A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

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Abstract

Unsupervised segmentation achieved through local causal states, which are built from the local causal equivalence relation over past and future lightcones. For spacetime point \( x(\tau, \xi) \), its past lightcone \( f^{-}(\tau, \xi) \) is set of all points that could possibly influence \( x(\tau, \xi) \), its future lightcone \( f^{+}(\tau, \xi) \) is set of all points which can be influenced by \( x(\tau, \xi) \). Two past lightcones are causally equivalent (belong to the same local causal state) if they have the same conditional distribution over future lightcones. A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

Local Causal States

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Figure: Homogeneous set of spatial configurations invariant under \( \Phi_{54} \). While no apparent symmetry in raw field (black and white squares above right), every other site is always white ("fixed zeros") and sites in between may be white or black ("wildcard"). This stochastic symmetry clearly displayed by the overlaid local causal states: A being the fixed zero state, and B the wildcard state. This agrees with the set of zero-wildcard configurations invariant under \( \Phi_{54} \). Stochastic symmetry gives rise to stochastic, random-walking structures. A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

Structure Segmentation Example: Rule 54

Domain of ECA 54 on left; raw domain field and overlaid local causal states in (a), invariant set of configurations in (b). Symmetries of local causal states match those of the invariant set. A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

From Cellular Automata to Climate

Since our approach is behavior-driven (data-driven), we give below a “ladder” of systems with increasingly complex behaviors, beginning with CAs and ending with climate. This allows us to isolate technical challenges and iteratively enhance our techniques. A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

Cellular Automata

Coherent structures prime behavior of interest. Most basic instantiation found in cellular automata models, which is why we start here. Correspondence between domain invariant sets gives external validation that symmetries found by local causal states are dynamically meaningful, and thus so are coherent structures. A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

Map Lattices

Lattices of iterated maps with local coupling. Largest technical challenge moving beyond CAs is handling real-valued fields. Map lattices are real-valued with CA-like behavior. Additional clustering step needed to estimate distributions over real-valued lightcones. A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

Canonical Fluid Flows

2+1 dimensions necessitated, introducing computational scaling challenges. System behavior also has clear physical meaning, so we can begin to investigate mechanistic insight. For CAs and map lattices, structures spontaneously organize from random initial conditions. For fluids and climate, structures form from external fluxes and internal dissipation, and have they more dynamic and diffuse boundaries. A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

Climate

Ultimate target goal. Everything comes together here; multiple classes of structure, realized over multiple physical fields, evolving on multiple time scales. Moving from canonical fluid flows to climate is largely a challenge of scaling, requiring fully-distributed execution on an HPC machine, with both data and model parallelism, and Python code base. With access to HPC experts from the Intel® Big Data Center and the NERSC Cori system at LBNL, we feel well-positioned to tackle these computational challenges. A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems

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