Early-warning signals for critical transitions

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Outline

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  • Skewness and flickering before transitions
  • Indicators in cyclic and chaotic systems
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• Precursors of transitions in real systems
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  • Finance

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Introduction

• Critical transitions: abrupt shift from one state to another
  • Happen when the system pass bifurcations
  • ex. asthma attacks, market crashes, ocean circulation shift...
• Hard to predict
  • Possibly little change in state of system before tipping point
  • Models of complex systems: not accurate enough
• But: certain generic symptoms may occur in a wide class of systems approaching a critical point
• Particularly relevant are 'catastrophic bifurcations'
Introduction
Critical slowing down

- One of the most important clues as indicators for reaching a critical threshold
- In the neighborhood of a fold bifurcation points
  - The dominant eigen-value characterizing the rates of change around equilibrium becomes zero
  - System becomes increasingly slow in recovering from small perturbations
- Thus: recovery from small perturbation can be used as indicator for closeness to bifurcation point
  - Only rate of change matters: small perturbation is adequate = no risk of driving the system over the threshold
Critical slowing down

• But in natural systems
  • Impractical to monitor recovery rates
  • Presence of natural perturbations

• Important prediction:
  • Slowing down $\rightarrow$ increase in 'memory'
  • Can be measured using autocorrelation
  • Autocorrelation increases long before critical transition

• Also: increased variance
  • Because impact of shocks do not decay
Skewness and flickering

- Skewness
  - Asymmetry of fluctuations may increase before catastrophic bifurcation
  - Not a result of critical slowing down

- Flickering
  - If stochastic forcing is strong enough to switch between two alternative attractors
  - Also early-warning if underlying slow change in condition persists
  - E.g. in climatic shifts and epileptic seizures
Indicators in cyclic/chaotic systems

• Previous principles need an attractor that corresponds to a stable point (e.g. the fold catastrophe)
• In cyclic/chaotic systems: less well studied
• Different classes of bifurcations exist
  • Transitions between stable, cyclic and chaotic regimes
  • Hopf bifurcation: signaled by critical slow down
  • Non-local bifurcations: → ?
    • Possible stretched oscillations
  • Phase locking: again: look for alternative attractors
    • e.g. increased variance and flickering before epileptic seizure
Spatial patterns as early warning

- Many systems consist of coupled units
- Units tend to take states similar to neighbours
- E.g. financial markets
- Distribution of the states of the units may change in characteristics ways
- E.g. models of desert vegetation becomes characterized by regular patterns when nearing a barren state
Precursors of transitions: climate

- E.g. the greenhouse-icehouse transition 34 Myr ago
- Difficult to unveil underlying mechanisms
- Increase in autocorrelation was found in each abrupt climate change analysed
- Flickering preceded the abrupt end of the Younger Dryas cold period

...
Precursors of transitions: ecosystems

- Alternative attractors have been demonstrated in lakes
- Also suggestions that stable states separated by critical thresholds occur in all kind of ecosystems ranging from rangelands to marine systems
- Increase in variance of the population of fish stocks
- Work on early warnings is just an emerging field...
- ...
Precursors: asthma attacks and epileptic seizures

- Human lungs can display a self-organized pattern of bronchoconstriction that might be the prelude to dangerous respiratory failure → comparable with desert vegetation

- Epileptic seizures
  - Synchronous firing of neighbouring cells
  - Difficult to predict in advance
  - But
    - Change in variance of the electrical signal minutes before
    - Reduced dimensionality of the signal up to 25 minutes before
    - Mild energy bursts followed by frequent symptomless seizures → flickering behaviour
Precursors of transitions: finance

• Prediction of shifts is heavily studied
• But: discovery quickly leads to its elimination
• Therefore, they are difficult to predict
• Still, literature shows that market dynamics may contain information presaging major events
  • e.g. increased trade volatility
  • Systematic relationships in variance and 1st order autocorr.
Outlook

• Similar early-warning signals can appear in widely different systems

• But more work is needed to find out how robust these signals are in chaotic / stochastic / spatial complex systems

• False negatives
  • Sudden transition without detectable early-warning signals
    • E.g. transition caused by a rare extreme event
    • E.g. fast and permanent change of external conditions (fig a)
  • Statistical difficulty of picking up the early-warning signal
    • E.g. very long time series for detecting increased autocorr.

• Changes of external perturbation regime
Outlook

• Although many similarities across disciplines, still many challenges to overcome
  • E.g. filtering techniques for time series to increase sensitivity
    • Result depends on parameter choices in filtering
    • Need for reliable statistical procedures to test significance of increase in autocorrelation, etc.
  • Perturbations will often trigger a transition before reaching a bifurcation point
    • Exact moment of transition remains difficult to predict
    • For practical applications: sufficiently early detection required
• General early-warning signals are only one of the tools
  • E.g. repeatability of transitions