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Biologically Plausible Computing: Navigating Energy Landscapes

Deep learning models, despite their power, lag behind the biological brain in interpretability, energy efficiency, and physical plausibility. This presentation explores the mathematical design principles of biological neural circuits -- building upon the classic concept that neural activity is fundamentally driven by cost minimization and energy landscapes.

We demonstrate a direct mathematical equivalence between the firing dynamics of recurrent neural networks and "proximal gradient descent," a novel dynamical system used to solve optimization problems. This framework provides a top-down explanation for how biological networks process information, illustrated through examples such as sparse signal reconstruction in the visual cortex and decision-making via the free energy principle. Finally, we extend these concepts to complex excitatory-inhibitory circuits, modeling neurons as players in a mathematical game. We conclude by briefly discussing how these biological insights can inspire next-generation analog and neuromorphic computing.

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Francesco Bullo is a Distinguished Professor and Mosher Chair of Mechanical Engineering at the University of California, Santa Barbara. He was previously with the University of Padova (Laurea degree, Italy), the California Institute of Technology (Ph.D. degree), and the University of Illinois at Urbana-Champaign. His research interests include contraction theory, mathematical neuroscience, and neural networks. He is the author or coauthor of Geometric Control of Mechanical Systems (Springer, 2004), Distributed Control of Robotic Networks (Princeton, 2009), Lectures on Network Systems (KDP, 2024), and Contraction Theory for Dynamical Systems (KDP, 2026). He served as IEEE CSS President and SIAG CST Chair. He is a Fellow of ASME, IEEE, IFAC, NetSci, and SIAM.