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Information flow and causality within stochastic systems

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Information flow or information transfer is an important concept in general physics and dynamical systems which has applications in a wide variety of scientific disciplines. In geosciences, for example, it may be utilized for the analysis of observational time series, and for the quantification of the interaction between dynamical events, say climate modes. But prior to Liang and Kleeman (2005, PRL 95, 244101), only empirical/half empirical formalisms existed. In this study, we show that a rigorous formalism can be established in the context of a generic stochastic dynamical system. An explicit formula is obtained for the resulting transfer measure, which possesses a property of transfer asymmetry and, if the stochastic perturbation to the receiving component does not rely on the giving component, has a form the same as that for the corresponding deterministic system. This formula is further illustrated and validated with a two-dimensional Langevin equation. A remarkable observation is that, for two highly correlated time series, there could be no information transfer from one certain series, say x2, to the other (x1). That is to say, the evolution of x1 may have nothing to do with x2, even though x1 and x2 are highly correlated. Information flow analysis thus extends the traditional notion of correlation analysis and/or mutual information analysis by providing a quantitative measure of causality between dynamical events, and this quantification is based firmly on a rigorous footing.