

From Astrocytes to Novel Algorithms: Multiplexed Gradient Descent and Rhythmic Sharing

Ian Whitehouse¹, Ryan O'Loughlin^{2,3}, Noah Chongsiriwatana⁴, Bakhrom Oripov², Nick Skuda², Wolfgang Losert⁴, Bradley Hayes³, Adam McCaughan², Sonia Buckley²

¹Department of Computer Science, University of Maryland, College Park, U.S.A.; ²Physical Measurements Laboratory, National Institute of Standards and Technology (NIST), Boulder, U.S.A.; ³Department of Computer Science, University of Colorado Boulder, Boulder, U.S.A.; ⁴Department of Physics, University of Maryland, College Park, U.S.A.

Motivation: Astrocytes are essential to learning, memory, and information processing

New research shows that astrocytes play a central role in cognition as controllers of neuronal synapses [1]. Astrocytes form tripartite synapses by physically assimilating the pre- and postsynaptic neurons at the synaptic cleft. Each astrocyte bonds to between 270,000 and 2 million synapses across layers of the cortex [2].

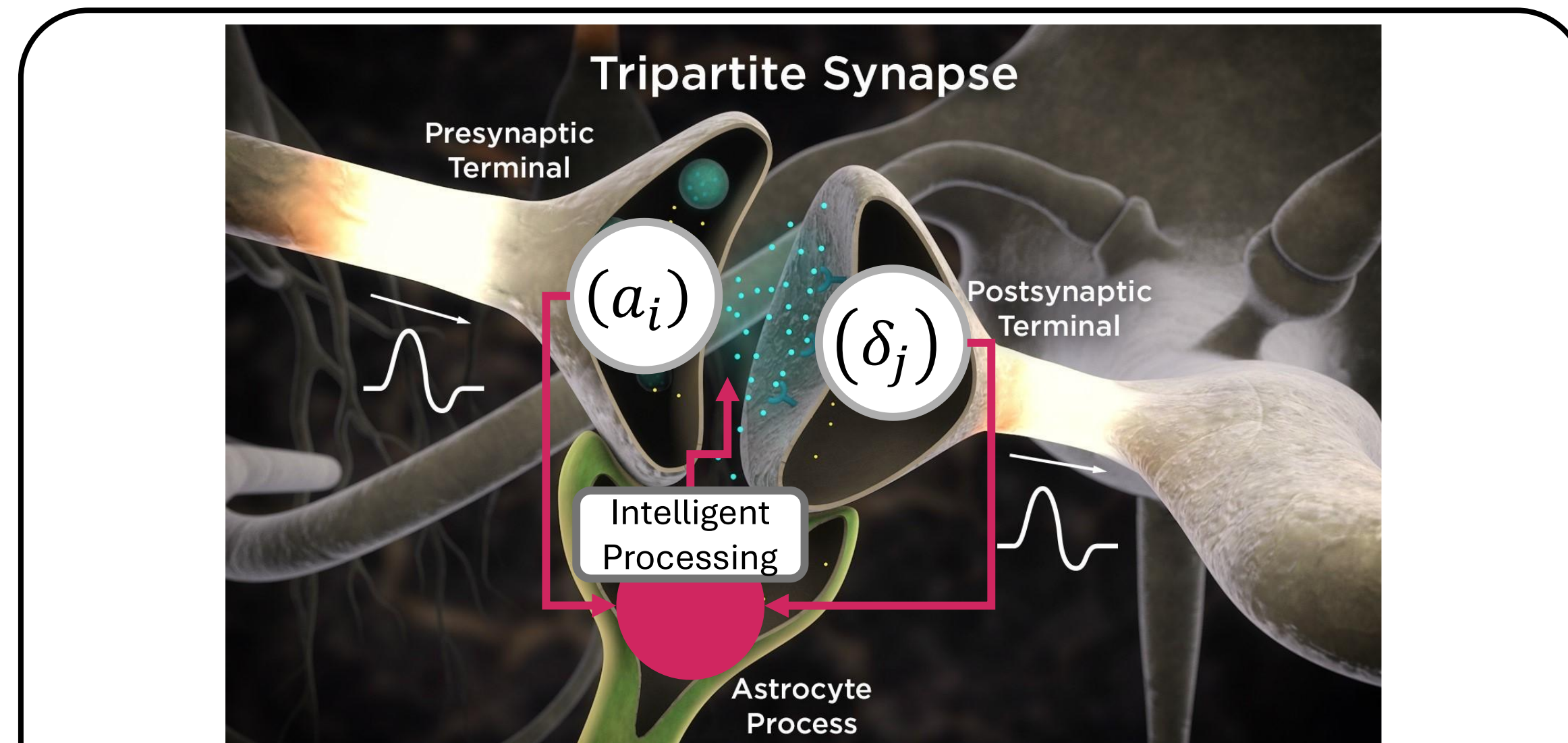


Figure 1: Diagram of a tripartite synapse between two neurons and an astrocyte, labeled with the locations of the presynaptic activations (a_i) and the postsynaptic gradients (δ_j). These are examples of local synaptic information that allow the astrocyte to modulate neuronal synapses.

When connected to synapses, astrocytes act as conductors, coordinating the neurons they connect. They use gliotransmitters and mechanical signals to modulate neurons and their links [3, 4].

Coordinating the perturbations of link strengths can intelligently aid machine learning algorithms. Astrocytes provide a plausible biological mechanism.

Here, we demonstrate two astrocyte-inspired algorithms. We believe their success can inspire future neuromorphic approaches.

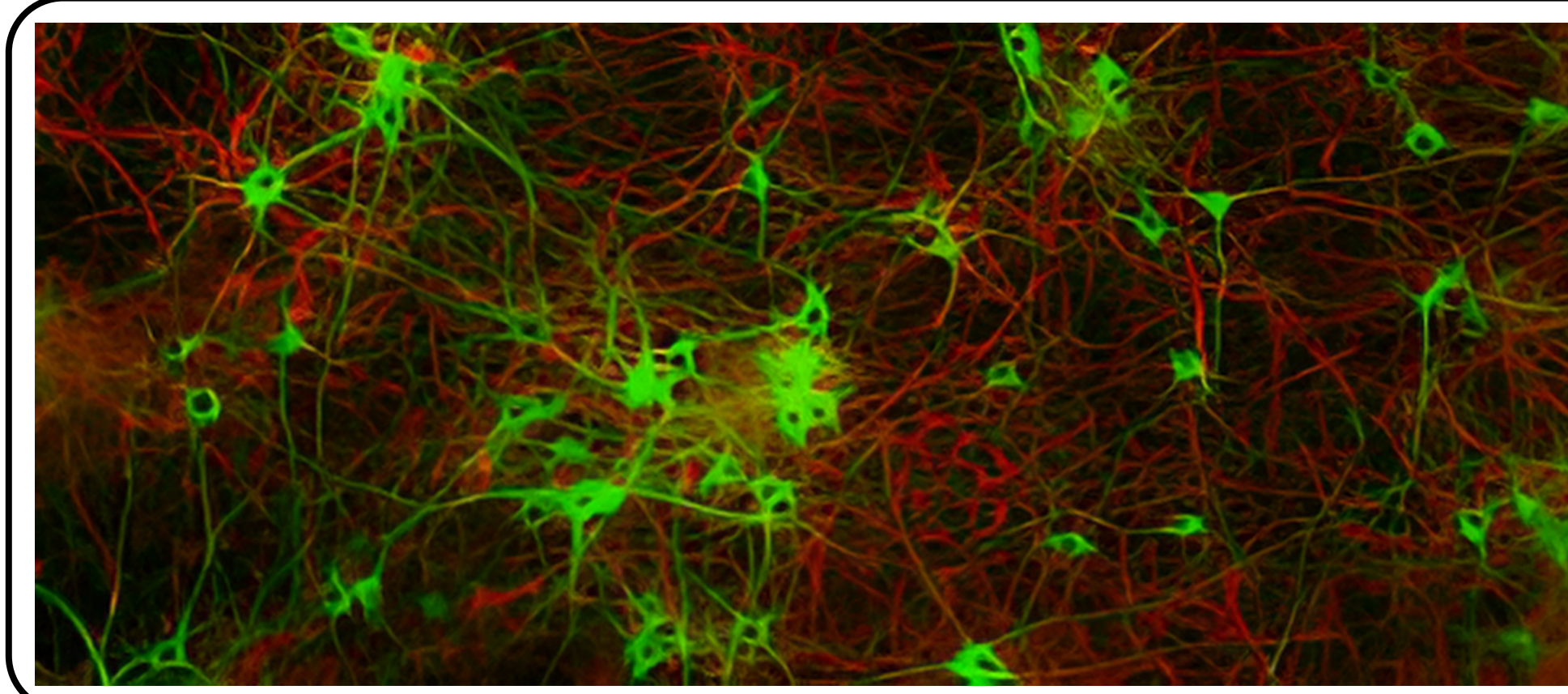


Figure 2: Stained astrocyte (red) and neuron (green) coculture. Astrocytes release and uptake neurotransmitters, providing a stable environment for the neurons. They also modulate the connections between the cells and coordinate distant cells.

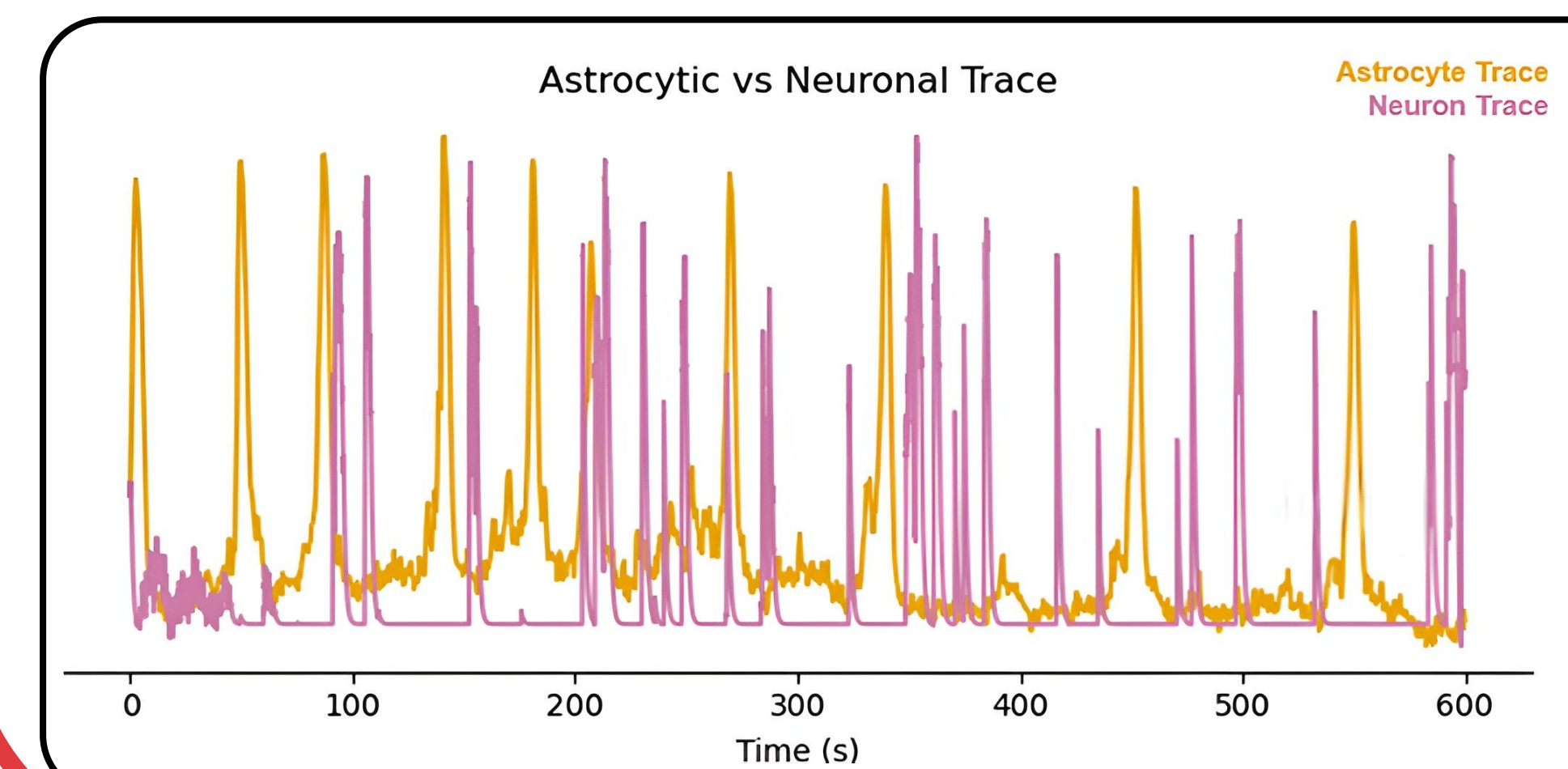


Figure 3: Calcium traces recorded from neuron (red) and astrocyte (orange) cells. The astrocytes operate on a significantly slower timescale than the neurons, allowing them to modulate the network over long time periods and providing homeostatic regulation of the brain.

δ -Multiplexed Gradient Descent Astrocyte-inspired Training for Hardware

Multiplexed Gradient Descent is a perturbative learning method by McCaughan et al. [5] that can be used as a drop-in replacement for backpropagation. δ -MGD improves on MGD by adding “astrocytes” that attach to “tripartite synapses” between artificial neurons in a neural network [6]. Using only local information, the astrocytes coordinate multiple weights to calculate intelligent perturbations.

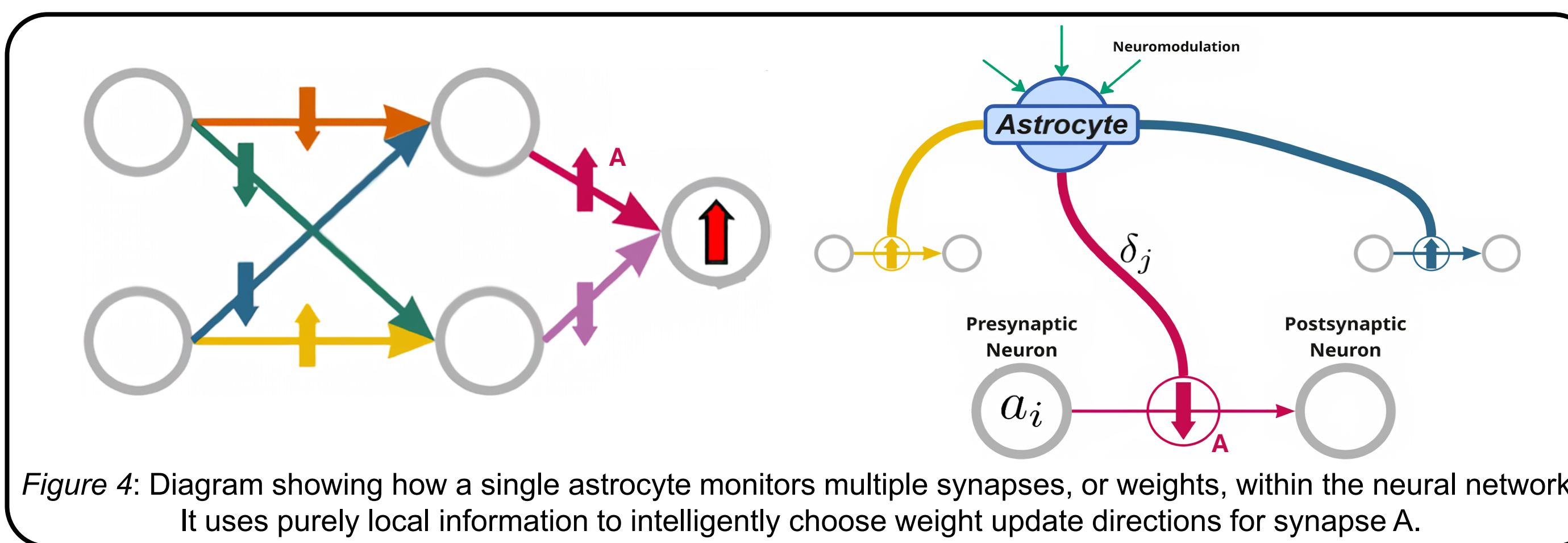


Figure 4: Diagram showing how a single astrocyte monitors multiple synapses, or weights, within the neural network. It uses purely local information to intelligently choose weight update directions for synapse A.

Astrocytes “guess” the direction of the gradient and intelligently coordinate perturbations of the synaptic weights.

δ - MGD reduces the number of calculations necessary for backpropagation-level performance. This could lead to size, weight and power reduction for machine learning model training.

Network	Dataset	BP	δ -MGD	% BP	\times Savings
Dense Net 128x128 $N_{\text{op}}=411,146$	MNIST	97.9%	97.2%	99.3%	$2 \cdot 10^5$
	Fashion	87.9%	87.2%	99.2%	$2 \cdot 10^5$
	CIFAR-10	51.9%	51.2%	98.7%	$8 \cdot 10^5$
Dense Net 1024x1024 $N_{\text{op}}=855,050$	MNIST	98.6%	98.2%	99.6%	$5 \cdot 10^5$
	Fashion	88.0%	88.8%	100.9%	$5 \cdot 10^5$
	CIFAR-10	55.2%	54.8%	98.0%	$1 \cdot 10^6$

Table 1: Across multiple datasets and models, δ -MGD achieves backpropagation-level performance with significantly fewer calculations, showing the impact of modeling astrocytes in neuromorphic systems

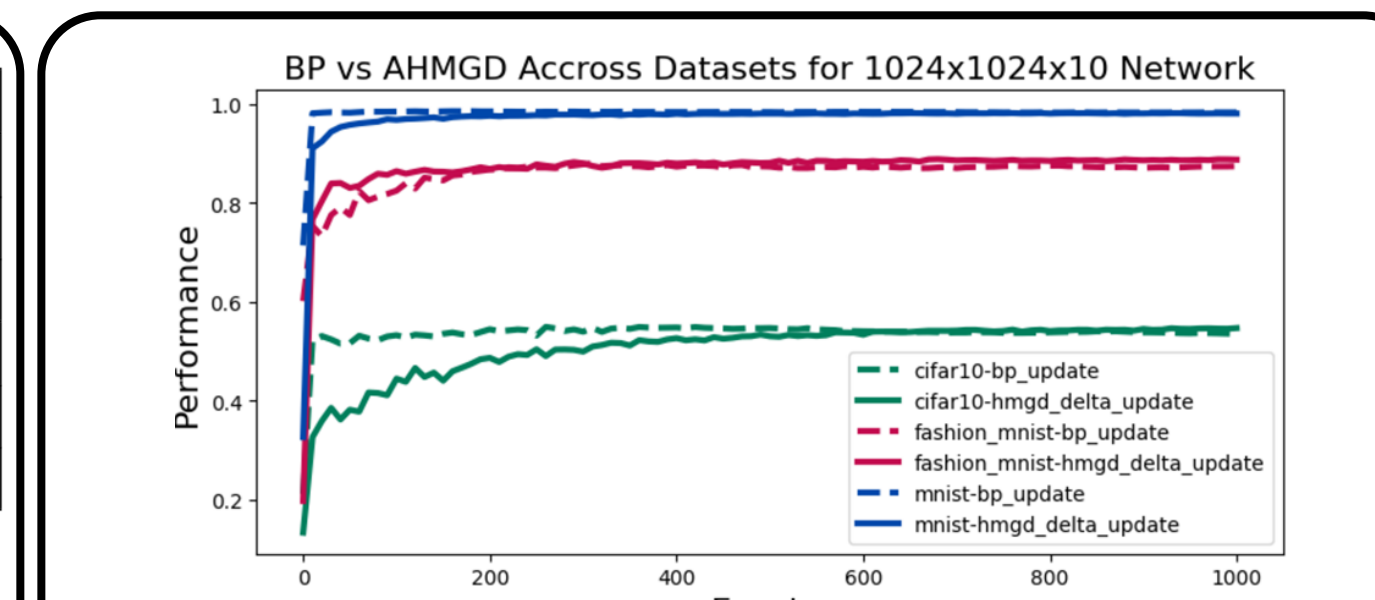


Figure 5: δ -MGD converges in relatively few epochs to the same performance as backpropagation

Rhythmic Sharing Detects and Adapts to Drifting Dynamics

The rhythmic sharing algorithm was originally proposed by Kang and Losert [7]. Built from an echo state network reservoir computer, the connections between the neurons in the reservoir have oscillating strengths, controlled by “astrocytes”. This rhythmic action is inspired by the rhythmic mechanical action seen in-vitro astrocytes [3].

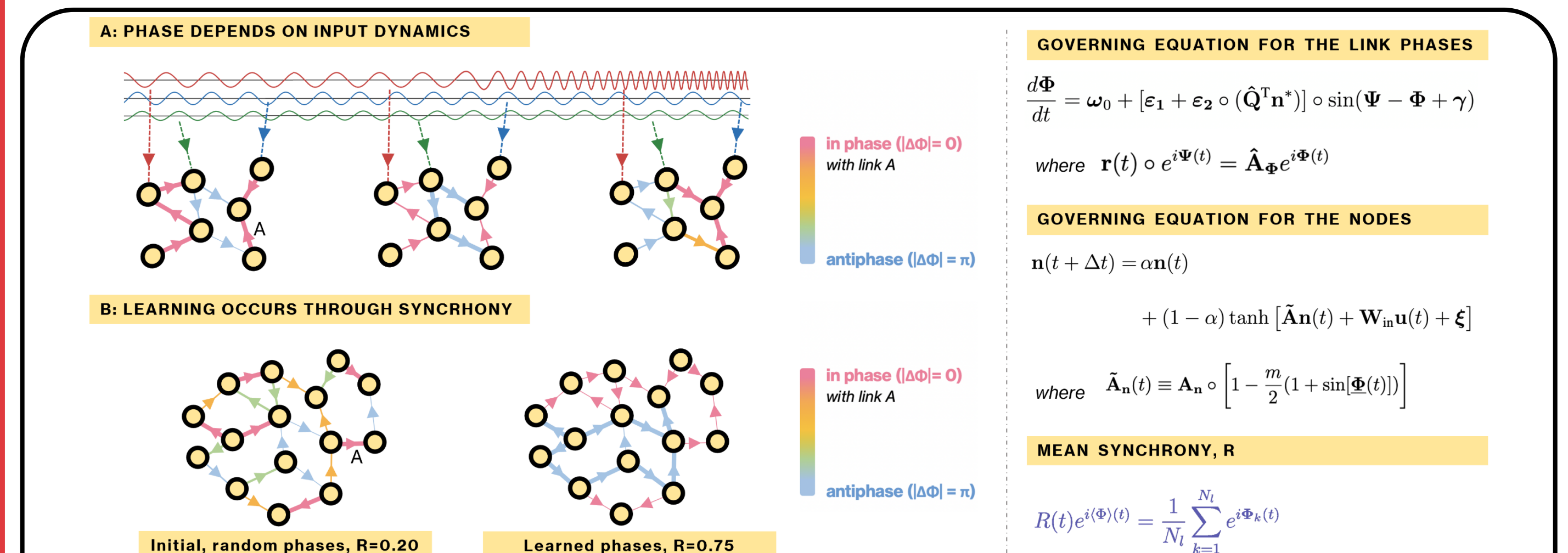


Figure 6: **A:** Instead of fixed weights, the model learns phases from the input dynamics. In this example, the model has learned two subnetworks, until the dynamics change, forcing it to change its learned phases. **B:** Synchrony is central to our learning scheme. The system starts with random phases but quickly learns new phases from the data.

Astrocytes adapt link strength, creating subnetworks within the reservoir that learn different dynamical systems.

Unlike normal reservoirs that only learn one set of dynamics, rhythmic sharing can learn and recall multiple. Link synchrony is sensitive to drifts in the input dynamics, which enhances drift detection algorithms.

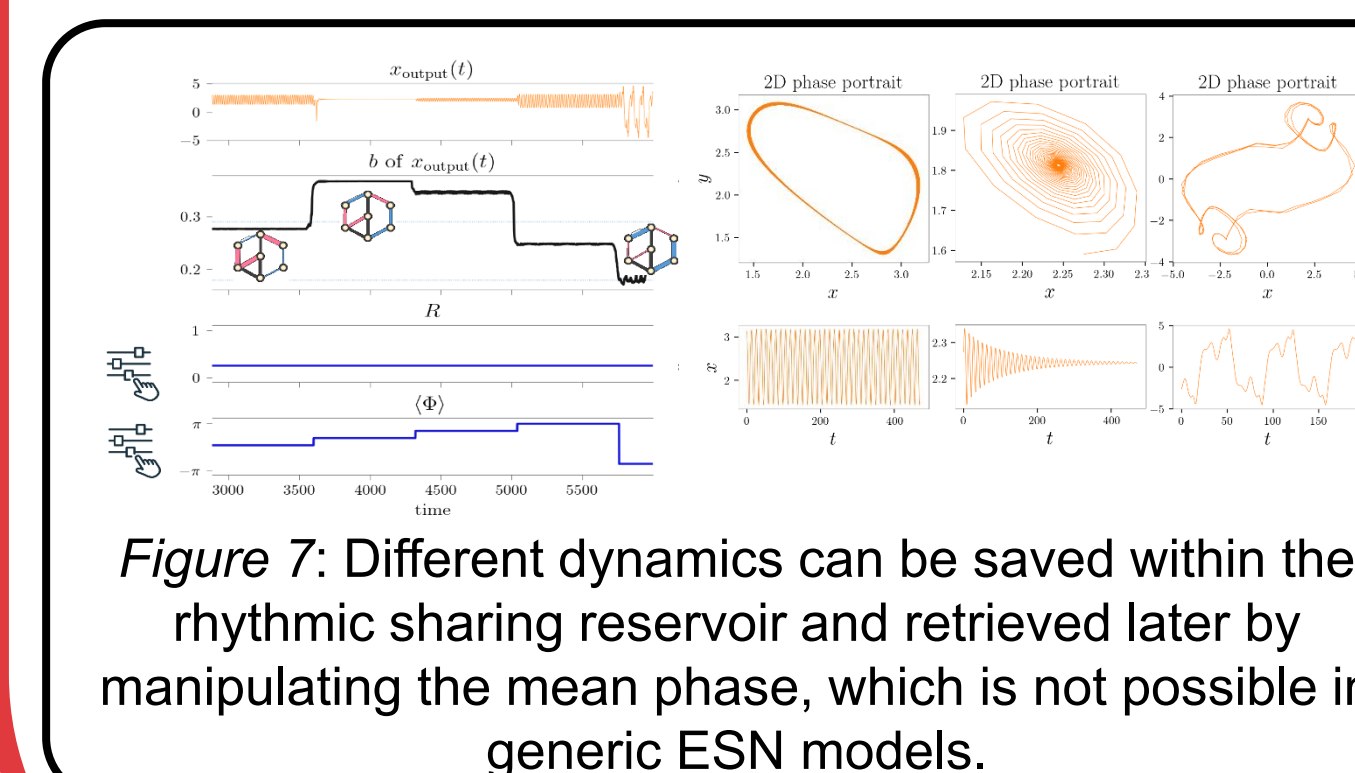


Figure 7: Different dynamics can be saved within the rhythmic sharing reservoir and retrieved later by manipulating the mean phase, which is not possible in generic ESN models.

Method	SWaT Dataset			WADI Dataset		
	Precision	Recall	F1-Score	Precision	Recall	F1-Score
DAGMM [7]	0.957	0.643	0.769	0.904	0.131	0.228
USAD [8]	0.995	0.629	0.771	0.243	0.462	0.319
BDM [9]	0.991	0.685	0.811	0.276	0.593	0.377
with RS	0.972	0.631	0.765	0.130	0.557	0.210
NSiBF [10]	0.892	0.712	0.792	0.234	0.496	0.318
with RS	0.943	0.810	0.871	0.574	0.876	0.694

Table 2: Synchrony, a feature provided by the astrocyte-inspired elements of the rhythmic sharing algorithm improves the performance of drift detection algorithms on the difficult SWaT and WADI datasets, leading to new SOTA results.

Conclusions

The two representative algorithms highlight the role of astrocytes in living neuronal networks and how they can be used in neuromorphic computing. δ -MGD shows that adding biologically-plausible astrocytes allows for backpropagation-level performance despite fewer computations when optimizing neural network weights, while rhythmic sharing demonstrates that astrocyte-inspired link oscillation organizes reservoir dynamics into distinct paths, unlocking new abilities for the network. Looking forward, biological research makes it clear that additional integration of astrocytes in neuromorphic algorithms and hardware will enable many of the features that makes the brain so powerful.

Acknowledgements and Declarations

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