

- Membrane potential buildup
- Threshold firing
- Refractory behavior
- Slow repolarization (potassium-like current)
- Fast depolarization (sodium-like current)

Just like a real neuron, the circuit stays quiet until the input stimulus crosses a threshold — then it fires a sharp voltage spike.



PULSE(0 5 0 0.00001 0.00001 0.01 0.012)
V3
R8
100k
R7
100k
V2
PULSE(0 5 0 0.00001 0.00001 0.01 0.06)
C1
0.47µ
R1
100k
2N3904
Q1
R2
100k
Q3
2N3906
R3
2k
V1
5
R4
500k
Q2
2N3904
R5
600
R6
100k
C2
1µ
.tran 0 0.3 0 0.0001

Membrane Model

Components:

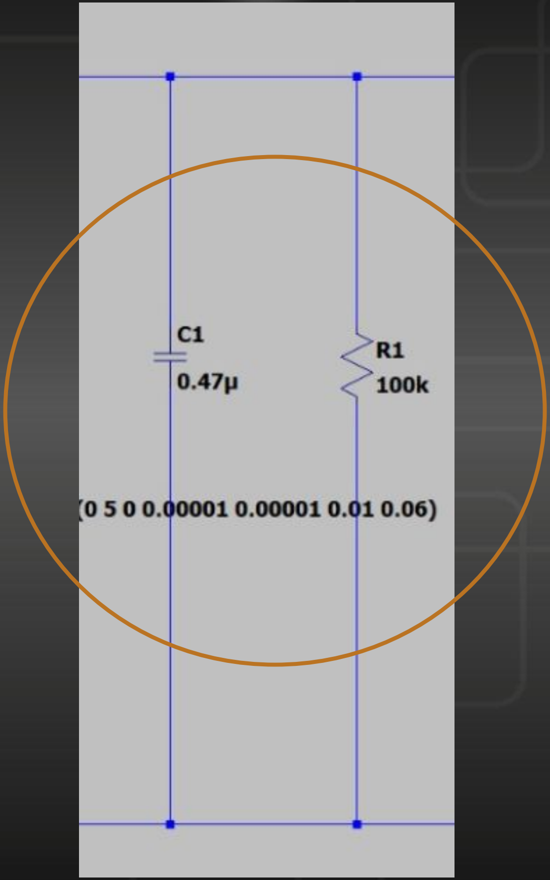
- R1 = 100k
- C1 = 0.47μF

Function:

- Represents neuron membrane.
- Voltage builds up gradually like biological membrane potential.

Equation:

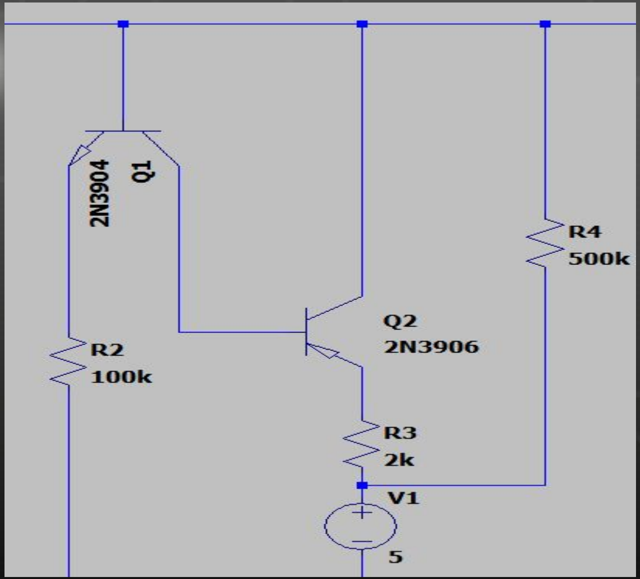
$$V_m(t) = V_{in}(1 - e^{-t/RC})$$



Sodium Channel (Depolarization) Model

Components:

- Q1, Q2 transistors
- R2, R5, R6



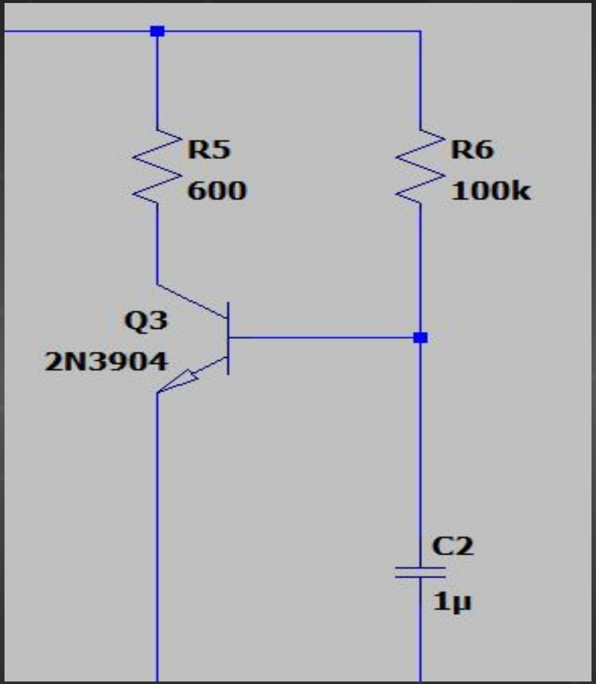
Function:

- Activates when membrane voltage crosses threshold (~0.7V).
- Produces fast depolarization spike.
- Simulates Na^+ ion influx.

$$I_{Na} = g_{Na}(V_m) \cdot (V_{Na} - V_m)$$

Transistor threshold: $$V_{th} \approx V_{BE} \approx 0.7V$$

Potassium discharge via Q3 and capacitor C2.



Potassium current: $I_K = g_K(V_{C2})(V_m - V_K)$

Activation depends on VC2 current:

$$g_K = g_{K,\max}\ if\ V_{C2} > V_{th}$$

Voltage on C2: $V_{C2}(t) = \frac{1}{C_2}\int I_{Na}dt$

This introduces spike fall and refractory behavior.

Potassium Channel (Repolarization) Model

$$C_1 \frac{dV_m}{dt} = I_{stim} - g_{Na}(V_m)(V_m - V_{Na}) - g_K(V_{C2})(V_m - V_K) - \frac{V_m}{R_1}$$

This is the hardware form of Hodgkin–Huxley equation:

$$C_m \frac{dV}{dt} = I_{ext} - I_{Na} - I_K - I_L$$

Final Hardware Form

Simulation Results