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Information Physical Complexity, Causality and Predictability across Coevolutionary Spacetimes: Theory and Hydro-Climatic Applications

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Complex System Dynamics, Causality and Predictability pose fundamental challenges even under well-defined structural stochastic-dynamic conditions where the laws of motion and system symmetries are known.

However, the edifice of complexity can be profoundly transformed by structural-functional coevolution and non-recurrent elusive mechanisms changing the very same invariants of motion that had been taken for granted. This leads to recurrence collapse and memory loss, precluding the ability of traditional stochastic-dynamic, information-theoretic and artificial intelligence approaches to provide reliable information about the non-recurrent emergence of fundamental new properties absent from the a priori kinematic geometric and statistical features.

Unveiling causal mechanisms and eliciting system dynamic predictability under such challenging conditions is not only a fundamental problem in mathematical and statistical physics, but also one of critical importance to dynamic modelling, risk assessment and decision support e.g. regarding non-recurrent critical transitions and extreme events.

In order to address these challenges, generalized metrics in non-ergodic information physics are hereby introduced for unveiling elusive dynamics, causality and predictability of complex dynamical systems undergoing far-from-equilibrium structural-functional coevolution, building from Perdigão (2017, 2018, 2020a, 2020b), Perdigão et al. (2020).

With these methodological developments at hand, hidden dynamic information is hereby brought out and explicitly quantified even beyond post-critical regime collapse, long after statistical information is lost. The added causal insights and operational predictive value are further highlighted by evaluating the new information metrics among statistically independent variables, where traditional techniques therefore find no information links. Notwithstanding the factorability of the distributions associated to the aforementioned independent variables, synergistic and redundant information are found to emerge from microphysical, event-scale codependencies in far-from-equilibrium nonlinear statistical mechanics.

The findings are illustrated to shed light onto fundamental causal mechanisms and unveil elusive dynamic predictability of non-recurrent critical transitions and extreme events across multiscale hydro-climatic problems.

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