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Spatiotemporal Computation through Traveling Waves in Biological and Artificial Neural Networks

High-resolution recordings of brain activity have revealed traveling waves of neural activity. These waves travel across single regions of the brain, each of which contains a map of visual space that is created by connections both within the region and external to it. Understanding how these connections between neurons generate spatiotemporal patterns and computation, however, is difficult in nonlinear systems. To address this, we developed a complex-valued matrix formulation of the Kuramoto model that establishes explicit connections between network topology, initial conditions, and emergent wave dynamics. This framework enables systematic analysis of traveling waves via a specific set of operators, and generalizes naturally to systems with heterogeneous time delays. We have demonstrated how mathematical insights from this framework illuminate computational mechanisms in artificial neural networks, leading in our most recent work to recurrent neural networks that can perform state-of-the-art computations while also being exactly solvable. This approach opens a new avenue for graph theory and nonlinear dynamics in machine learning, by showing the possibility of computationally powerful neural networks that can also be precisely understood through tools from these branches of mathematics.