Brennen Hill - BrennenHill.com
Applicant for a PhD in Computer Science

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, outperforming 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. 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 Stanford University

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

I am captivated by Dr. **Dr. Jay McClelland's** foundational work on complementary learning systems (CLS) and mathematical cognition. Building on experience combining computational neuroscience and LLM training, I propose addressing generalization disparities in "On the generalization of language models from in-context learning and finetuning" by mapping in-context learning to the fast-learning and fine-tuning to the slow-learning processes in CLS. We could investigate if reasoning traces as interleaved replay patterns for finetuning consolidate capabilities into stable weight updates.

Fascinated by CWM's ability to concentrate scene dynamics into sparse patch tokens, I propose extending **Dr. Yamins**' work on "Understanding Physical Dynamics with Counterfactual World Modeling" for zero-shot robotic planning. Leveraging background in model-based RL, I aim to train a self-supervised action-token adapter that maps robotic end-effector velocities to CWM's patch displacements. Treating the frozen CWM predictor as a differentiable visual simulator and employing Model Predictive Control to backpropagate task objectives to optimize action sequences, we could investigate whether the visual structures CWM extracts are robust state representations.

Drawn to **Dr. Jiajun Wu**'s finding in "Range, not Independence, Drives Modularity in Biologically Inspired Representations" that rectangular support governs modularity in energy-efficient networks, I aim to extend this theory to physical scene understanding by building on experience in embodied AI. We could investigate whether the physical exclusion principle, challenging the convex hull condition required for modularity, forces mixed selectivity and if modifications to energy constraints are required to recover modular objects.

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

Statement 2: Enriching the Learning Community

My research on neuroscience-inspired intelligent systems began with the scholarly challenge of academic isolation. Professors in AI told me that researching the application of neuroscience for AI is uncommon. Noting I was the only engineer in his class, a neuroscience professor expressed a wish for research on building AI's neurons into hardware, independently envisioning neuromorphic computing, unheard of in his department. I had a passion for a field that, on my campus, did not seem to exist.

Driven by relentless curiosity, I searched for insights from textbooks and numerous papers outside of my coursework. I began to understand the active areas of research in this discipline and gain the skills required to work in them. I learned that the relevant subdisciplines were separated into distinct departments at UW-Madison, forming a systemic barrier to discovery.

In my early studies, I sought a way to connect to others with similar interests, a mentor to teach me about neuroscience-inspired AI, or collaborators to help me start conducting relevant research. Yet I found none. To spare others that same isolation, I created the community I once sought.

I founded the Wisconsin Neuromorphic Computing and NeuroAI Lab (WNCNL) to create both an interdisciplinary research hub and a learning community. I secured funding, dedicated space, support from Dr. Akhilesh Jaiswal as advisor, and an official partnership with the NeuroAI startup FinalSpark. I was delighted to see the collaborative nature of the environment: students from neuroscience explaining the biomechanics of a neuron to engineers and computer scientists explaining artificial neural networks to biologists.

To share my passion for learning and for this field, I give lectures on relevant topics and organize weekly meetings including biweekly workshops. When members run into challenges like low model performance, I give advice on how to resolve them. I also explain concepts, provide research proposals, point to relevant literature, and propose avenues for future research. For instance, explaining spiking neural networks' aptitude for sparse event-driven processing motivated one group to begin new research on meteor detection.

My work with the WNCNL demonstrates my value of building scholarly community, a value I am eager to bring to Stanford. Seeing students explain concepts from their own disciplines solidified for me that this cross-pollination is essential. I am keen to scale this model at Stanford, such as by organizing a workshop series that operationally connects findings from the Wu Tsai Neuroscience Institute with engineering challenges at the Stanford AI Lab (SAIL). This value also aligns with the mission of the Center for Mind, Brain, Computation and Technology (MBCT) where I could contribute to its mission of building tools for future generations of scientists. My lived experience of academic isolation is what drives me to mentor. Seeing that SAIL accepts undergraduates, I would actively work to give them what I lacked: a vibrant, supportive, and interdisciplinary research community from day one. At Stanford, I aim to be both a researcher and a community builder who ensures no student's passion exists in isolation.