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Operator theoretic measures of causality in linearized dynamical systems

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ABSTRACT:

Understanding cause-and-effect in complex systems is central to advancing science and engineering, yet traditional tools for quantifying causality often rely on statistical correlations that may obscure the underlying physics. In this talk, I introduce Linear Operator Causality Analysis (LOCA), a physics-based framework that extracts causal relationships directly from the governing equations of linearised dynamical systems. By leveraging the matrix exponential of these equations, LOCA captures both direct and indirect causal pathways and defines new metrics for immediate, delayed, and global causality. This operator-theoretic perspective not only bridges connections with established approaches—such as Granger causality, transfer entropy, controllability, and graph-theoretic transitive closure—but also offers improved robustness against misleading inferences caused by correlations or reduced-order truncations. Complementing this, I present a data-driven variant akin to Dynamic Mode Decomposition, enabling practical estimation of causal interactions from time-series data. I show two important results based upon these developments:

1. The widely used Proper Orthogonal Decomposition for nonlinear systems is causally suboptimal whereas Balanced Truncation is more causally optimal - it remains to be proven if Balanced Truncation is the globally causally optimal linear decomposition for nonlinear systems.
2. The widely used causality metric - Granger causality - which has been used in fields as varied as economics, market analysis, neuroscience, and climate science, is affected by correlation. With LOCA, we can show exactly how much this metric is affected by correlation.

LOCA provides a rigorous and interpretable path forward for causality analysis in nonlinear mechanics and dynamics.

BIOGRAPHY:

Dr. Ankit Srivastava is a Professor in the Mechanical, Materials, and Aerospace Engineering department at the Illinois Institute of Technology in Chicago. He received his undergraduate degree in Civil Engineering from the Indian Institute of Technology Guwahati. He has an M.S. and a PhD in Structural Engineering from the University of California San Diego (UCSD) and he did a postdoc stint with Prof. Sia Nemat-Nasser in the Mechanical and Aerospace Engineering department at UCSD. At Illinois Tech, he has held several leadership roles with the current being the chair of the University Faculty. In the past, he has received the NSF CAREER award. He serves on the editorial board of Mechanics of Materials and is also the main organizer of the longstanding Midwest Mechanics Seminar Series which has been continuously organized since 1957. His research interests are varied and includes homogenization theory, waves heterogeneous media, causality and passivity, and operator perspectives in mechanics.