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

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***Abstract*—Astrocytes are glia cells that were previously believed to play a maintenance role within the brain; however, new research proposes that they play a central role in cognition. Potential mechanisms for how they control neuronal synapses are explored in two algorithms. The first, Multiplexed Gradient Descent, uses zero-order optimization to optimize model weights, potentially like how astrocytes control the strength of synapses. The second, Rhythmic Sharing, uses controlled, astrocyte-inspired oscillations to allow a reservoir computer to learn multiple dynamical regimes and extrapolate to unseen parameters. These algorithms provide testable hypotheses about astrocytes' role in the brain, and show how neuromorphic computing offers a path towards energy-efficient, adaptable AI.**

I. Introduction

Astrocytes are glia cells that perform homeostatic maintenance within the brain, regulating the flow of neurotransmitters and water to neurons. However, recent research has proposed that they play a central role in cognition. The first work to discuss this, Araque et al., discovered the tripartite synapse, where astrocytes bond to neuronal synapses [1]. Astrocytes form tripartite synapses by physically assimilating the pre and postsynaptic neurons at the synaptic cleft. A single astrocyte may bind to between $270,000$ and 2 million synapses [2]. Since astrocytes can modulate neuronal activity via gliotransmitters, they form a rich, excitable synaptic network on top of the neuronal network. Other research suggests that astrocytes oscillate in response to external signals, inhibiting or exciting the synapses they are connected to [3].

Current deep learning approaches suffer from many problems that are solved by astrocytes and neurons in our brain. State-of-the-art deep learning algorithms are data-hungry, energy-intensive, and are unable to learn non-stationary dynamics or extrapolate to out-of-domain samples. In contrast, our brains learn from very few samples, use almost negligible power, and quickly adapt to changing, multi-timescale dynamics. This posits that continuing to look to the brain for inspiration for machine learning algorithms is a productive endeavor.

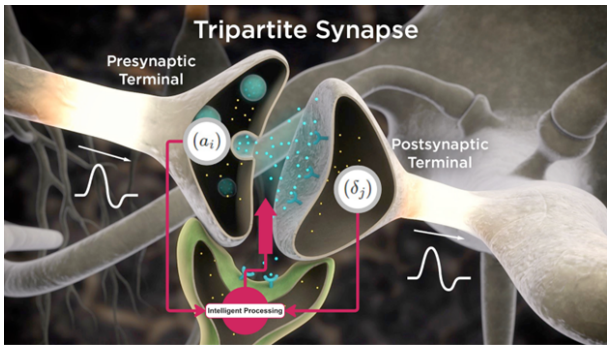

Fig. 1. Diagram of a tripartite synapse between two neurons and an astrocyte, labeled with the locations of the presynaptic activations (a_i) and the postsynaptic gradients (δ_j). These are examples of local synaptic information that may allow the astrocyte to choose "smart" perturbation directions.

II. Astrocyte-Inspired Algorithms

This presentation is an overview of two novel algorithms that attempt to bring the astrocytic governing network to machine learning systems. The first, Multiplexed Gradient Descent, is a class of algorithms for zero-order gradient calculation that perform within 1% of backpropagation and are simple and biologically plausible [4]. The second algorithm, Rhythmic Sharing, emulates the oscillatory nature of astrocytes, along with their synaptic modulation capabilities [5]. These algorithms provide hypotheses about the role of astrocytes in cognition that can be tested in in-vitro systems. Further research of biological astrocytes could provide further inspiration for similar algorithms that improve machine learning's accuracy, generalization, or efficiency.

A. Multiplexed Gradient Descent

Perturbative learning methods, like Multiplexed Gradient Descent (MGD), correlate small parameter-wise perturbations with global changes in cost to calculate a gradient. This suggests a theory that astrocytes are the mechanism for providing the modulation of synaptic weights, if the brain uses this type of learning algorithm.

Additionally, recent work shows that choosing "smart" perturbation directions can lead to significant speedup and accuracy gains over Bernoulli perturbations. These perturbations can be estimated by using per-synapse values, which are available to the astrocytes and shown in Figure 1. The synaptic update direction is then a function of these local values and a global cost/reward signals.

Since the astrocytes have access to the per-synapse values, they need access to a global cost/reward signal. Within the brain, astrocytes display an understanding of the body's state and environment. Perea et al. shows that astrocytes respond to physical stimulation of a mouse's whiskers or to it running, and O'Neil et al. shows they respond to chemical signals [6], [3]. They may use this information to intelligently strengthen or weaken synapses, and Vasile et al. discusses how different types of astrocytes control both local and global neuronal collaboration [2].

B. Rhythmic Sharing

Proposed by Kang and Losert, Rhythmic Sharing is a reservoir computing scheme where the links between reservoir nodes are endowed with astrocyte-inspired oscillations [5]. The phases of these oscillations are modulated by a group-informed subnetwork, which represents astrocytes. In testing, we find that this allows the same readout network to represent an output system with changing hyperparameters, something that normal reservoir are brittle to. The astrocytic elements allow this by choosing different levels of phase separate for different parameters.

$$\frac{d\Phi}{dt} = \omega_0 + \left(\epsilon_1 + \epsilon_2 \hat{Q}^T n^*\right) \circ \sin\left(\Psi - \Phi + \gamma\right) \qquad (1)$$

Equation 1 governs this modulation, and depends on a given link's mean field and the link's activation at the time, in the style of a Kuramoto model [7]. This implies that the link is modulated by both the synaptic activation, as well as the synchronization of the coupled astrocytic subnetwork.

The astrocyte-like mean field and synaptic modulation in the Rhythmic Sharing algorithm allows for different signal pathways in the network based on different input dynamical states. By having many possible neuronal network states, the emergent link synchronization can be observed and used to characterize the parameter space of the input dynamics, even if said parameters are not explicitly given to the network.

III. Conclusions and Future Work

This presentation discusses two complementary neuromorphic learning schemes inspired by in-vitro astrocyte dynamics. New biological results have shown that astrocytes play a active role within cognition, motivating our decision to apply theories of their mechanisms to artificial intelligence. Multiplexed Gradient Descent (MGD) shows that biologically-plausible mechanisms allow for near-backpropagation performance when optimizing weights, similarly to how astrocytes respond to chemical signals. Rhythmic Sharing demonstrates

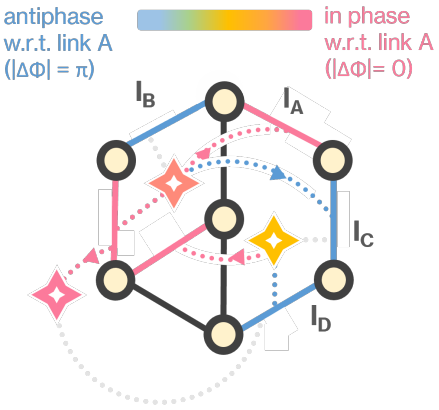

Fig. 2. Diagram showing how astrocytes coordinate the link dynamics in the Rhythmic Sharing algorithm. In the image, the nodes (circles) are connected by oscillating links. The astrocytes (stars) control the phases of the links, making some links oscillate in phase with each other.

that astrocyte-inspired link oscillation organizes reservoir dynamics into distinct paths that capture multiple dynamic regimes and allow extrapolation to unseen parameters.

Looking forward, there are several promising directions. In machine learning, integrating the two algorithms may yield systems that learn both efficiently and with sparse supervision, adapting to non-stationary environments. In hardware, astrocyte-inspired perturbation units and link-phase controllers are natural candidates for neuromorphic implementations of these algorithms. Finally, the results suggest testable hypotheses of the computational role of astrocytes as governors of neural cognition. By closing the loop between these experiments and algorithm design, astrocyte-based learning can advance AI efficiency and robustness while also clarifying the computational significance of glia in the brain.

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