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# Unfolding the Manifold Flavours of Causality

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The present communication provides a contribution to an overarching cross-methodological causality investigation, encompassing a methodological synergy among physical, analytical, information-theoretic and systems intelligence approaches to causal discovery and quantification in complex system dynamics. These efforts methodologically lead to the emergence of a broader causal framework, valid not only in classical recurrence-based dynamical systems, but also on the generalized information physics of non-ergodic coevolutionary spatiotemporal complexity.

This study begins with a comprehensive cross-examination of causality metrics derived from these diverse domains, by synthesizing causality insights from information theory, which enables the quantification of information flow among variables; differential geometry, which captures the curvature and structure of causal relationships; dynamical systems, which analyze the temporal evolution of systems and associated kinematic geometric properties; and fundamental physical metrics, which elucidate causal connections in the physical world from fundamental thermodynamic principles. Through this analysis, we aim to deepen our understanding of causality in complex systems, with physical process understanding and geophysical applications in mind.

Having laid out some of the key methodological flavours of causality, the present communication introduces new metrics further contributing to a broader non-Shannonian information theoretic causality pool of methods, along with additional advances on quantum thermodymamical, nonlinear statistical mechanical, differential geometric and topologic approaches on causality. Positioning ourselves in a broader nonlinear non-Gaussian non-ergodic setting to tackle far-from-equilibrium structural-functional coevolution and synergistic emergence in complex system dynamics, our derivations further contribute to a new generation of information theoretic, dynamical systems and non-equilibrium thermodynamic causality approaches, along with their synergistic articulation towards a unified framework. This brings out further cross-methodological comparability, portability and complementary insights on dealing with the intricate causality of complex multiscale far-from-equilibrium Earth system dynamic phenomena.

By unveiling manifold flavours of causality and their interconnections, this study brings out their commonalities, synergies, and further potential synergistic applications across disciplines. This interdisciplinary approach not only enhances our theoretical understanding of causality but also provides practical implications for applications in fields such as data science, network theory, and complex systems analysis, with direct relevance across the Earth system sciences and beyond.