



University College Dublin
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Gamma - Frequency Resonance in
Networks of Neurons
Literature Review

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1 Introduction to Mathematical Neuroscience

1.1 Historical Background

The study of the nervous system has evolved from early theories to the sophisticated neuroscience of today. Galen, an ancient Greek physician, believed the brain acted as a gland, transmitting fluid through nerves. In the 19th century, researchers found that nerves communicate electrically, and Golgi and Ramón y Cajal produced the first detailed neuron illustrations, foundational to modern neuroscience. Harrison's work on neuron growth and pharmacologists' discovery of receptor-based drug interactions further advanced understanding.

Neuroscience has since diversified: molecular neuroscience studies neuron structures, systems neuroscience focuses on large neural networks, and cognitive neuroscience explores links between brain function and cognition. Mathematical approaches began in the 1940s with Norbert Wiener's cybernetics, which compared neural and computational processes, influencing von Neumann's work on digital computers.

A breakthrough in the 1950s by Hodgkin and Huxley introduced a quantitative model of action potentials, marking the start of mathematical neuroscience, which has since grown significantly. Neuroscience models are either empirical, focusing on input-output relationships, or mechanistic, aiming to reflect structural details. Many models span multiple scales and strive for quantitative accuracy, revealing mechanisms underlying brain behavior and advancing interdisciplinary insights into neural functions [6].

1.2 Neurons

The nervous system is divided into the peripheral and central nervous systems, both of which can be further analyzed. The neuron, as the foundational unit, serves as the starting point for studying this complex system. Neurons are specialized cells that transmit electrical signals, known as action potentials (APs), across distances, although at much slower speeds than light. Each neuron has essential parts: the soma (cell body), dendrites that receive incoming signals, and the axon, which transmits signals to other neurons.

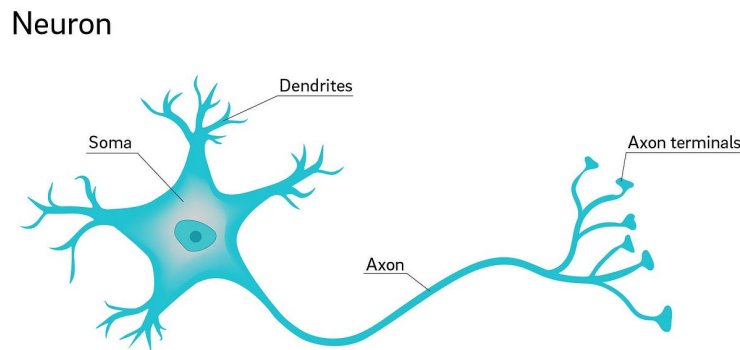


Figure 1: Neuron diagram [8].

Dendrites are tree-like extensions at the beginning of a neuron that help increase the surface area of the cell body. These tiny protrusions receive information from other neurons and transmit

electrical stimulation to the soma. Dendrites are also covered with synapses. The soma, or cell body, is where the signals from the dendrites are joined and passed on. The soma and the nucleus do not play an active role in the transmission of the neural signal. Instead, these two structures serve to maintain the cell and keep the neuron functional. The axon is the elongated fiber that extends from the cell body to the terminal endings and transmits the neural signal. The larger the diameter of the axon, the faster it transmits information. Some axons are covered with a fatty substance called myelin that acts as an insulator. These myelinated axons transmit information much faster than other neurons [2]. Axon terminals are the ends of axons which transmit messages to other cells via use of neurotransmitters at synapses [1].

There are two main types of neurons: projection neurons, which are often excitatory and carry signals long distances within the CNS or brain regions, and interneurons, which have shorter axons and usually provide inhibitory inputs. An excitatory transmitter promotes the generation of an electrical signal called an action potential in the receiving neuron, while an inhibitory transmitter prevents it [4]. Projection neurons play a key role in the brain's cognitive functions, while interneurons modulate local circuits.

Dendrites receive inputs densely (about two per micrometer), with each neuron typically having a total of 4 mm of dendritic length. Neurons can form thousands of connections, and axons themselves have about 180 synapses per millimeter on average. Human neurons vary significantly in size and shape, with the longest axons reaching over a meter in length. In total, the human brain contains roughly 100 billion neurons, connected by about 100 trillion synapses, highlighting its immense complexity.

1.3 Action Potentials

The neuron's membrane contains numerous ion channels, which are specialized pores allowing selective passage of ions like Na^+ , K^+ , Ca^{2+} , and Cl^- . These channels open or close in response to the membrane voltage (the electrical potential difference across the membrane) or external/internal signals. When the neuron is at rest, it maintains a resting potential of about -70 mV, kept stable by ion pumps that expel Na^+ ions and bring in K^+ ions. During an action potential (AP), this voltage temporarily changes by around 100 mV, lasting about a millisecond. Ions move through channels according to concentration and voltage gradients, with positive ions moving toward lower potential areas and negative ions toward higher potential. Positive current, defined as outward ion flow, hyperpolarizes the cell (makes it more negative), while negative inward current depolarizes it (makes it more positive).

Depolarization can trigger a spike if it reaches a threshold level, causing a large voltage fluctuation known as an action potential. This spike begins as Na^+ channels open, allowing Na^+ ions to rush in and raise the membrane voltage, followed by the opening of K^+ channels that permit K^+ ions to flow out, restoring the voltage below resting levels as Na^+ channels close. After a spike, a neuron enters an absolute refractory period, where it cannot spike again, followed by a relative refractory period, during which spiking is difficult but possible as ion gradients recover.

Subthreshold potentials, or minor voltage changes that don't reach spike threshold, dissipate quickly along the axon and are undetectable beyond about 1 mm from the soma. Action potentials, in contrast, regenerate along the axon and travel without losing strength. This active wave propagation, facilitated by ionic movement across the membrane, differs from passive wave transmission, such as sound waves in air or electrical currents in wires. Certain cells, like retinal bipolar cells, exhibit only non-spiking, subthreshold voltage changes [6].

1.4 Synapses

Neurons communicate through two main types of connections: chemical synapses (synapses) and electrical synapses (gap junctions). Gap junctions allow direct electrical influence between neigh-

boring cells, functioning much like electrical resistors. At a chemical synapse, an axon from the presynaptic neuron contacts a dendrite on the postsynaptic neuron. When an action potential (AP) reaches the presynaptic terminal, Ca^{2+} channels open, allowing calcium to enter. This influx triggers neurotransmitter-filled vesicles to fuse with the membrane, releasing neurotransmitters into the synaptic cleft (space after axon terminal between the next target cell [7]). These neurotransmitters bind to receptors on the postsynaptic dendritic spine, opening ion channels that generate currents. These currents either excite (depolarize) or inhibit (hyperpolarize) the postsynaptic neuron, leading to excitatory or inhibitory postsynaptic potentials (EPSPs or IPSPs), respectively [6].

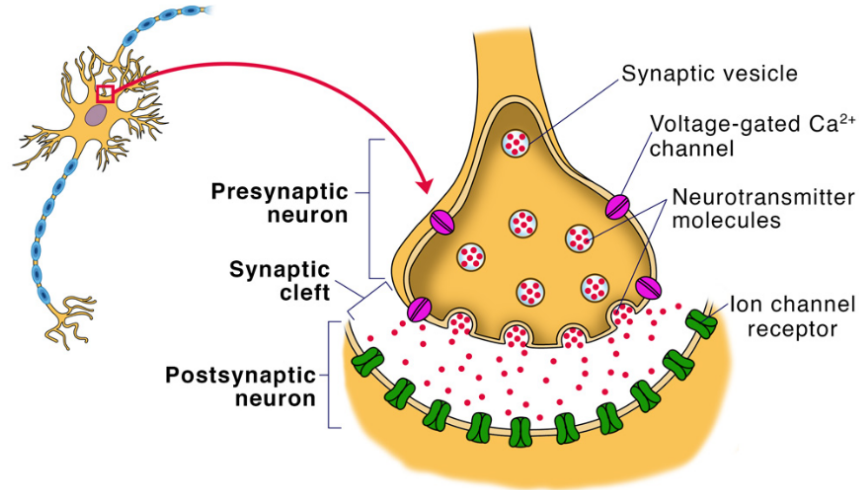


Figure 2: Synapse diagram [9].

2 Hodgkin - Huxley Model

2.1 Ions

As mentioned, neuronal electrical activity is sustained by ionic currents across the cell membrane, primarily involving sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and chloride (Cl^-) ions. Sodium, potassium, and calcium are positively charged cations, while chloride is a negatively charged anion. The different concentrations of these ions inside and outside the cell create electrochemical gradients that drive neural activity. The extracellular space is rich in Na^+ , Cl^- , and Ca^{2+} , while the intracellular space has high K^+ concentrations and negatively charged molecules (A^-).

Ion channels in the cell membrane allow selective ion flow based on these electrochemical gradients, especially for K^+ and Cl^- . This movement maintains concentration differences due to two factors:

Passive Redistribution: The impermeable intracellular anions (A^-) attract K^+ into the cell and repel Cl^- , maintaining the gradients.

Active Transport: Ion pumps, such as the Na^+ - K^+ pump, actively transport ions to uphold these gradients, moving three Na^+ ions out for every two K^+ ions brought in.

The Nernst potential describes the balance of forces driving ions across a cell membrane. Ion movement is influenced by both concentration and electrical potential gradients. For example, K^+ ions diffuse out of the cell because their concentration is higher inside than outside. As K^+ exits, it leaves behind a net net negative charge, creating an outward current and an electric potential

gradient across the membrane. This gradient slows K^+ diffusion as the positive ions are attracted back to the negative interior and repelled from the positive exterior. Eventually, an equilibrium is reached where the concentration and electric forces are balanced out, and net ion movement ceases.

The equilibrium potential for each ion is given by the Nernst equation [5]:

$$E_{\text{ion}} = \frac{RT}{zF} \ln \frac{[\text{Ion}]_{\text{out}}}{[\text{Ion}]_{\text{in}}} \quad (1)$$

where:

- $[\text{Ion}]_{\text{in}}$ and $[\text{Ion}]_{\text{out}}$ are the ion concentrations inside and outside the cell.
- R is the gas constant.
- T is the temperature in Kelvin.
- F is Faraday's constant.
- z is the ion's valence (e.g., 1 for K^+ and Na^+ , -1 for Cl^- and 2 for Ca^{2+}).

The ionic currents and conductances within neurons regulate membrane potentials and influence how signals are propagated. Membrane potential, V , is defined as the voltage difference across the cell membrane, and each ion has a corresponding Nernst potential (E_{Na} , E_{Ca} , E_K and E_{Cl}). When V equals a specific ion's equilibrium potential, its current (i.e., $I_{Na/Ca/K/Cl}$) is zero, creating no net ion movement. If V differs from an ion's equilibrium potential, the current becomes:

$$I_{Na/Ca/K/Cl} = g_{Na/Ca/K/Cl}(V - E_{Na/Ca/K/Cl}) \quad (2)$$

where $g_{Na/Ca/K/Cl}$ is the ion's conductance, acting as a driving force for ion flow.

Generally, ionic currents vary over time and are impacted by membrane voltage, neurotransmitters, and other agents, making them nonlinear. This variability enables neurons to produce action potentials, or spikes, as conductances change dynamically.

Neurons are often represented by an equivalent circuit model. Here, the total current I across the membrane consists of the membrane capacitive current and the sum of ionic currents:

$$I = C \frac{dV}{dt} + I_{Na} + I_{Ca} + I_K + I_{Cl} \quad (3)$$

If no external current flows into the cell, $I = 0$, and the resting membrane potential V_{rest} balances inward (e.g., I_{Na} , I_{Ca}) and outwards (e.g., I_K , I_{Cl}) currents, given by:

$$V_{\text{rest}} = \frac{g_{Na}E_{Na} + g_{Ca}E_{Ca} + g_K E_K + g_{Cl}E_{Cl}}{g_{Na} + g_{Ca} + g_K + g_{Cl}} \quad (4)$$

The term $g_{\text{inp}} = g_{Na} + g_{Ca} + g_K + g_{Cl}$ represents the total input conductance, with its reciprocal $R_{\text{inp}} = 1/g_{\text{inp}}$ defining the membrane's input resistance, which modulates the voltage response to injected currents.

At rest, potassium and chloride conductances dominate, keeping V near their equilibrium potentials. During an action potential, however, sodium or calcium conductances briefly increase, driving V closer to their respective equilibrium values. This mechanism underlies the rapid voltage changes central to neural signaling [5].

2.2 Conductances

Ionic channels are crucial components of neuronal membranes, serving as transmembrane proteins with aqueous pores that allow ions to flow according to their electrochemical gradients. These channels are gated, meaning their open or closed states can be modulated by various factors:

Membrane Potential: For instance, voltage - gated sodium (Na^+) and potassium (K^+) channels respond to changes in membrane voltage.

Intracellular Agents: Calcium - gated potassium channels (Ca^{2+} - gated) are activated by intracellular second messengers.

Extracellular Agents: Neurotransmitters and neuromodulators (like AMPA, NMDA, or GABA receptors) can influence the state of the channels.

Despite the stochastic nature of individual channel gating, the collective behaviour of a large population of identical channels can be captured by the equation:

$$I = \bar{g}p(V - E) \quad (5)$$

where:

- I is the net ionic current.
- \bar{g} is the maximal conductance of the population.
- p is the average proportion of channels in the open state.
- E is the reversal potential for the current (equivalent to the Nernst equilibrium potential for selective channels).

2.2.1 Voltage - Gated Channels

Voltage-gated channels have gates sensitive to membrane potential, which can activate (open) or inactivate (close) the channel. The activation probability for Na^+ channels is denoted by m , while h represents the probability of inactivation. The proportion of open channels p can be expressed as:

$$p = m^a h^b \quad (6)$$

Here, a is the number of activation gates and b is the number of inactivation gates per channel. Channels can be partially activated ($0 < m < 1$), completely open ($m = 1$), or closed ($m = 0$). Inactivated channels have $h = 0$, while those released from inactivation have $h = 1$. Channels without activation gates result in persistent currents, while those with inactivation produce transient currents.

2.2.2 Dynamics of Activation and Inactivation

The dynamics of the activation variable m can be modeled by the first - order differential equation:

$$\dot{m} = \frac{(m_\infty(V) - m)}{\tau(V)} \quad (7)$$

- $m_\infty(V)$ is the steady - state activation function, indicating the maximum value of m at a fixed voltage.
- $\tau(V)$ is the time constant, determining how quickly m reaches its steady - state value.

The steady - state activation function typically exhibits a sigmoid shape, while $\tau(V)$ has a unimodal shape.

2.2.3 Inactivation of Transient Currents

The inactivation variable h is governed by a similar differential equation:

$$\dot{h} = \frac{(h_{\infty}(V) - h)}{\tau(V)} \quad (8)$$

Where $h_{\infty}(V)$ describes the steady - state inactivation function, which indicates the proportion of inactivation gates open at a given membrane potential.

Voltage - clamp experiments help characterize $h_{\infty}(V)$ by initially holding the membrane at a pre-step potential until the activation and inactivation variables reach steady states, followed by a step increase in voltage. This approach allows researchers to determine how inactivation depends on prior membrane potential conditions.

2.2.4 Hyperpolarization-Activated Channels

Some neuronal channels, such as hyperpolarization - activated currents (often referred to as I_h or I_{Kir}), are unique in that they open during hyperpolarization and close upon depolarization. While traditionally categorized separately, from a theoretical perspective, they can be treated similarly to transient currents that are always activated (either $a = 0$ or $m = 1$) but can be deactivated by depolarization.

2.3 Hodgkin - Huxley Equations

The Hodgkin-Huxley model is a foundational mathematical framework in neuroscience for describing how neurons generate action potentials. Developed from experimental work on the squid giant axon, this model quantifies the nonlinear interactions between membrane potential and ionic currents, and it is based on three main currents:

- **Voltage - Gated Persistent K^+ Current:** Described by an activation variable n , this current depends on four activation gates, resulting in a term n^4 in the model's equations.
- **Voltage - Gated Transient Na^+ Current:** This current has three activation gates and one inactivation gate, modeled as m^3h .
- **Leak Current (I_L):** This is an Ohmic current carried primarily by chloride ions (Cl^-).

The space clamped Hodgkin - Huxley equations describe the membrane potential V in terms of these ionic currents, accounting for their voltage - dependent conductances:

$$C \frac{dV}{dt} = I - (\bar{g}_K n^4 (V - E_K) + \bar{g}_{Na} m^3 h (V - E_{Na}) + g_L (V - E_L)) \quad (9)$$

where:

- C is the membrane capacitance.
- \bar{g}_K , \bar{g}_{Na} and g_L are the maximal conductances for K^+ , Na^+ and leak currents, respectively.
- E_K , E_{Na} and E_L are the reversal potentials for each ion type.

The dynamic variables n , m and h represent probabilities related to the gating of K^+ and Na^+ channels and are described by differential equations of the form:

$$\frac{dn}{dt} = \alpha_n(V)(1 - n) - \beta_n(V)n \quad (10)$$

$$\frac{dm}{dt} = \alpha_m(V)(1 - m) - \beta_m(V)m \quad (11)$$

$$\frac{dh}{dt} = \alpha_h(V)(1 - h) - \beta_h(V)h \quad (12)$$

Here α and β are voltage - dependent rate functions for the transitions between open and closed states of each gate. These rate functions are:

$$\alpha_n(V) = 0.01 \frac{10 - V}{\exp\left(\frac{10 - V}{10}\right) - 1}, \quad \beta_n(V) = 0.125 \exp\left(\frac{-V}{80}\right) \quad (13)$$

$$\alpha_m(V) = 0.1 \frac{25 - V}{\exp\left(\frac{25 - V}{10}\right) - 1}, \quad \beta_m(V) = 4 \exp\left(\frac{-V}{18}\right) \quad (14)$$

$$\alpha_h(V) = 0.07 \exp\left(\frac{-V}{20}\right), \quad \beta_h(V) = \frac{1}{\exp\left(\frac{30 - V}{10}\right) + 1} \quad (15)$$

In Hodgkin and Huxley's setup, the membrane potential was shifted by approximately 65 mV for convenience, resulting in equilibrium potentials of:

- $E_K = -12\text{mV}$,
- $E_{Na} = 120\text{mV}$,
- $E_L = 10.6\text{mV}$.

Typical values for maximal conductances are:

- $\bar{g}_K = 36 \text{ mS/cm}^2$
- $\bar{g}_{Na} = 120 \text{ mS/cm}^2$
- $\bar{g}_L = 0.3 \text{ mS/cm}^2$

To simplify, the original Hodgkin-Huxley equations can also be written using steady-state activation/inactivation functions and time constants:

$$\frac{dn}{dt} = \frac{n_\infty(V) - n}{\tau_n(V)} \quad (16)$$

$$\frac{dm}{dt} = \frac{m_\infty(V) - m}{\tau_m(V)} \quad (17)$$

$$\frac{dh}{dt} = \frac{h_\infty(V) - h}{\tau_h(V)} \quad (18)$$

where:

$$n_\infty(V) = \frac{\alpha_n(V)}{\alpha_n(V) + \beta_n(V)}, \quad \tau_n(V) = \frac{1}{\alpha_n(V) + \beta_n(V)} \quad (19)$$

$$m_\infty(V) = \frac{\alpha_m(V)}{\alpha_m(V) + \beta_m(V)}, \quad \tau_m(V) = \frac{1}{\alpha_m(V) + \beta_m(V)} \quad (20)$$

$$h_\infty(V) = \frac{\alpha_h(V)}{\alpha_h(V) + \beta_h(V)}, \quad \tau_h(V) = \frac{1}{\alpha_h(V) + \beta_h(V)} \quad (21)$$

These reformulated equations are advantageous because they separate steady-state behavior and dynamic response times, providing a clearer picture of how each variable approaches equilibrium.

While the Hodgkin-Huxley model was derived for the squid giant axon, it provides a generalizable framework for describing ion channel kinetics in many types of neurons. In the central nervous system, neurons may have additional currents, each with unique activation and inactivation kinetics that can be incorporated using this formalism.

In conclusion, the Hodgkin-Huxley equations effectively model the action potential's genesis and provide a rich basis for understanding the nonlinear interactions between membrane potential and ionic currents. This model remains fundamental in computational neuroscience, where it supports more complex studies of neuronal dynamics and excitability.

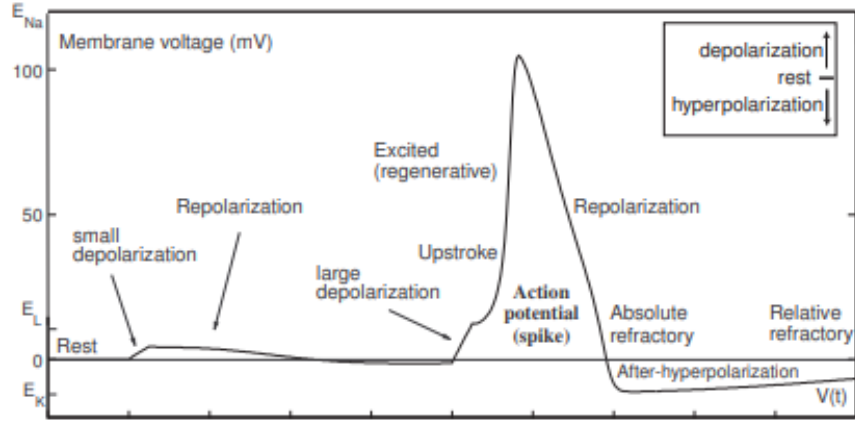


Figure 3: Action Potential in the Hodgkin - Huxley Model [5].

3 Simple Models

3.1 Integrate - and - Fire

The integrate - and - fire model simplifies neuronal dynamics by representing subthreshold behaviour with Ohmic leakage. This behaviour is captured by the differential equation:

$$C \frac{dV}{dt} = I - g_{\text{leak}}(V - E_{\text{leak}}) \quad (22)$$

where C is the membrane capacitance, g_{leak} is the leakage conductance and E_{leak} is the leakage potential. When the membrane potential V reaches a threshold E_{thresh} , the neuron is said to "fire" and V is reset to E_K .

In its rescaled form, the model can be represented as:

$$\frac{dv}{dt} = b - v, \quad \text{if } v = 1, \text{ then } v \leftarrow 0 \quad (23)$$

where v is the normalized voltage, b represents resting state, and $v = 1$ is the threshold. This model fires periodically when $b > 1$ with period $T = -\ln(1 - 1/b)$. Some of the key features of this model are as follows:

- **All - or - none spiking:** Spikes are uniform in size and duration.
- **Threshold and Refractory Period:** Clear spike threshold with a brief period of decreased excitability post - spike.

- **Class 1 Excitability:** Modulates firing rate based on input intensity.

While computationally efficient, the integrate - and - fire model lacks realistic bifurcation dynamics and spike latency, making it suitable primarily for theoretical studies rather than detailed spiking simulations.

3.2 Resonate - and - Fire

The resonant - and - fire model extends the integrate - and - fire by introducing resonant currents, adding a second variable W to denote the magnitude of such currents. This is described by:

$$C \frac{dV}{dt} = I - g_{\text{leak}}(V - E_{\text{leak}}) - W \quad (24)$$

$$\frac{dW}{dt} = \frac{V - V_{1/2}}{k} - W \quad (25)$$

If $V \geq V_{\text{thresh}}$, the neuron "fires", resetting V and W to specified values. This model can be further simplified with complex coordinates as:

$$\frac{dz}{dt} = (b + iw)z + I \quad (26)$$

where $z = x + iy$. The real part, x , is a current-like variable. It describes the dynamics of the resonant current and synaptic currents. The imaginary part, y , is a voltage-like variable. The neuron is said to fire a spike when y reaches the threshold $y = 1$ [5]. When the spike fires, z is reset to z_{reset} . Some of the key features of this model are:

- **Damped Oscillations and Rebound Spiking:** Exhibits frequency preference and post - inhibitory spiking.
- **Excitability:** Fires periodically without a directly proportional frequency response to input.

The resonant - and - fire model effectively captures resonant neuron behavior but, like the integrate - and - fire model, does not represent detailed spike waveforms, making it more suitable for mathematical analysis than for detailed neuronal simulations.

4 Izhikevich Neuron Model

The Izhikevich model is a simplified two-dimensional model that captures a neuron's subthreshold dynamics by using two main variables: a fast voltage variable and a slower recovery variable. The recovery variable generally represents the activity of potassium channels, the inactivation of sodium channels, or a combination of these. Like integrate-and-fire models, the Izhikevich model emphasizes efficiency in simulation over intricate details of spike generation.

In this model, the voltage is allowed to increase towards a defined peak. When this peak is reached, the recovery variable receives a positive current, and the voltage resets to the resting level. Mathematically, the model is represented as:

$$\frac{dV}{dt} = \frac{1}{C}(k(V - V_r)(V - V_t) - ku \cdot u + I), \quad \text{if } V \geq V_{\text{peak}} \quad (27)$$

$$\frac{du}{dt} = a[b(V - V_r) - u], \quad V \leftarrow c, \quad u \leftarrow u + d \quad (28)$$

where:

- k represents the neuron's rheobase (measure of membrane potential excitability [10]),
- b is associated with input resistance,
- a is the time constant of recovery, and
- ku scales the recovery variable u .

The value of b influences how the recovery variable affects neuron behavior. For $b < 0$, the neuron responds to depolarizing currents with an increase in membrane potential. Positive b values can also cause spiking but typically require a stronger input current [3].

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