Quantification of causal interactions in complex systems

**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 illustrate how to apply 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 (Plots in the left column) and attempt to assess their causal interactions.

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

By calculating the flocking behaviour of a system of ten agents (Top), using different parameter configurations (High, Low and Random flocking behaviour), we demonstrate that our causality measure can discover causal relationships between causally interacting behavior and measured emergence.

**Measuring emergence**

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