Spiking Scallop: A Neuromorphic Model for Directional Sensing and Response in Biological Systems

Adam Gottesman
Imperial College London
adam.gottesman24@imperial.ac.uk

This abstract presents Spiking Scallop, an interactive neuromorphic system that attempts to mimic the directional sensing and responsive behaviours observed in biological organisms. The model leverages interconnected Neuron PCBs, each embodying the leaky integrate-and-fire (LIF) neuron model with tuneable parameters, enabling real-time demonstration of neuronal dynamics through event-driven computation.

The design allows manual adjustment of neuronal characteristics, including membrane leakage voltage (V_{leak}), synaptic weights (τ_{syn}, W), membrane time constants (τ_{mem}), and input types (excitatory or inhibitory, S_{sign}), thus providing substantial flexibility in configuring neural response patterns.

Directional sensing is achieved through multiple sensory modules, each equipped with a photosensor representing an “eye”. Each sensory module incorporates a bio-inspired latch structure termed “bio-latch” combined with a Winner-Take-All (WTA) network to determine dominance among activated sensors. Simultaneous activation of multiple eyes results in coupling between the WTA mechanism and the bio-latch subsystem. This coupling leads to the generation of Central Pattern Generators (CPGs), enabling rhythmic neuronal dynamics similar to those observed in biological systems.

Spiking Scallop serves primarily as an educational tool, implemented as a large-scale (1.7 m × 1.7 m) interactive installation. Each photosensor-driven sensory module visually indicates neuronal voltage levels via LEDs, intuitively illustrating neuromorphic principles and making complex neural dynamics accessible to users. Figure 1 presents the detailed block diagram of a single sensory module, showing the bio-latch structure, the Winner-Take-All (WTA) mechanism, and their interaction. These components are described in the subsequent sections.

1 LIF Model

The neuronal voltage dynamics within Spiking Scallop are governed by the LIF equation:

$$\tau_{mem}\frac{dV(t)}{dt} = -(V(t) - V_{leak}) + R_m I(t)\sum_{i=1}^{3} S_{sign,i}W_i$$

where τ_{mem}, V_{leak}, $S_{sign,i}$, and W_i are parameters directly adjustable on the Neuron PCB. The membrane potential $V(t)$ evolves until reaching a threshold voltage V_{thresh}, generating an output spike:

$$y(t) = \begin{cases} 1 & V(t) \geq V_{thresh} \\ 0 & \text{otherwise} \end{cases}, \quad V(t) \to V_{reset} \text{ immediately after } y(t) = 1$$

2 Bio-latch

Each sensory module integrates a photosensor and a bio-inspired latch structure, termed a “bio-latch”, consisting of mutually inhibiting neurons. Generally, the bio-latch subsystem can be represented compactly by the state-space equation:

$$\tau_{mem}\frac{d\mathbf{x}^{(\text{latch})}}{dt} = -(\mathbf{x}^{(\text{latch})} - \mathbf{V}_{leak}^{(\text{latch})}) + R_m\mathbf{W}^{(\text{latch})}\mathbf{y}^{(\text{latch})} + R_m\mathbf{I}^{(\text{external})}$$

Expanding explicitly, we have:

$$\mathbf{x}^{(\text{latch})} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}, \quad \mathbf{V}_{leak}^{(\text{latch})} = \begin{bmatrix} V_{leak,1} \\ V_{leak,2} \\ V_{leak,3} \end{bmatrix}, \quad \mathbf{I}^{(\text{external})} = \begin{bmatrix} I_{\text{sensor}}(t) \\ 0 \\ 0 \end{bmatrix}$$

with connectivity explicitly defined as:

$$\mathbf{W}^{(\text{latch})} = \begin{bmatrix} 0 & 0 & -W_{3\to 1} \\ W_{1\to 2} & 0 & 0 \\ 0 & -W_{2\to 3} & 0 \end{bmatrix}$$

illustrating that Neuron 1 excites Neuron 2, driving the transition into the “reactive” state, while Neuron 2 inhibits Neuron 3, effectively suppressing the “default” state. Conversely, Neuron 3 inhibits Neuron 1, enabling a return to the “default” state once sensory input ceases.

3 Winner Take All (WTA)

Directionally selective dominance among multiple eyes is enforced by a Winner-Take-All (WTA) network represented as:

$$\tau_{mem}\frac{d\mathbf{x}_k^{(\mathrm{WTA})}}{dt} = -(\mathbf{x}_k^{(\mathrm{WTA})} - \mathbf{V}_{leak}^{(\mathrm{WTA})}) + R_m\mathbf{W}^{(\mathrm{WTA})}\mathbf{y}_k^{(\mathrm{WTA})} + R_m\mathbf{I}_k^{(\mathrm{WTA})}$$

explicitly expanding as:

$$\mathbf{x}_k^{(\mathrm{WTA})} = \begin{bmatrix} V_{4,k} \\ V_{5,k} \end{bmatrix}, \quad \mathbf{V}_{leak}^{(\mathrm{WTA})} = \begin{bmatrix} V_{leak,4} \\ V_{leak,5} \end{bmatrix}, \quad \mathbf{W}^{(\mathrm{WTA})} = \begin{bmatrix} 0 & W_{4\to5} \\ 0 & 0 \end{bmatrix}, \quad \mathbf{I}_k^{(\mathrm{WTA})} = \begin{bmatrix} W_{2\to4}y_{2,k} - \sum_{j\neq k}(W_{4,j} + W_{5,j})y_{4,j} \\ 0 \end{bmatrix}$$

illustrating that within each sensory module, Neuron 4 excites Neuron 5, while both Neurons 4 and 5 inhibit Neuron 4 in adjacent modules. Crucially, once photosensor input ceases, the directional sensing mechanism remains latched onto the last stimulated eye until another eye becomes sufficiently activated, preserving directional information.

4 Central Pattern Generators (CPGs)

Simultaneous activation of multiple eyes couples the bio-latch and WTA mechanisms, generating Central Pattern Generators (CPGs). This coupled interaction can generally be represented as:

$$\tau\frac{d\mathbf{X}}{dt} = -(\mathbf{X} - \mathbf{V}_{leak}) + R_m\mathbf{W}\mathbf{Y} + R_m\mathbf{I}(t)$$

Explicitly expanded:

$$\mathbf{X} = \begin{bmatrix} \mathbf{x}^{(\mathrm{latch})} \\ \mathbf{x}^{(\mathrm{WTA})} \end{bmatrix}, \quad \mathbf{V}_{leak} = \begin{bmatrix} \mathbf{V}_{leak}^{(\mathrm{latch})} \\ \mathbf{V}_{leak}^{(\mathrm{WTA})} \end{bmatrix}, \quad \mathbf{W} = \begin{bmatrix} \mathbf{W}^{(\mathrm{latch})} & \mathbf{0} \\ \mathbf{W}^{(\mathrm{coupling})} & \mathbf{W}^{(\mathrm{WTA})} \end{bmatrix}, \quad \mathbf{I}(t) = \begin{bmatrix} \mathbf{I}^{(\mathrm{external})} \\ \mathbf{I}^{(\mathrm{WTA})} \end{bmatrix}$$

Here, $\mathbf{W}^{(\mathrm{coupling})}$ captures the coupling between bio-latch neurons (specifically Neuron 2) and WTA neurons (specifically Neuron 4), leading to emergent rhythmic neuronal dynamics typical of biological CPGs.

Spiking Scallop demonstrates how neuromorphic hardware can mimic biological sensing and responses. While the system can be described precisely by coupled state-space equations, its primary goal is educational: by visualising neuronal interactions through an interactive network of Neuron PCBs, it provides an engaging way for students to explore and develop intuition about neural dynamics and neuromorphic systems.

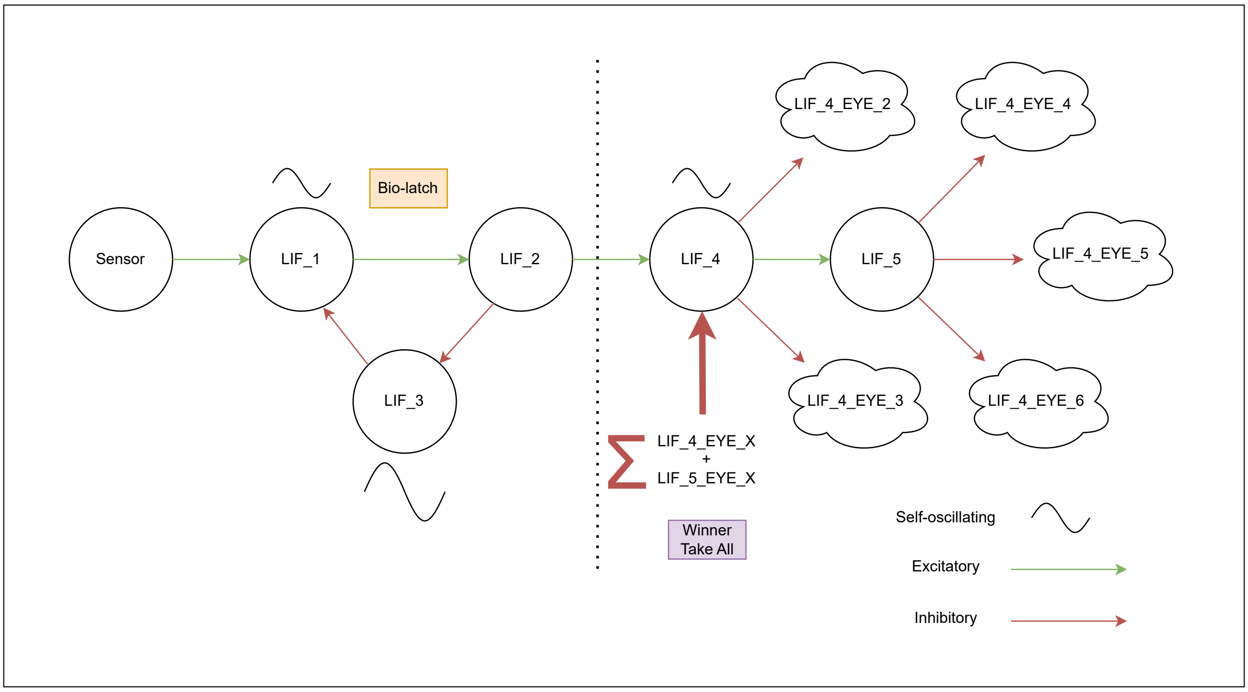

Figure 1: Block diagram of a single sensory module.