SYNCHRONIZATION AND PATTERN FORMATION IN DIRECTED HIGHER-ORDER STRUCTURES

SEMINAR

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Abstract

Many complex systems cannot be adequately described through pairwise interactions alone. In biological, social, and technological systems, collective dynamics often emerge from interactions involving several units simultaneously. Accounting for these higher-order interactions is therefore essential for understanding phenomena that conventional network models may fail to capture, including synchronization, pattern formation, and dynamical instabilities.

Hypergraphs provide a natural framework for representing such interactions by allowing a single connection—a hyperedge—to involve multiple nodes. Directed hypergraphs further encode asymmetric influence among groups of nodes. In particular, (m)-directed hypergraphs make it possible to distinguish the source and target groups participating in an interaction and thus offer a flexible mathematical representation for investigating nonlinear dynamics on directed higher-order structures.

A theoretical framework for coupled nonlinear dynamical systems defined on (m)-directed hypergraphs is introduced. Its applicability is illustrated through two paradigmatic collective phenomena. First, diffusion-driven instabilities and the emergence of Turing patterns are examined, emphasizing how directionality and higher-order topology affect the onset and spatial organization of these patterns. Second, the synchronization of Stuart–Landau oscillators is investigated, highlighting how directed higher-order interactions influence the existence and stability of coherent states. These results underscore the key role played by the interplay between nonlinear dynamics, interaction order, and structural directionality in shaping collective behavior.

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