Quantification of causal interactions in complex systems

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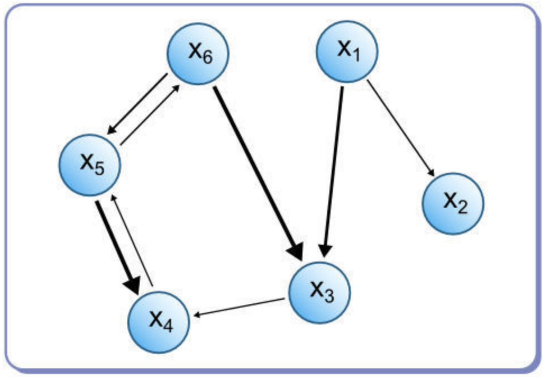
Introduction

The notion of causality has been tackled by philosophers for many centuries but only recently, several attempts have appeared to formally define causality in physical systems. One of the proposed approaches is the Wiener-Granger method for statistical analysis of causal interactions.

We provide a theoretical introduction to this method defining its basic concepts and properties. Afterwards we first use this method to analyze artificially generated time series, and later we apply this method to measure emergent behaviour in an artificial system of bird flocking.

Causality

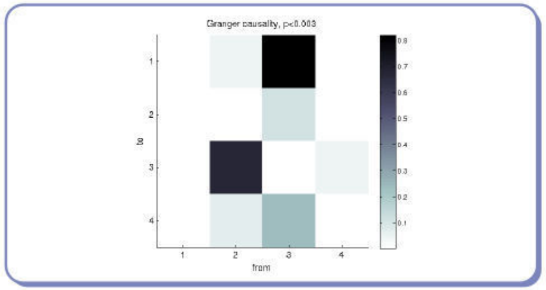
Causality can be viewed as the influence of one element on another, i.e. activity (or inactivity) of one process directly causes a shift in the behavior of another process.



Time-series analysis

Using the method of Wiener-Granger causality we proceed to reveal the underlying causal relationships between a number of processes by analyzing their individual behaviour represented by time series.

We observe a system of six processes (Figure in the left column) and attempt to assess their causal infrastructure.



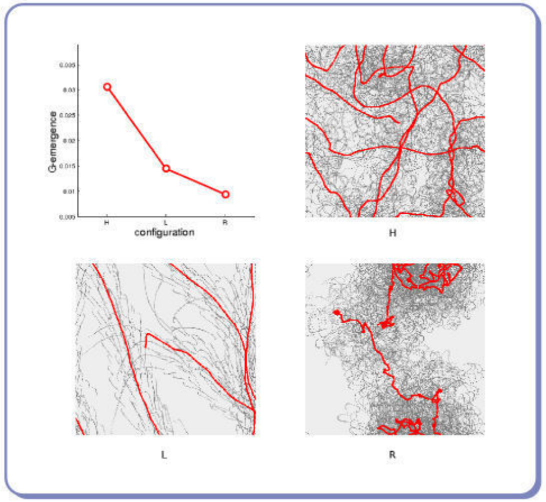
The results of our analysis can be observed in the causal matrix (a column causes a row) in the above figure. We can clearly see that the causal influences measured between the processes have been discovered correctly.

Measuring emergence

Emergence is a phenomenon which occurs when its macroscopic property arises from interactions and interdependent behavior of microscopic elements. Such a macroscopic element has a behavior on its own, yet this independent behaviour is still partly a result of its

We demonstrate that the principle behind Granger causality can be extended to quantify emergent properties of a system.

By simulating the flocking behaviour of a system of ten agents (boids), using different parameter configurations (High, Low and Random flocking behaviour), we demonstrate that our causality measure can discover a correlation between visually compelling behavior and measured emergence.



Above figure shows the trajectories of boids under different configurations. The top left part of this figure shows the comparison of the emergence measurements for the three configurations. The movement of boids is imagined by gray traces and flock's center of mass by a red line.