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Applicant for a PhD in Neurobiology and Behavior

Research Motivation

I am captivated by the open challenges in machine learning that biology evolved to solve. Backpropagation can be inefficient due to global error signals while static architectures seem to lack the plasticity to prevent catastrophic forgetting. This rigidity in vision models appears to cause poor generalizability and vulnerability to adversarial attacks. Such fragilities in complex tasks can create intractable exploration spaces and unscalable communication. **I am motivated to research how integrating the principles of computation from biological substrates may reduce these limitations**.

Selected Research Experiences

My research with Drs. Hanna, Sala, and Berland has resulted in **eight first-author full-length papers: five peer-reviewed publications in NeurIPS** workshops (four in archival proceedings), one in NSF BRAID, and two preprints under review.

World Models for MARL. My research began with exploring bio-inspired multi-agent reinforcement learning (MARL), contributing to my team's **first-place finish at RoboCup**, the international MARL robotics competition. Leading a group investigating inter-agent communication, we found that an emergent strategy, inspired by signaling in simple organisms, collapsed to 12.2% success at task allocation with partial observability despite stabilization. Pivoting to experiment with a **world-model based approach** improved to 96.5% success, revealing the value of an agent internally simulating the environment. This taught me to remain open to unexpected results and shift focus based on data.

Active Inference & Structural Plasticity. Inspired by theories of intelligence like the free energy principle and Dr. Michael Levin's work on basal cognition, I addressed the intractability of **active inference** by developing a novel approximation using **principles from RL**. After grounding this work in discussions with Dr. Josiah Hanna (RL) and Dr. Levin (biology), **Dr. Levin invited me to extend this research under his mentorship**. Without a reward, the model maintained 82% success in Cart Pole, forming a step towards computable active inference. This research strengthened my ability to navigate the intersection of theoretical biology and machine learning.

Visual-Cortex Architecture. Curious about macro-level perspectives, I led a team experimenting with **primate visual cortex architectures** for light field identification. We implemented biological features including **dual-stream processing and predictive coding**. Despite engineering challenges of integration, the model achieved 74.4% accuracy, outperformed the next-best by 2.3 percentage points while being 2.5 times smaller, and demonstrated the value of inductive bias through geometric neuroscience. I learned to manage complex component interactions essential to building brain-inspired systems.

Industry Embodied AI. Concurrently, I **lead state estimation research** at an industry AI R&D lab. State-of-the-art (SOTA) algorithms proved unsuited for our constrained hardware and low-accuracy sensors. This drove me to develop an algorithm reducing dimensionality by disentangling data manifolds. The algorithm achieved over 100x improvement in accuracy over SOTA. It is now **deployed on all company robots** and received extensive positive customer feedback. This experience taught me to navigate the entire research-to-deployment pipeline under real-world constraints.

Research Leadership and Mentoring

To create an interdisciplinary structure for this research at UW-Madison, **I founded and direct the Wisconsin Neuromorphic Computing and NeuroAI Lab**, securing formal funding, dedicated space, support from Dr. Akhilesh Jaiswal as advisor, and partnership with neuroAI startup FinalSpark. Through **nine graduate-level AI and neuroscience courses**, I gained technical foundations to lead this initiative. My role involves **mentoring 15 undergraduate researchers**, providing advice to over 100 researchers, developing research proposals, organizing biweekly workshops, and lecturing on topics like spike-timing-dependent-plasticity drawing audiences of over 100 undergraduates, graduates, and professionals.

Sample Research Extension

One fascinating direction building on my prior research investigates autonomous **emergence of state space** through predictive compression of high-dimensional sensory streams **during navigation**. While successor representations (SR) via spike timing-dependent plasticity are established, current models rely on pre-defined place cells or passive perception.

A **visual-cortex-based encoder** fuses with internal motion cues and lateral inhibition encourages self-organization of sparse place cells. Distinctly, the model navigates to **minimize expected surprise** of its SR map. This research explores if such a bio-mimetic objective **stabilizes the online emergence of predictive maps**.

How a PhD Fits My Career Goals

Researching in industry, my development process was one of empirical iteration. I realized a deeper understanding of underlying mathematical theory may yield more efficient solutions. While I have strong practical skills, **I am driven to gain the theoretical depth to more rigorously devise novel algorithms**.

My long-term objective is conducting **research within a group like DeepMind's neuroscience lab**. Conversations with the current and previous lead, Drs. Kim Stachenfeld and Matthew Botvinick, solidified a PhD as the essential path to gain the theoretical depth and research freedom required. Dr. Kim Stachenfeld further showed me that the Center for Theoretical Neuroscience at Columbia University has a fascinating combination of neuroscience and AI interests. Receiving an **invitation from Dr. Karl Friston** to present my prospective doctoral research at his theoretical neurobiology group reinforced the value of a PhD for engaging with these ideas.

Why Columbia University

I am applying to Columbia University because its unique concentration of faculty researching applications of neuroscience for AI provides the ideal environment to pursue my research goals.

My interest in the intersection of biological synaptic rules and artificial continual learning aligns closely with the work of **Dr. Larry Abbott**, especially the HebbFF framework in "Meta-Learning Synaptic Plasticity and Memory Addressing for Continual Familiarity Detection". Building on my experience in computational neuroscience and deep learning, I aim to extend this framework by investigating how these emergent addressing mechanisms generalize to recurrent architectures processing complex temporal dependencies to stabilize the stability-plasticity dilemma.

Dr. Stefano Fusi's research on representational geometry, particularly his findings in "Abstract Representations Emerge Naturally in Neural Networks Trained to Perform Multiple Tasks", are fascinating. Leveraging my background in theoretical physics, I propose extending this mechanistic explanation for how the brain achieves low-dimensional, factorized coding to engineer systems that prioritize flexible generalization. We could explore how multi-task abstraction principles scale such as to multi-step planning to enhance few-shot learning and out-of-distribution generalization.

I am captivated by **Dr. Kenneth Miller's** work on the geometric principles of biological decision-making. Applying my experience in neural geometry, I propose to mathematically formalize the manifold curvatures from "The Geometry of the Neural State Space of Decisions", in which the decision process was framed as a population trajectory along a curved, two-dimensional manifold. This formalization could then be applied to explore networks that dynamically modulate their own integration regimes based on signal uncertainty.

I am eager to bring my unique background in collaborative research and interdisciplinary curiosity to Columbia University and to contribute to its research community.