Community Interactions: Modeling Species Interactions

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Ecosystem and Community Studies: A Dilemma

- Investigator frequently cannot even identify all interacting components (i.e., different species at different locations within system), much less have time series data on all components
- How to identify system or characterize system dynamics in the face of this uncertainty?

Surveillance Monitoring and Ecosystem/Community Studies

- View time series (e.g., of different species abundances) as sources of information and consider methods of extraction
- Conceptual underpinnings reside in methods of nonlinear dynamics and information theory
- Consider inductive inferential methods for:
  - System identification
  - Characterization of interactions among system components
  - Detection of system change and degradation

Interactions Between System Components: Dynamical Interdependence

- Data: time series of 2 different state variables
- Questions:
  - Are they functionally related?
  - What can we learn about 1 state variable by following or knowing another?
- Ecological applications:
  - Monitoring program design (indicator species, indicator locations, etc.)
  - Population synchrony and its cause(s)
  - Food web connections
  - Competitive interactions

Dynamical Interdependence from Time Series Data: Methods

- Linear systems
  - Linear cross-correlation
- Nonlinear systems
  - Attractor-based methods
    - Mutual prediction
    - Continuity tests
  - Information-theoretic
    - Mutual information
    - Transfer entropy

System Attractor

- Geometric characterization of a dynamical system
- Closed set of points in state space, such that a trajectory starting on or near attractor will converge to it

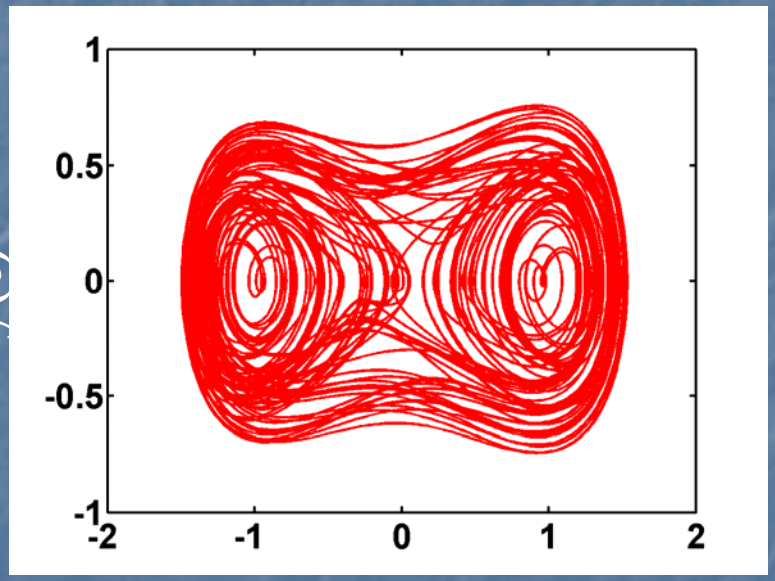
Attractor Reconstruction

- Takens' (1981) embedding theorem: trajectory of dynamical system in phase space can be reconstructed from a time series of a single state variable
- Attractor reconstruction: based on delay coordinates of state variable *x*

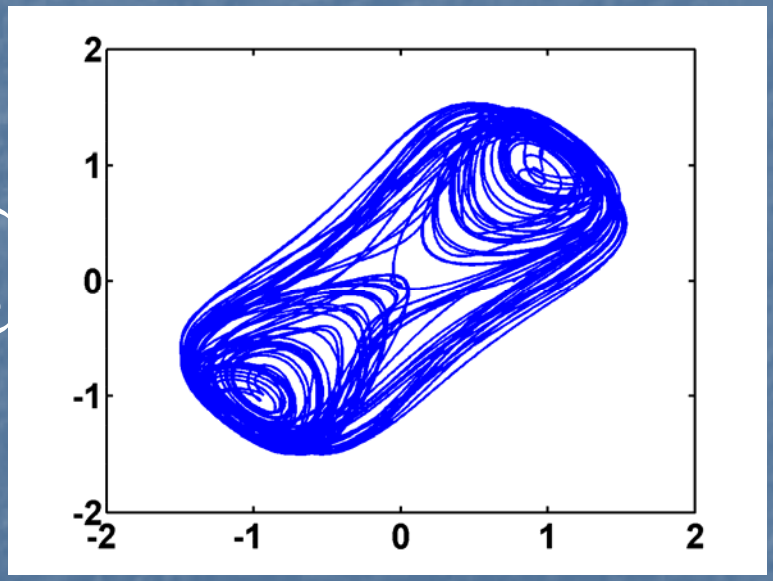
$$\underline{x}(t) = (x(t), x(t+T), \ldots x(t+[d-1]T))$$

Attractor Reconstruction

Actual attractor



Reconstructed attractor



Dynamical Interdependence: Attractor-based Methods

- If 2 state variables are dependent and belong to same system, then their attractors should exhibit similar geometries (Takens 1981)
  - (1) Continuity: focus on function relating 2 attractors
  - (2) Mutual prediction: degree to which dynamics of 1 attractor can be used to predict dynamics of the other
  - Application to ecological systems (J.M. Nichols et al. 2005, TPB)

Transfer Entropy

- Transfer Entropy (Schreiber 2000) is an information-theoretic approach that measures the degree of dependence of one system variable on another
- Transfer Entropy has recently been used to measure information flow in structural health monitoring (J.M. Nichols 2006, J.M. Nichols et al. 2006*ab*) and in model ecological systems (Moniz et al. in review *ab*)

Kullback Entropy

- Kullback entropy, K_Y, focuses on discrepancy in information between the true probability distribution, $p(y_i)$, and a different distribution, $q(y_i)$:

$$K_Y = \sum_y p(y_i) \log_2 \left(\frac{p(y_i)}{q(y_i)} \right)$$

- K_Y is the difference (excess) in average number of bits needed to encode draws of Y if $q(y_i)$ is used instead of $p(y_i)$

Transfer Entropy: Introduction

- Consider a Markov process in which value of random variable, *Y*, at any time depends on past values (*k* time units into the past)
- Consider another possible system variable, *Z*, and ask whether it is related to (contributes information about) *Y*
- Absence of information flow from *Z* to *Y*:

$$p(y_{t+1} \mid y_t^{(k)}) = p(y_{t+1} \mid y_t^{(k)}, z_t^{(l)})$$

Transfer Entropy (Schreiber 2000)

- Transfer Entropy, $T_{Z \to Y}$, measures the degree of dependence of Y on Z
- Transfer Entropy is not symmetric
  - Transfer Entropy is a Kullback entropy that focuses on the deviation of the process from the generalized Markov property

$$T_{Z \to Y} = \sum_{yz} p(y_{t+1}, y_t^{(k)}, z_t^{(l)}) \log_2 \frac{p(y_{t+1} \mid y_t^{(k)}, z_t^{(l)})}{p(y_{t+1} \mid y_t^{(k)})}$$

Dynamical Interdependence Assessment: Ecological Applications

- Surveillance monitoring strategies
  - Select species that provide the most information about a dynamical system (formal approach to defining “indicator species”)
  - Dynamical spatially distributed systems: select locations that provide the most information about the dynamical system (“indicator sites”)
- Change detection
  - Use attractor-based or information-theoretic approaches for time series before and after some intervention to infer system change from measurement of small number of system components
- Food web connections
  - Use time series data to infer community relationships and degrees of interaction (e.g., indirect inference about competition coefficients and predation coefficients)