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CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

Modeling Adaptation in Complex Systems

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline of Presentation

- Brief Biographical Note
- Where this Section Fits in the Structure of the Complex Systems Course
- Complex Systems and Adaptation
- Definition of Adaptation
- Why Should You Care
- Complex Behavior as Adaptive Response
- Kinds of Adaptation
- Models Showing Adaptation
- Question & Answer Session

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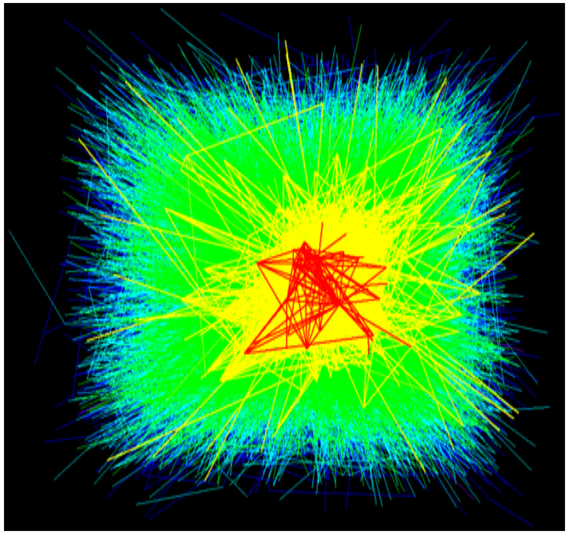
Adaptation and Complex Systems



Brief Biographical Note on Walt Beyeler

- Education:
  - BSEE from UNM

- SNL Work Experience
  - 1990s: Subsurface flow and transport modeling for GCD, WIPP; Decision analysis for directing characterization
  - 2001-current: infrastructure modeling and analysis, including
    - Applying complex systems ideas to infrastructures, especially financial systems
    - Using decision support to steer characterization

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Adaptation and Complex Systems

Focus of this session

- Fundamentals of Complex Systems [x]
- Methods
  - Modeling Techniques [x]
  - Approaches to Examining Complex Systems [x]
- Applications
  - Examples of the use of complex systems fundamentals to solve problems [ ]
  - Learning how to use complex systems ***analysis*** tools [ ]

Why are Complex Systems Interesting?

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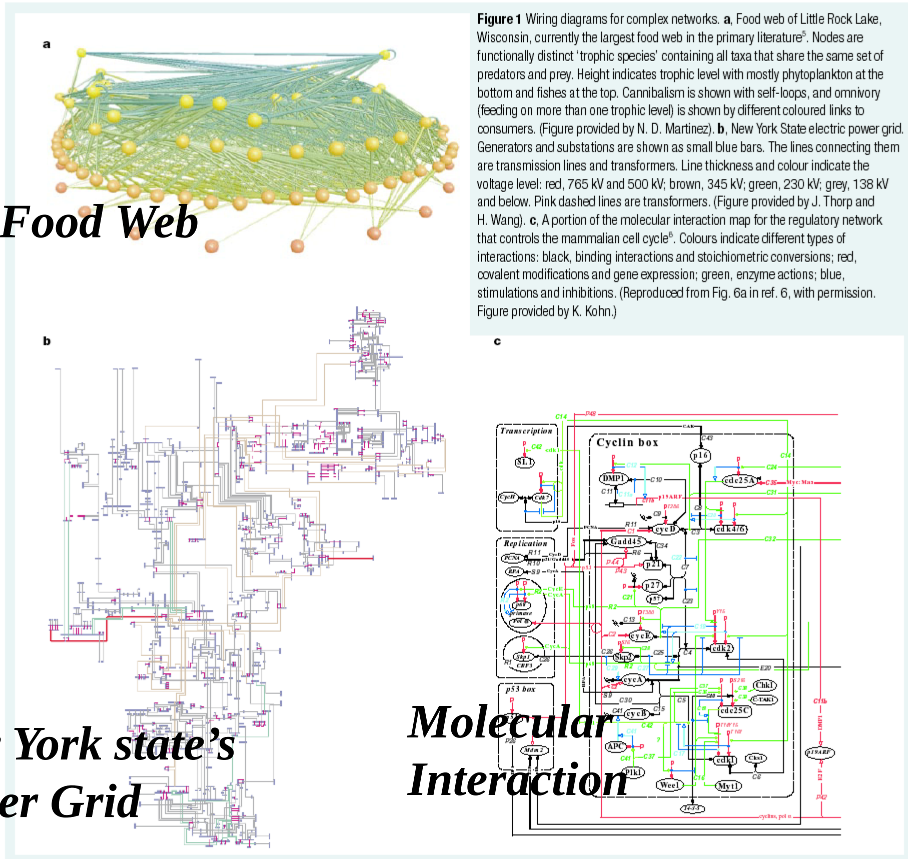


Illustrations of natural and constructed network systems from Strogatz [2001].

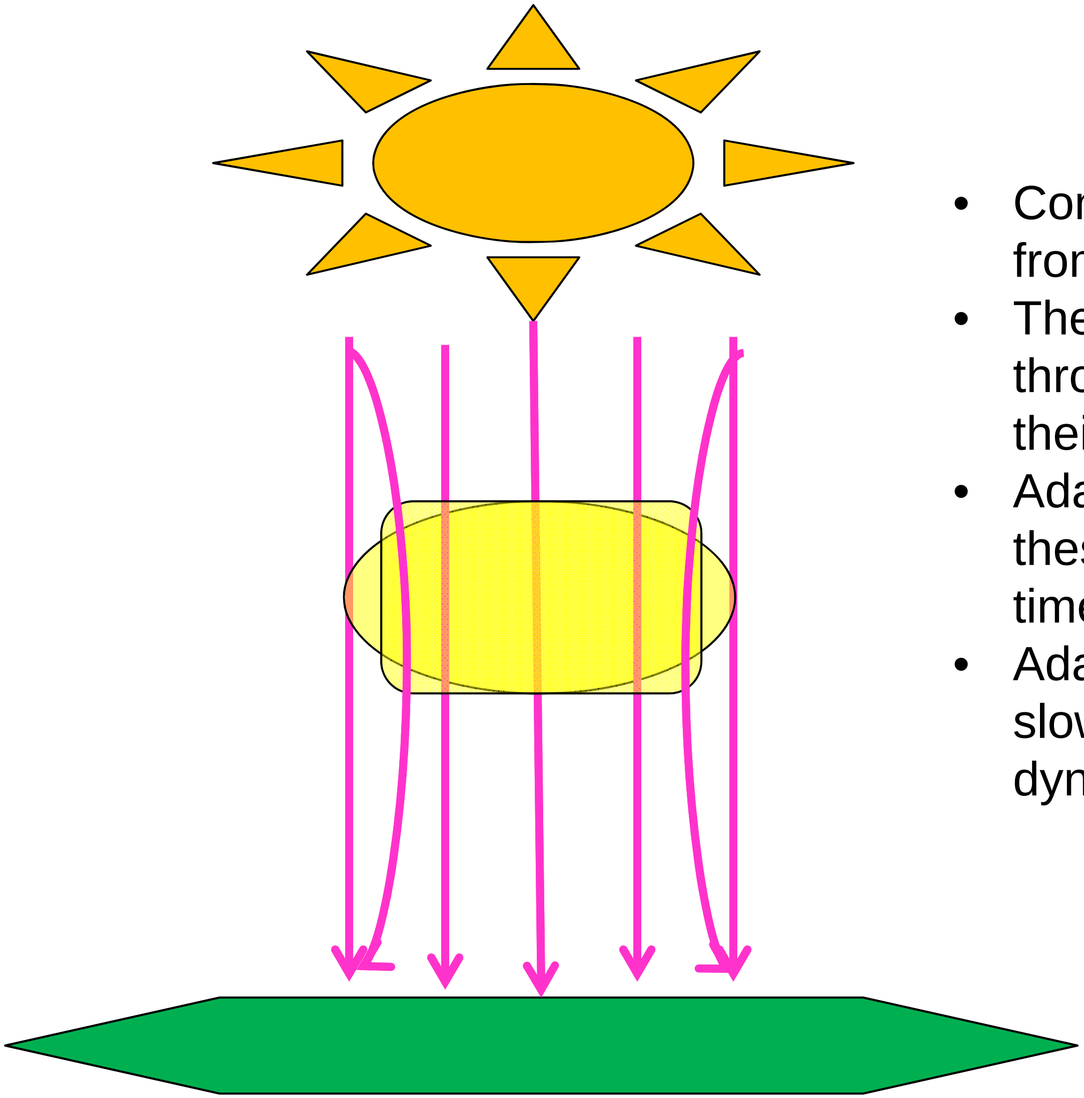
Complex Systems

- Systems composed of many interacting parts
- … but every system is. What's distinctive?
- Both the system-level behavior *and* the component-level behavior are interesting. How do these two kinds of behavior relate to one another?
- How does component-level behavior give rise to system-level behavior?
- How does system-level behavior shape component-level behavior?
  - Engineering
  - Adaptation

Adaptation

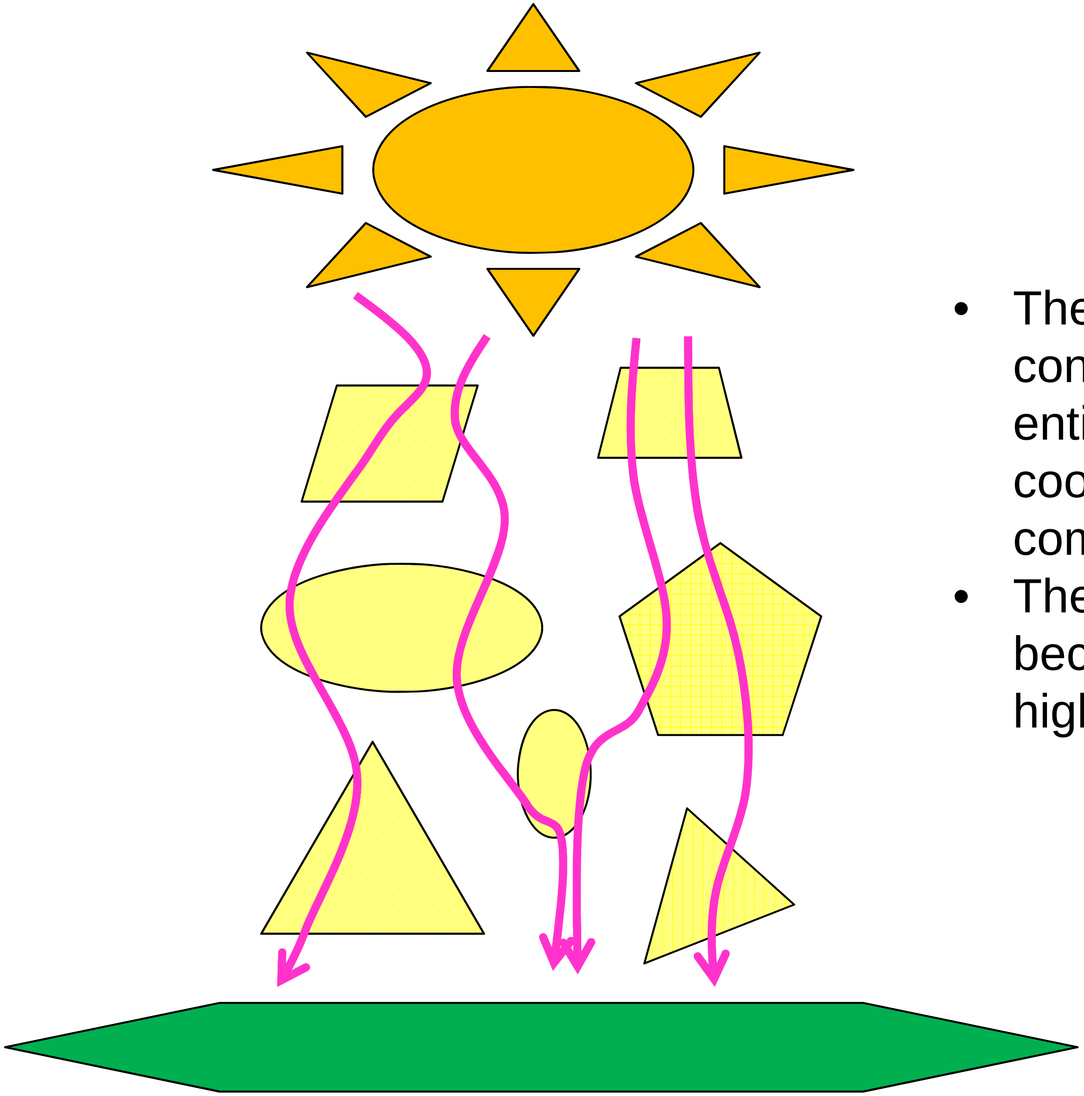
- Definition 0 – A change in a system in response to a change in its environment
- …. Getting hit by a car?
- Definition 1 – A change that makes a system perform better in its environment
- …. What if it’s a lucky guess?
- Definition 2 – A change that makes a system perform better and that is made because it makes the system perform better
- Adaptation is the process by which the environment can conjure behavior or structure from a system
- This notion includes biological evolution, but allows other mechanisms as well. For example learning counts as a kind of adaptation

Adaptation to Environment



- Complex systems are far from equilibrium
- They maintain themselves through interactions with their environment
- Adapting systems improve these interactions over time
- Adaptation is typically slower than “internal” dynamics

Adaptation to Environment



- The environment may consist of other adapting entities, creating a mesh of cooperative and competitive relationships
- These relationships might become reified in some higher-order structure

Why Should You Care

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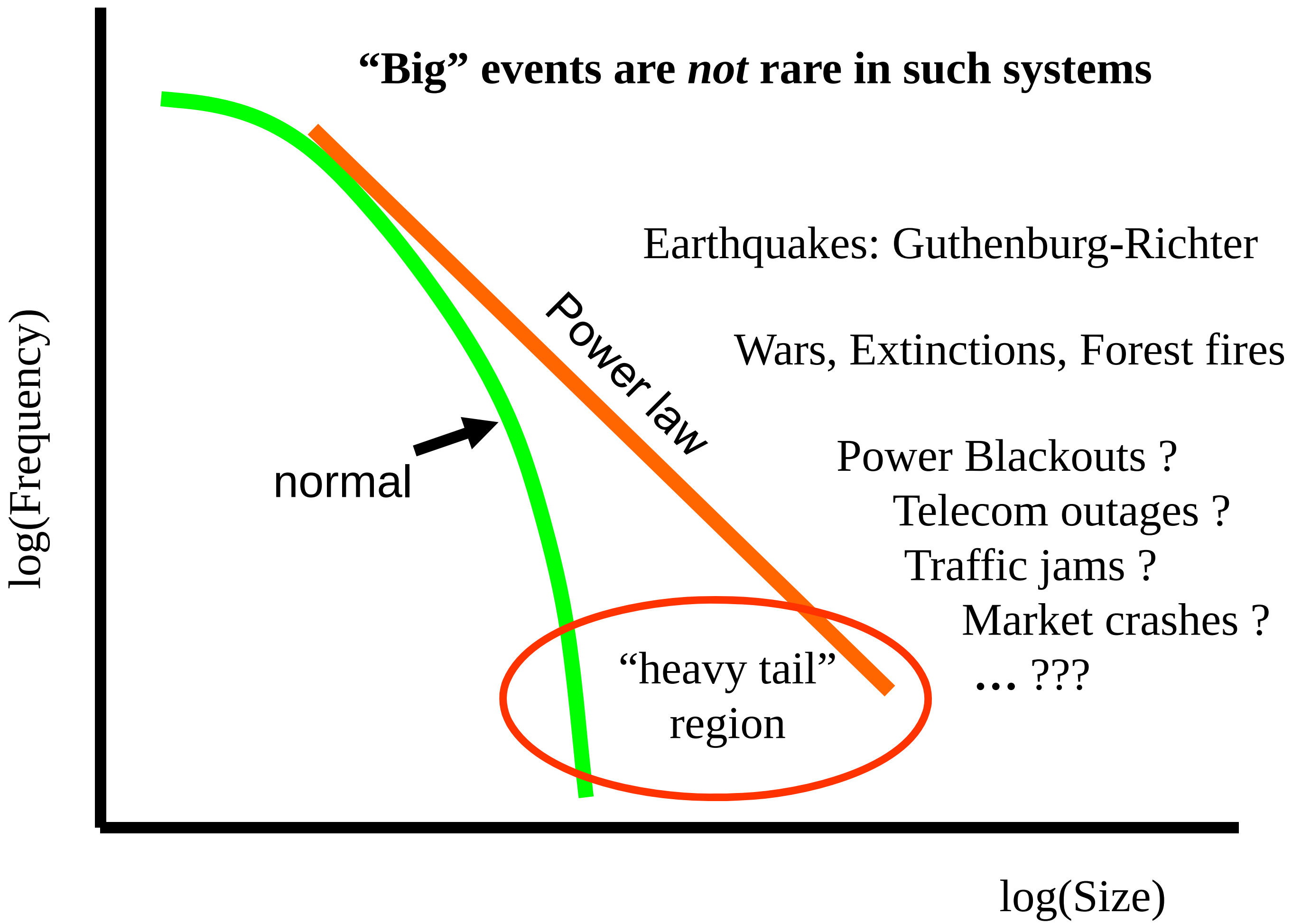
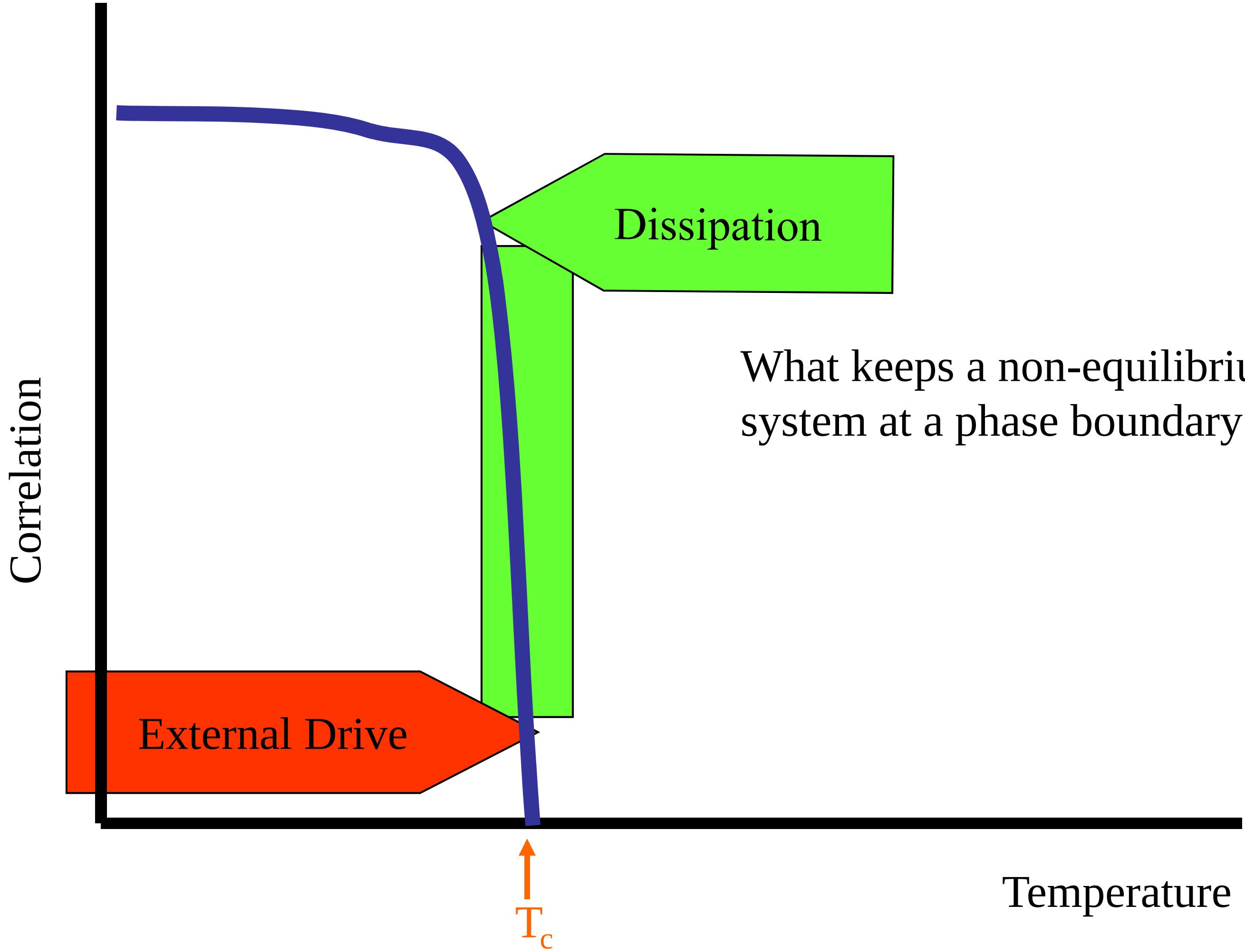
- If it’s a part of your system and you neglect it you can be badly frustrated
- Maybe you can save work by using it to solve your problem
- Adaptation can make a system robust yet fragile

Explaining Complex System Behavior



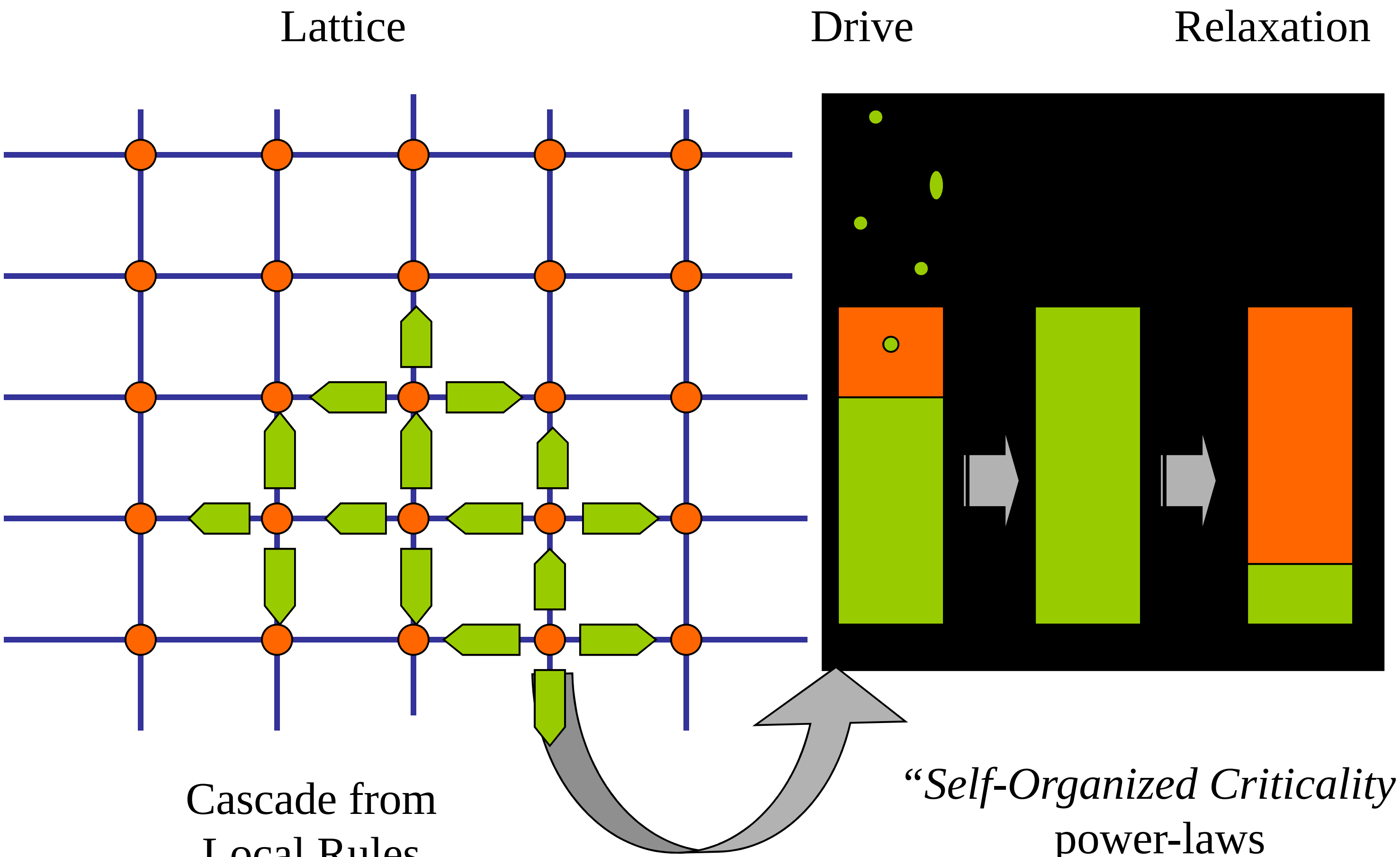
Complex Behavior and Phase Transitions



What keeps a non-equilibrium system at a phase boundary?

Self-tuning Systems

1987 Bak, Tang, Wiesenfeld's "Sand-pile" or "Cascade" Model

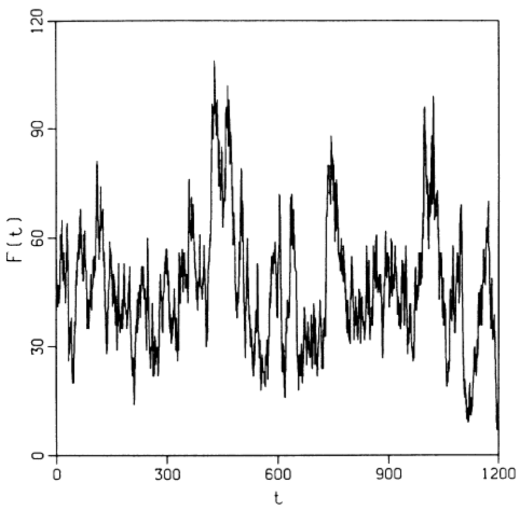


Cascade from
Local Rules

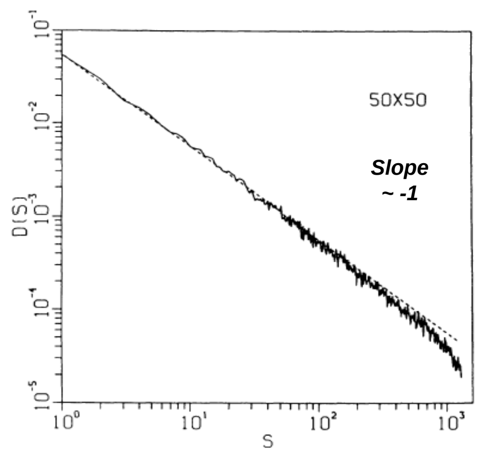
"Self-Organized Criticality"
power-laws
fractals in space and time
time series unpredictable

BTW Results

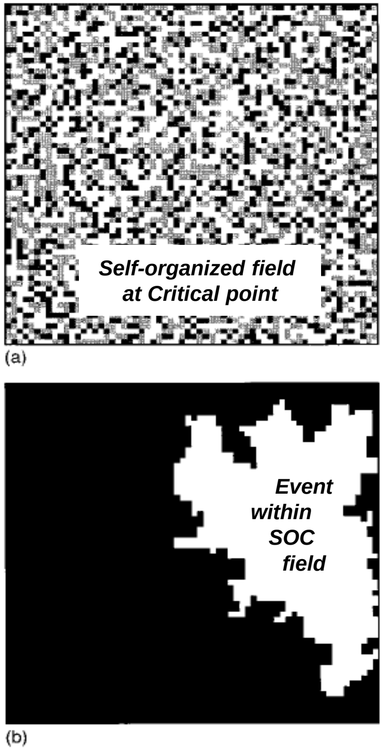
"Self-Organized Criticality"
power-laws
fractals in space and time
time series unpredictable



Time Series of Events



Power-Law Behavior (Frequency vs. Size)



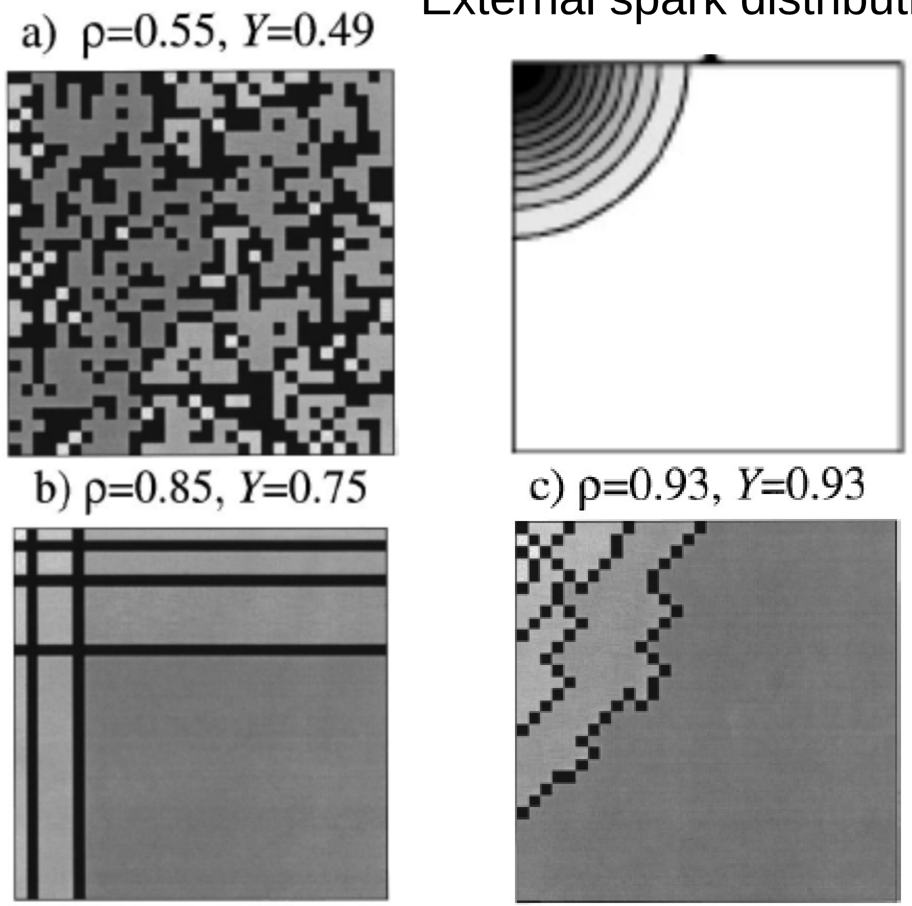
Cascade Behavior

1999 Carson and Doyle's Highly Optimized Tolerance "HOT"

Simple forest fire example

- Robust yet Fragile
- Structure
- Power laws

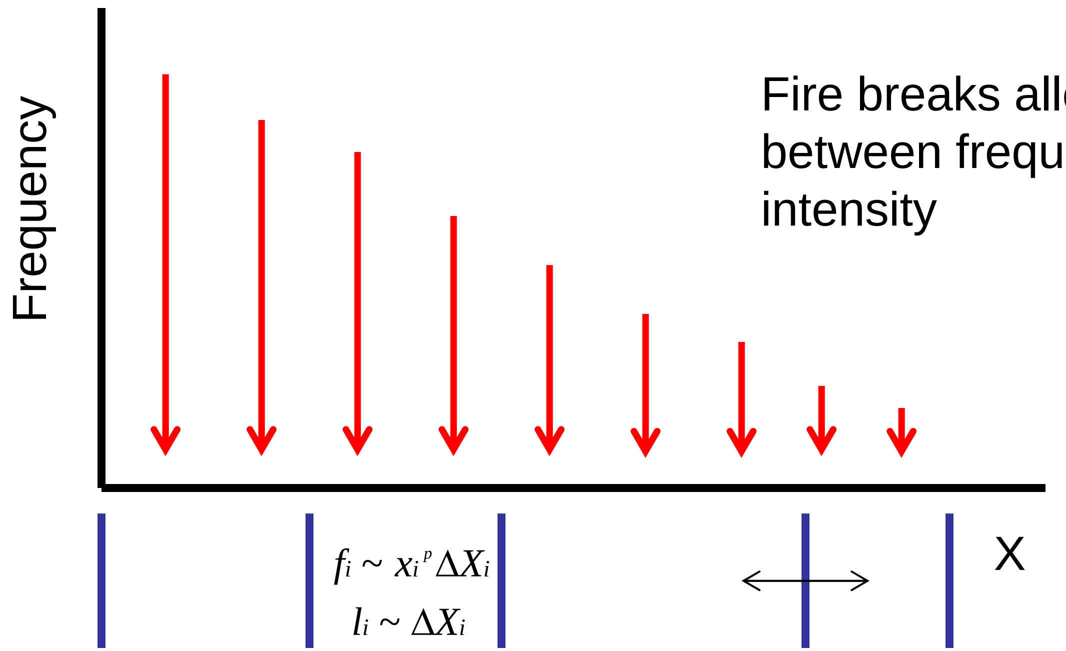
External spark distribution



designed

adapted

How Adaptation Produces Complex Behavior in Carson and Doyle



Fire breaks allow a trade-off between frequency and intensity

$$\min(\sum f_i l_i) \Rightarrow f_i l_i = f_j l_j$$

Minimization requires that each event has the same expected cost

Mechanisms of Adaptation

- Adaptation involves adjustment to some system feature over a time scale that is typically much longer than that of the dynamics of the system.
- Different kinds of system features might be adjusted:
  - Composition of a population of variable individuals

    A Simple Model of Herd Behavior

    Abhijit V. Banerjee

    The Quarterly Journal of Economics, Vol. 107, No. 3, (Aug., 1992), pp. 797-817
  - Parameter of a persisting system

    Spider webs designed for rare but life-saving catches

    Samuel Venner and Jerome Casas

    Proc. R. Soc. B (2005) 272, 1587–1592

    Adaptation to the Edge of Chaos in the Self-Adjusting Logistic Map

    Paul Melby, Jorg Eaidel, Nicholas Weber, Alfred Hubler

    PRL, Vol 84 No 26, p5991
  - Relationships among components

    Spontaneous Emergence of Complex Optimal Networks through Evolutionary Adaptation

    Venkat Venkatasubramanian, Santhoji Katare, Priyan R. Patkar, Fangping Mu

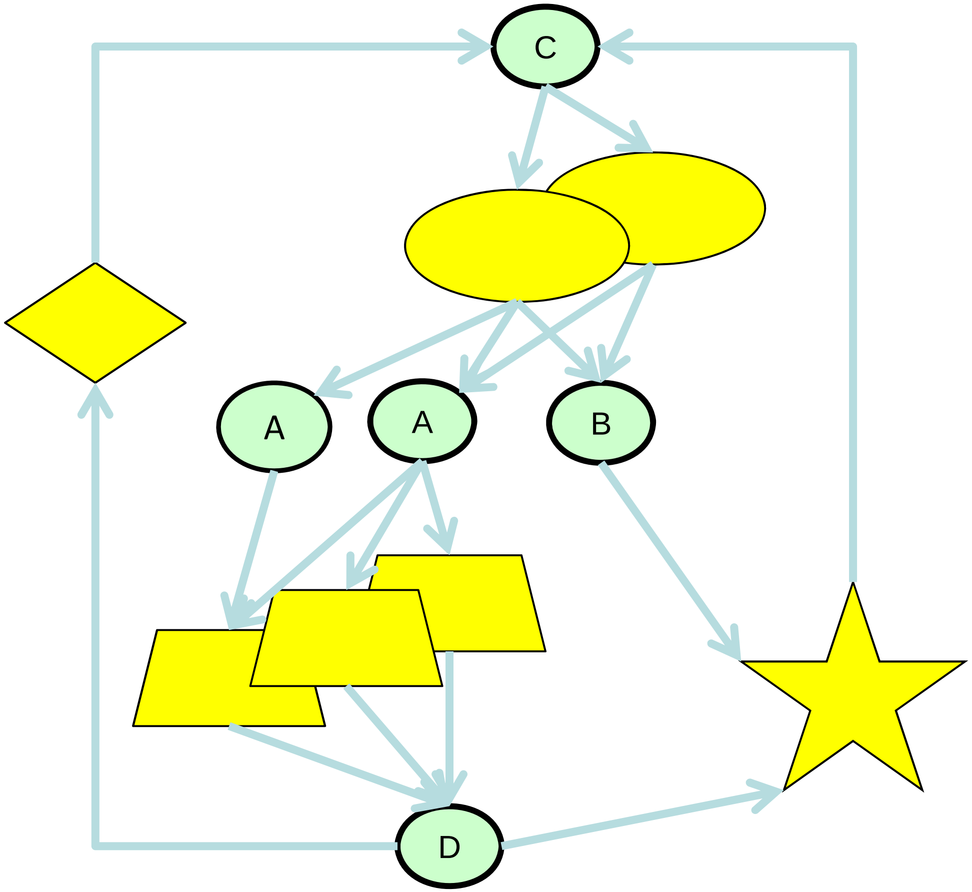
    (http://arxiv.org/abs/nlin/0402046)

A Generalized Complex Systems Model

- Consider the diverse problems we confront involving systems composed of adapting interacting components (infrastructures, ecosystems, producers of goods and services…)
- Find the most basic features and processes that are common to all systems, and that dictate their ability to function as individuals and as viable parts of an interacting system
- Build and understand a formal model that captures these features and processes
- Approach the motivating problems through this common formal structure

- Entities that manage resource for their own benefit, and that interact to acquire resources they need.
- Closure: all resources come from somewhere, and that source has its own requirements
- Basic questions:
  - How does the system react to disruptions (loss of resources, producing entities, interconnection)?
  - How do remediations change these reactions?
  - Are there general insights that derive from specific system studies?

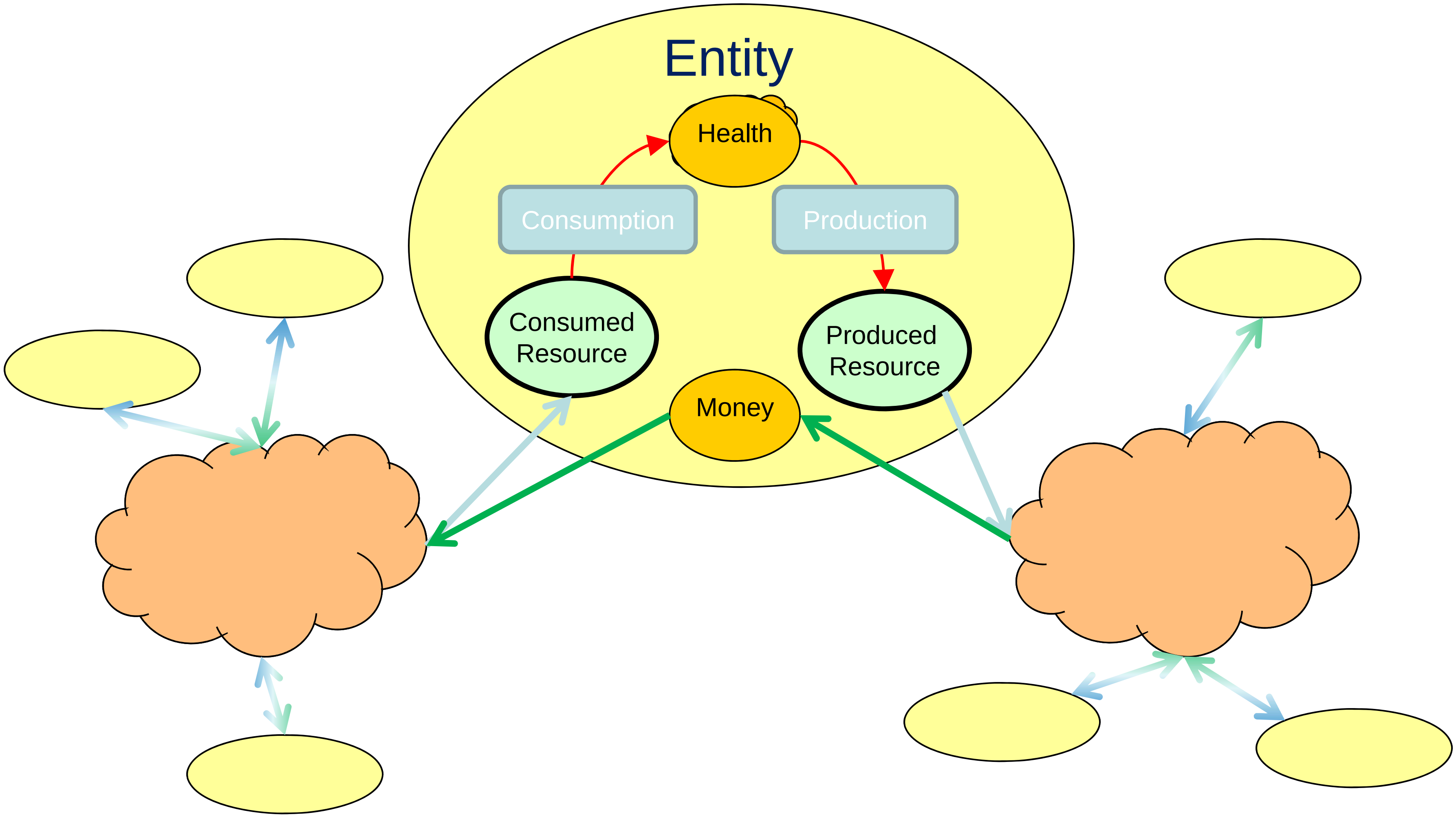
Essential Processes



- Resource consumption and production by entities
- Resource exchange among entities
- Change in entities' state as they respond to resource availability
- Change in entity size or capacity
- Change in connection patterns among entities
- Change in the kinds of entities in the system

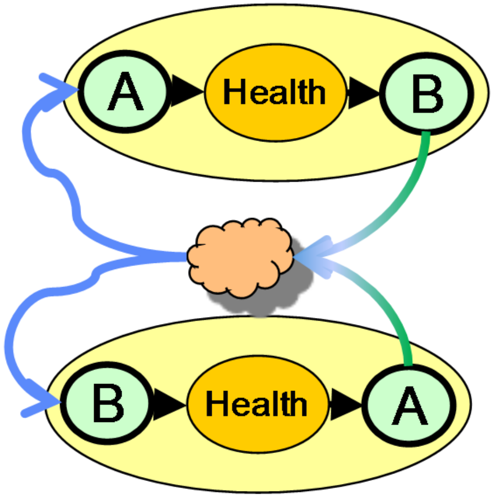
- Only some of these might be relevant for a particular problem. Time constants generally increase from top to bottom, so that slow processes can be considered "frozen".
- The framework allows us to include all of these processes, and to set time constants so that the dynamics interact

Basic Elements



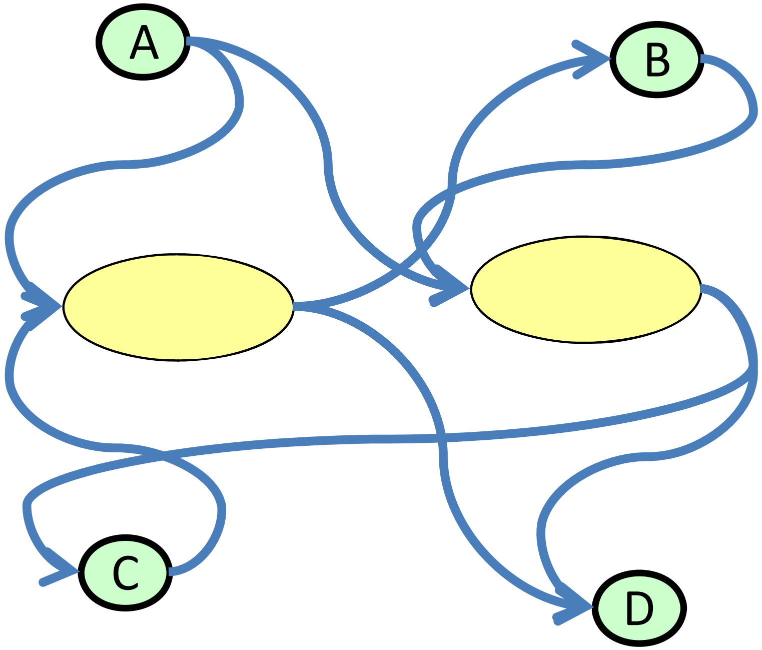
Exploring Simple Patterns of Interaction

Complete Interdependency



Some equilibrium results can be derived; Sensitivity to exchange process can be studied…

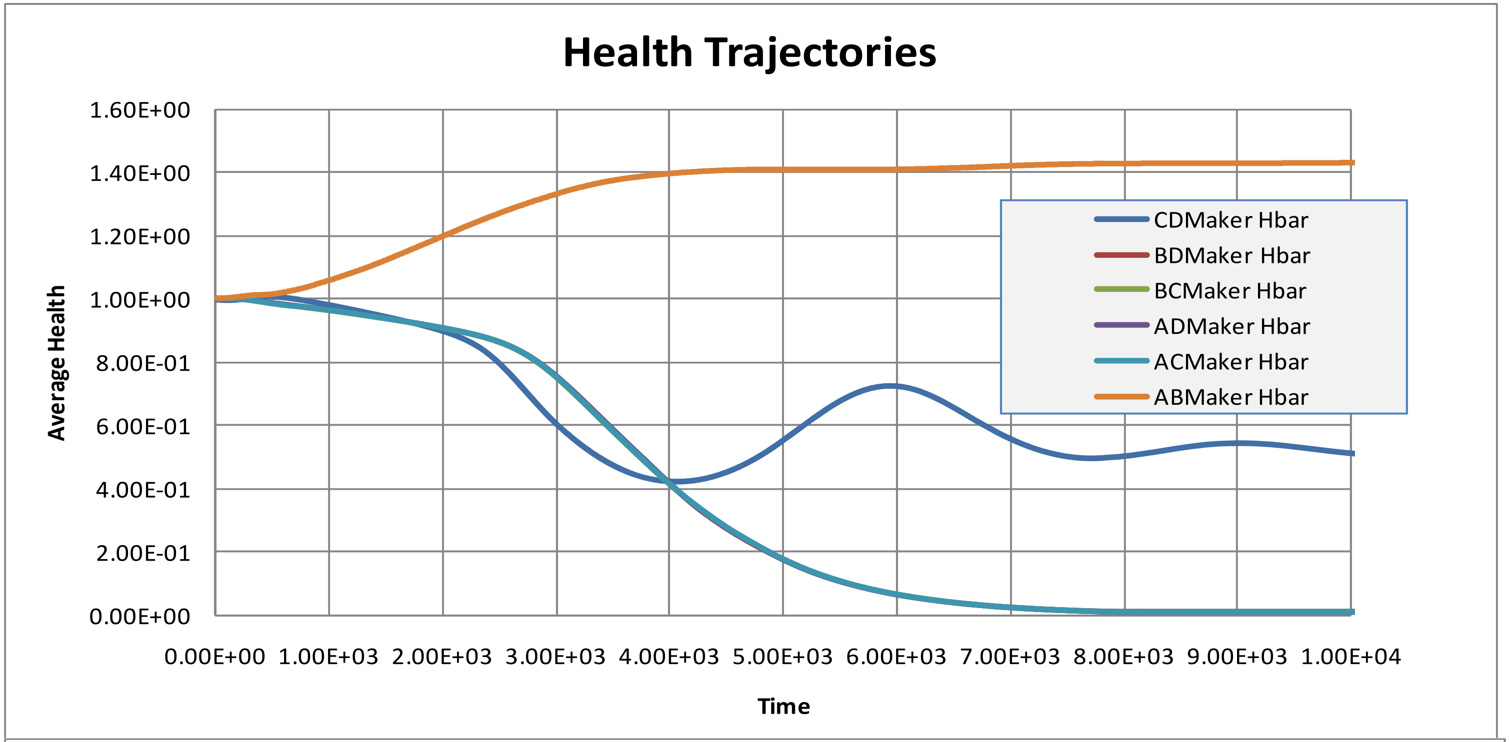
Using four resources minimally allows for input substitution and output specialization



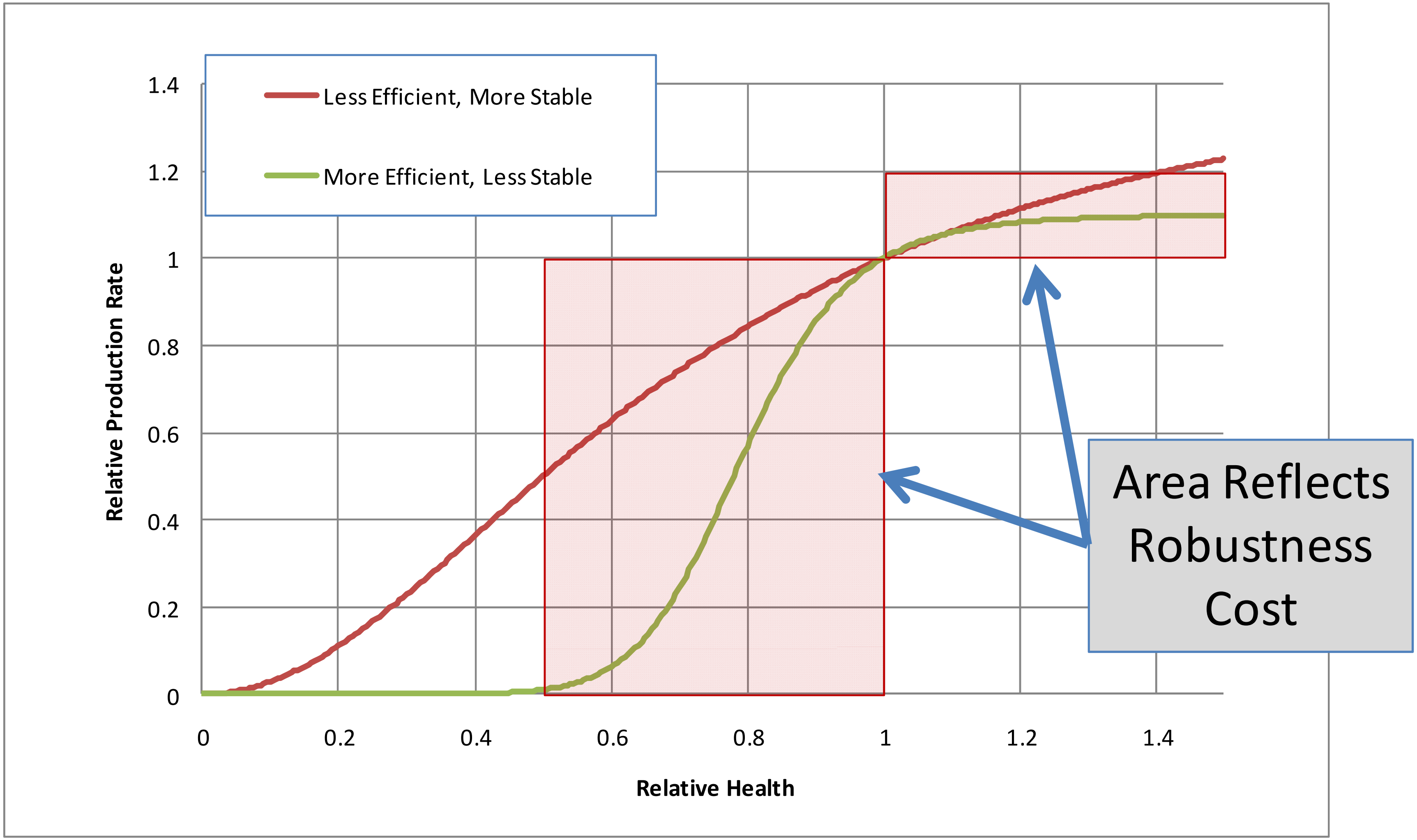
Six distinct input/output patterns are possible

What happens when one type is especially productive?

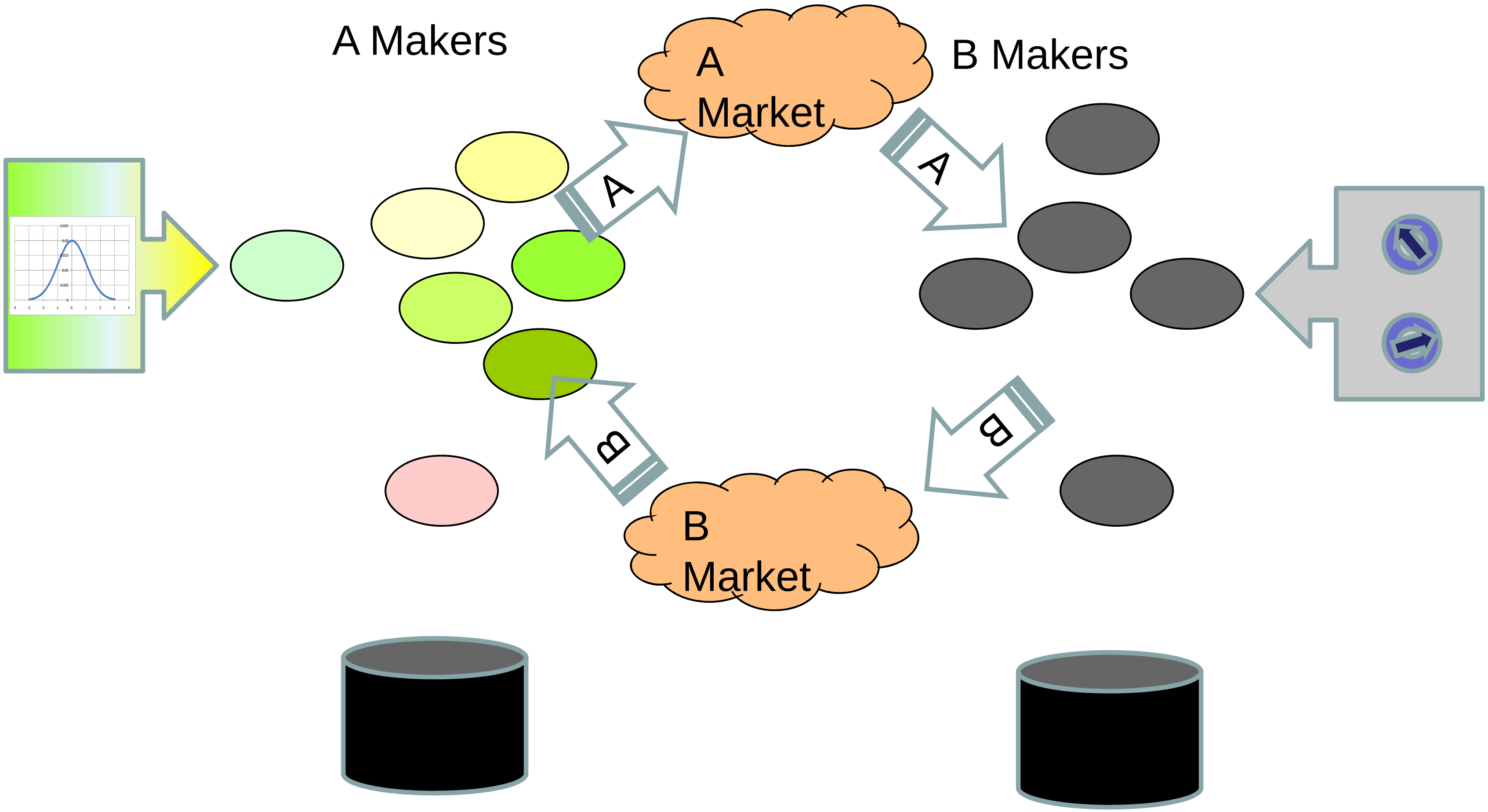
Competitive Exclusion



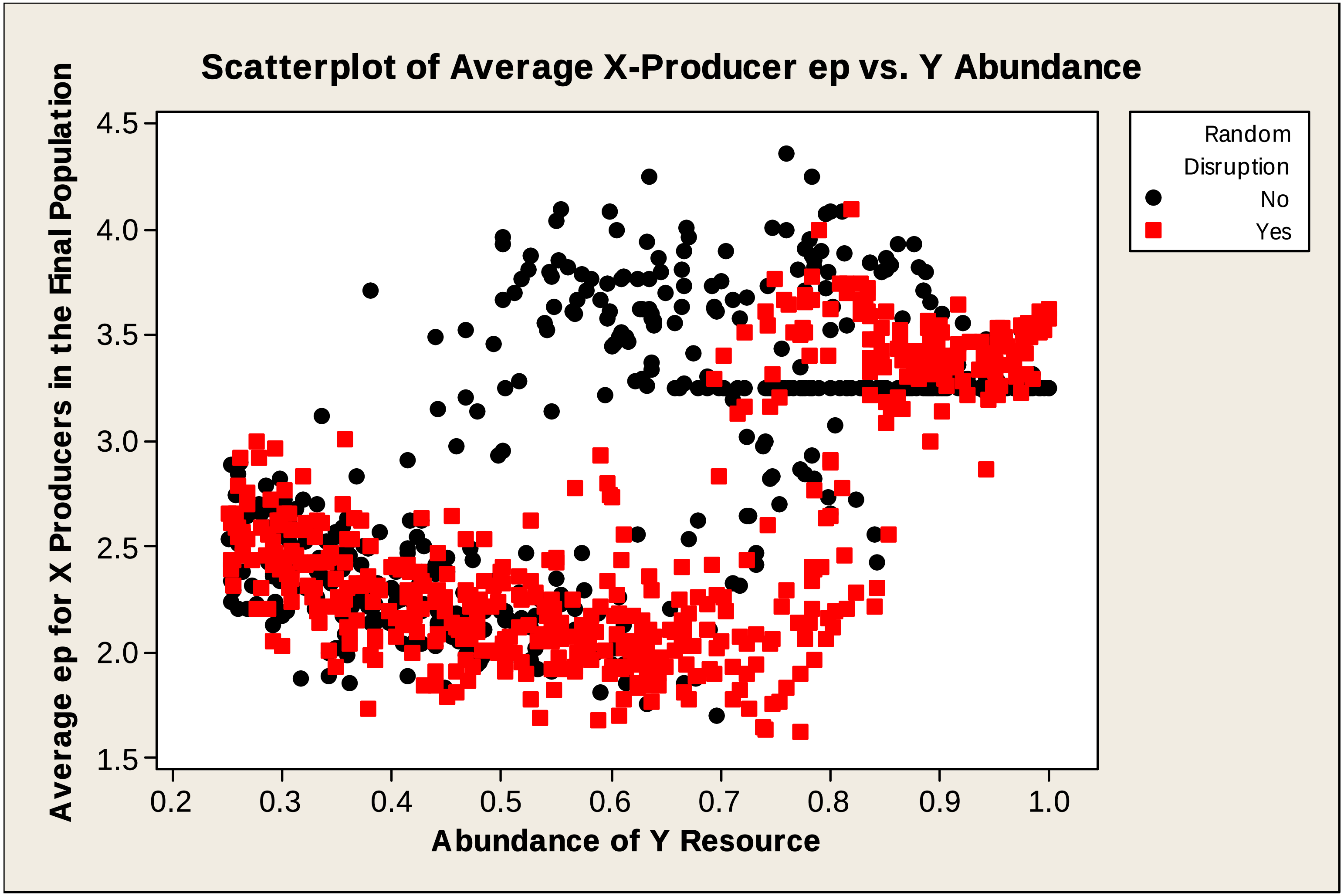
Robustness/Efficiency Tradeoff



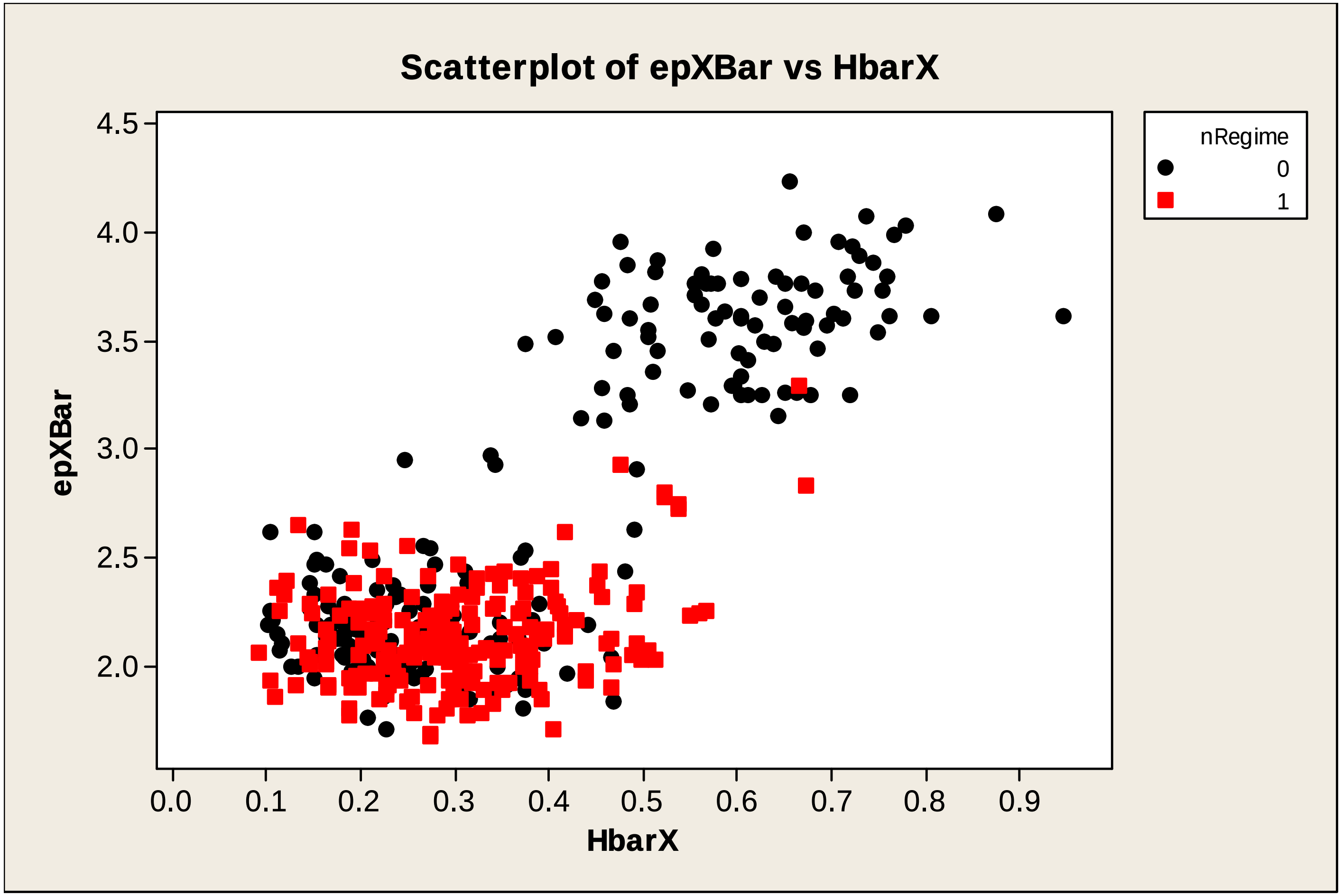
Robustness/Efficiency Configuration



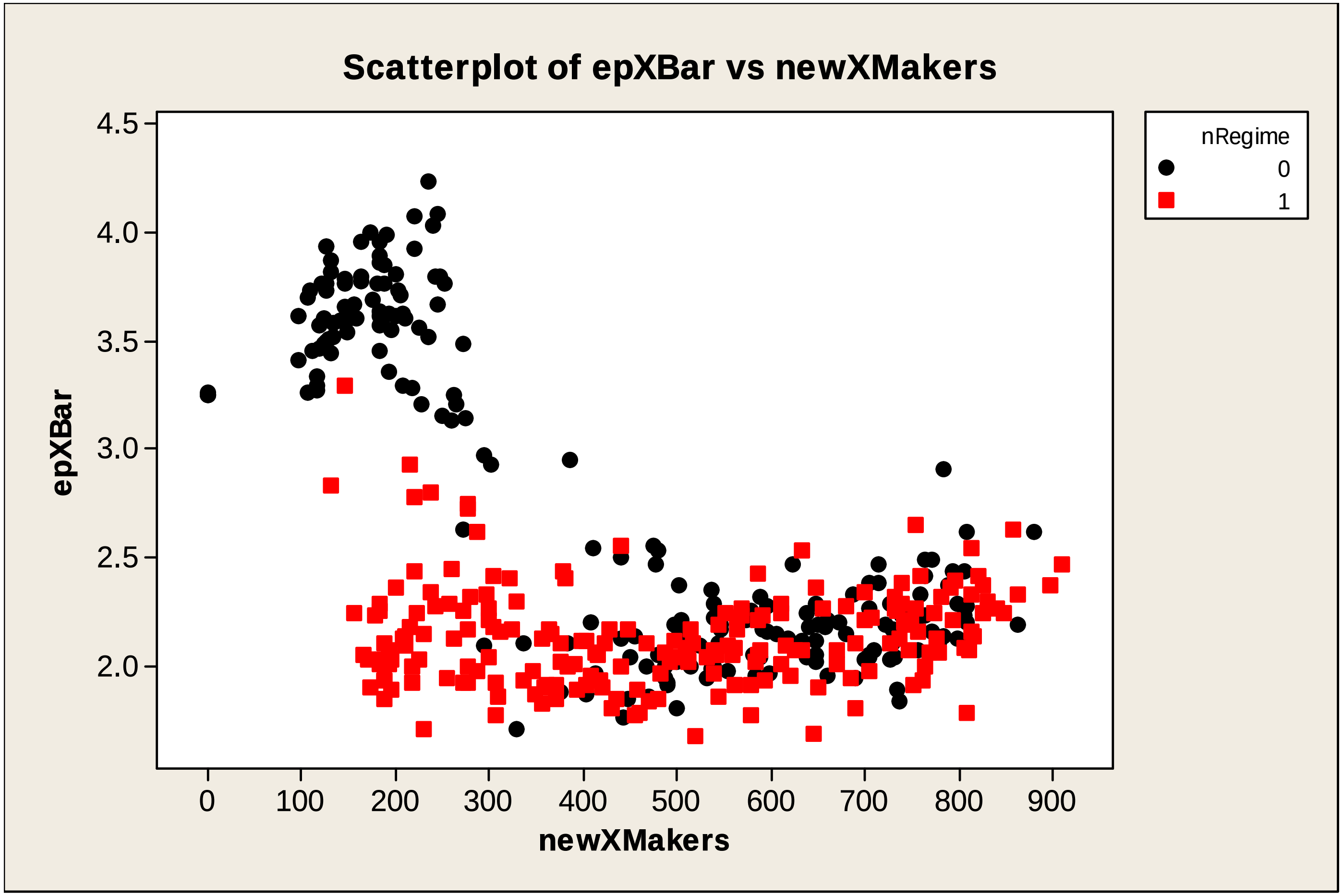
Robustness/Efficiency Tradeoff



Robustness/Efficiency Tradeoff

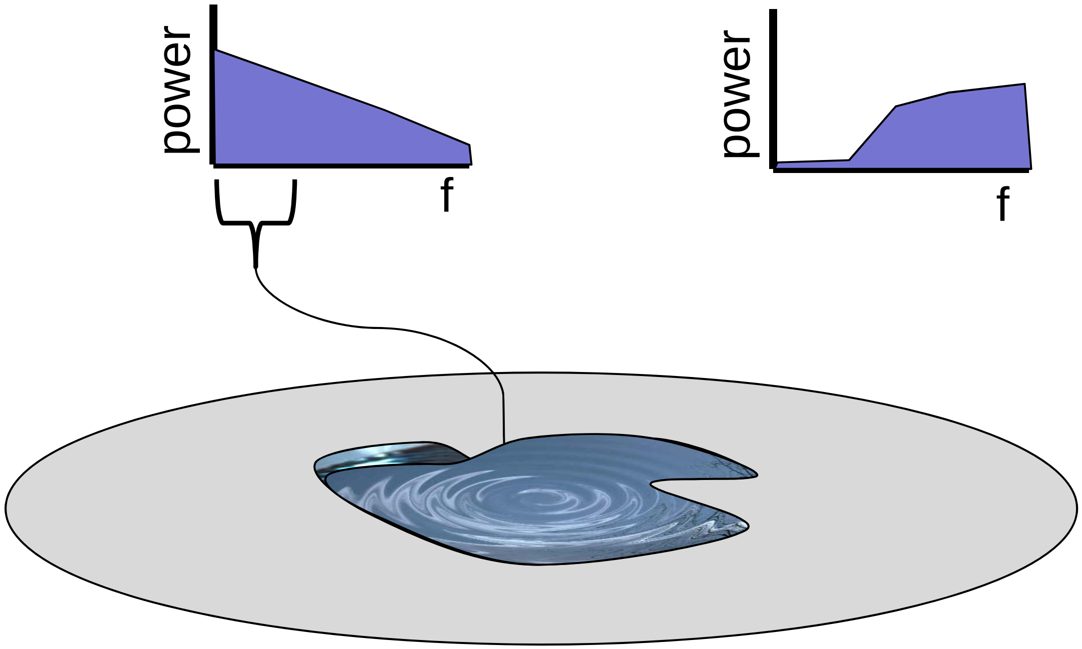


Robustness/Efficiency Tradeoff



Water Drop Adaptation

An Illustration of the process described in Melby et al.



Summary

- Complex systems are open systems, so interaction with the environment is essential for their success
- Adaptation is an internal response by the system that helps the system persist
- Adaptation can create and tune emergent properties
- Adaptive process are slow compared to the usual dynamics of the system
  - This can make them easy to overlook
  - They should track the dynamics of whatever features of the environment they couple with. If not….

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QUESTIONS & ANSWERS

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