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# CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

## Modeling Adaptation in Complex Systems

*Walt Beyeler*

Sandia National Laboratories, New Mexico (USA)

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# CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

## *Adaptation and Complex Systems*

### **Outline of Presentation**

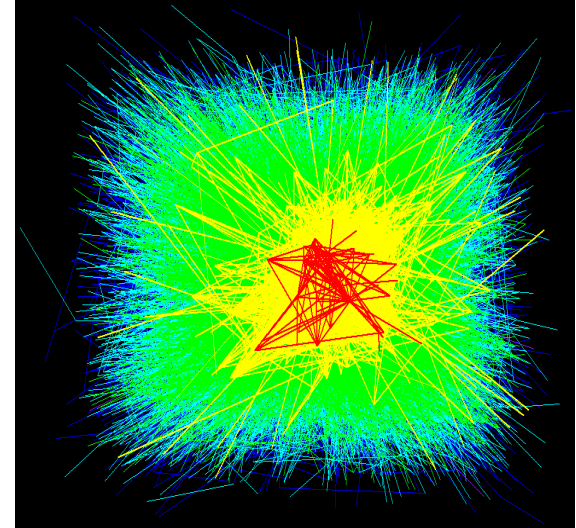
- Brief Biographical Note
- Where this Section Fits in the Structure of the Complex Systems Course
- Complex Systems and Adaptation
- Definition of Adaptation
- Why Should You Care
- Complex Behavior as Adaptive Response
- Kinds of Adaptation
- Models Showing Adaptation
- Question & Answer Session

# CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

## *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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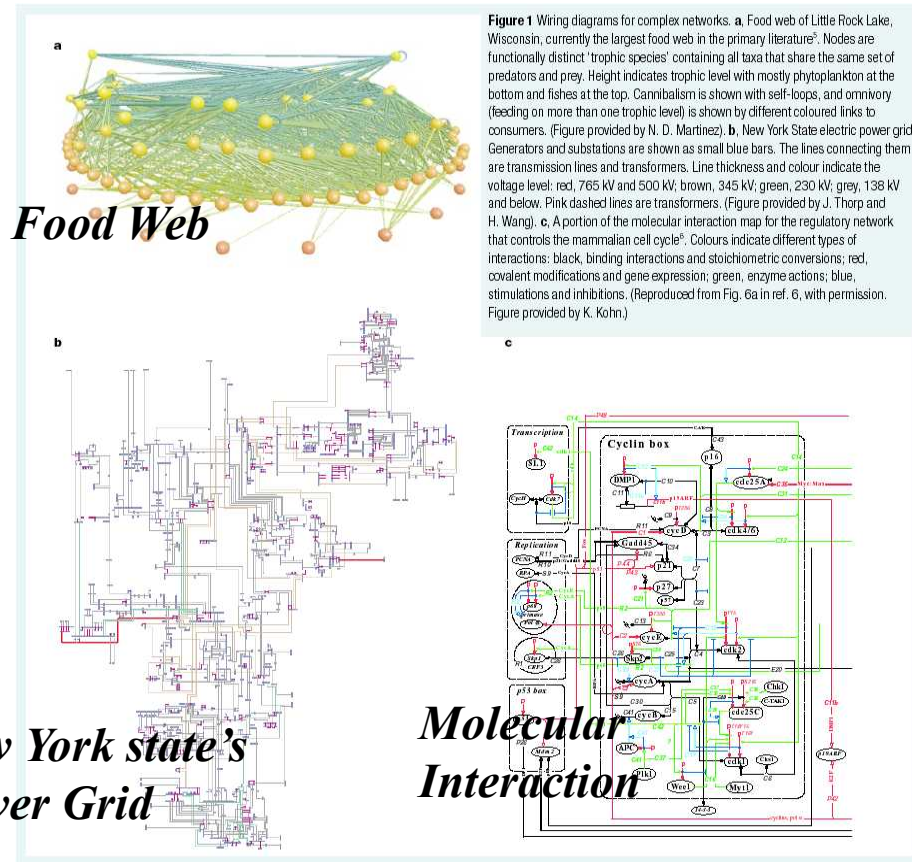
## *Adaptation and Complex Systems*

*Focus of this session*

- Fundamentals of Complex Systems
- Methods
  - Modeling Techniques
  - Approaches to Examining Complex Systems
- 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?



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

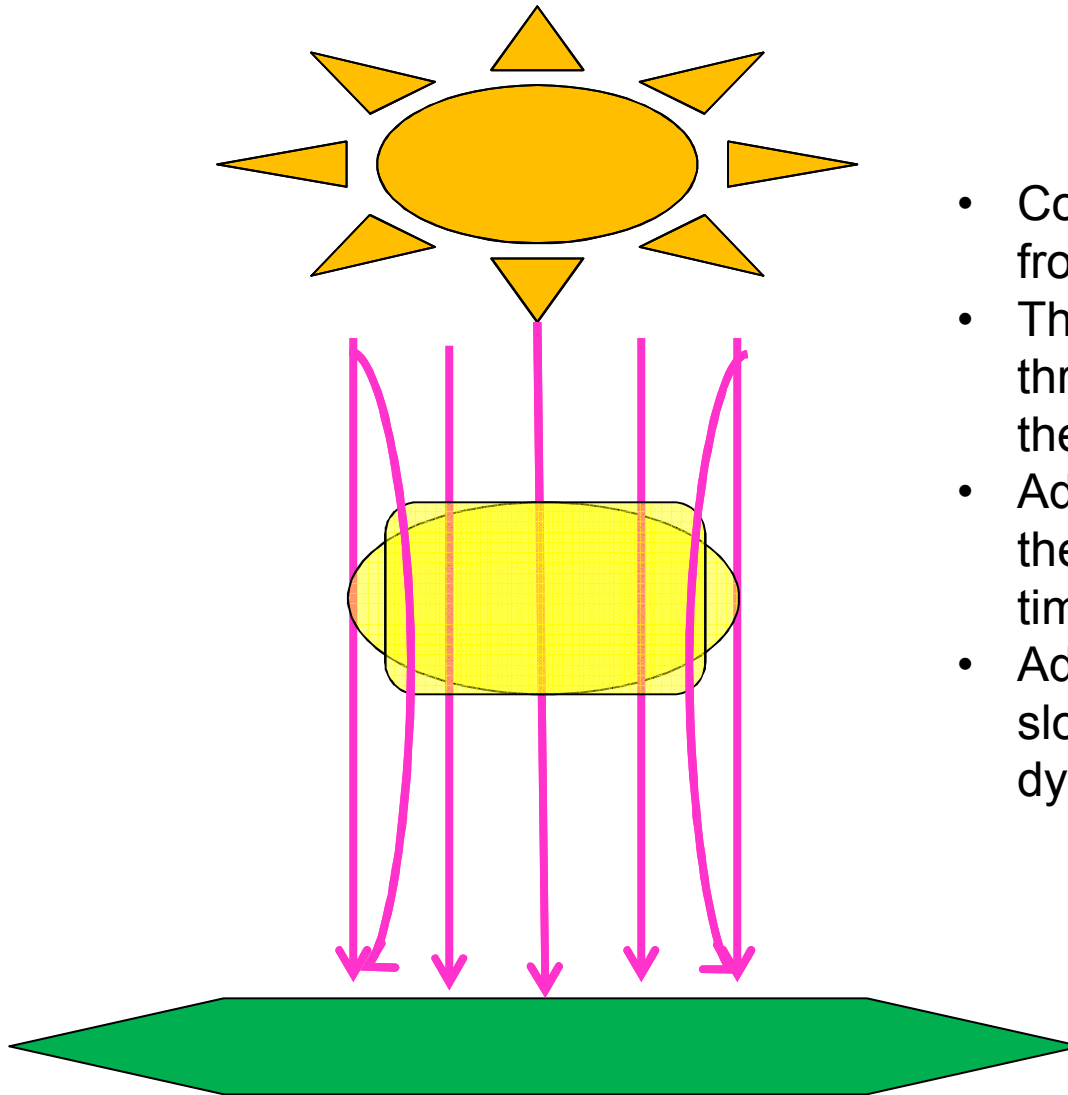
# Complex Systems

- 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

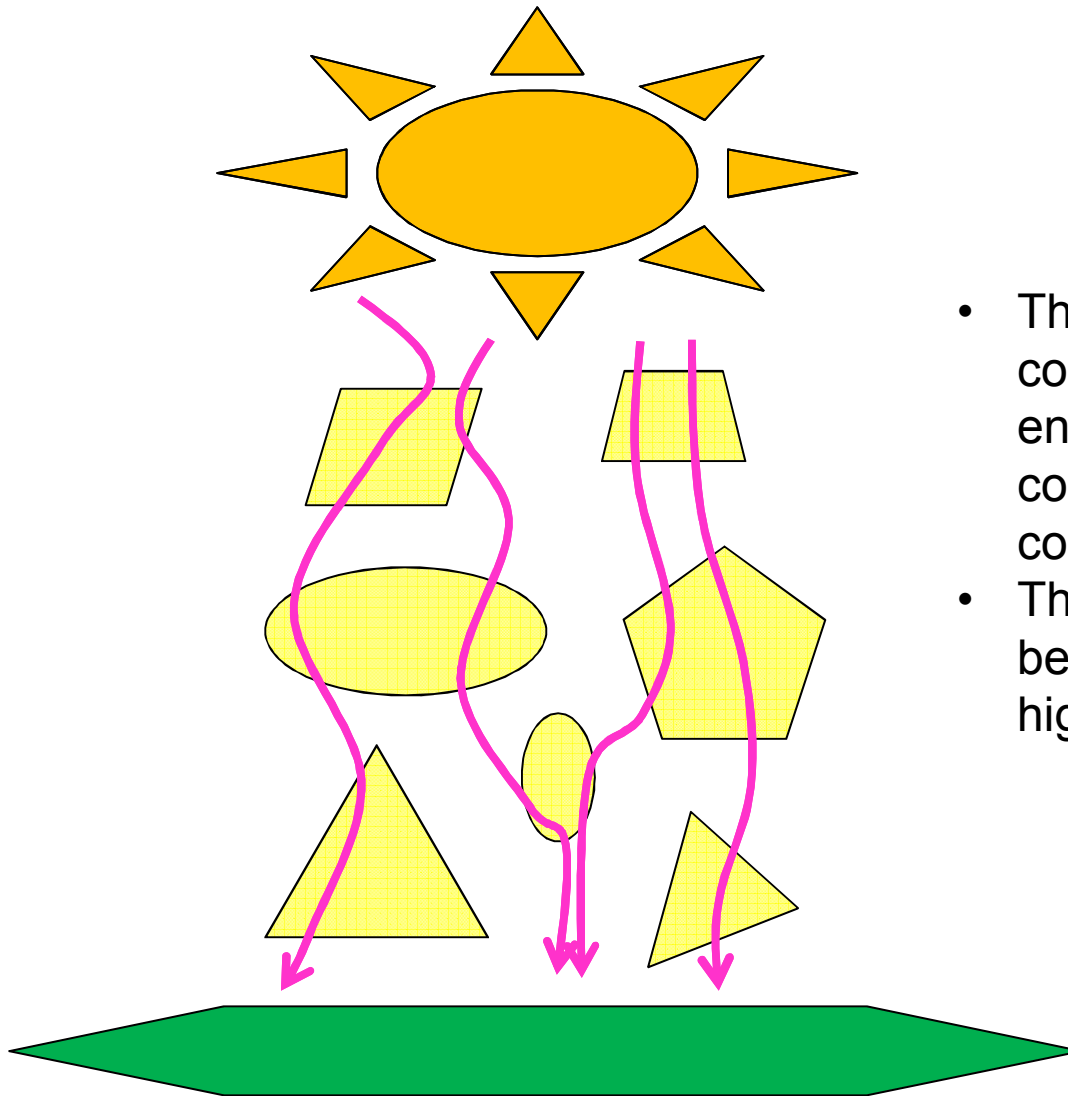
# Adaptation to Environment



- 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

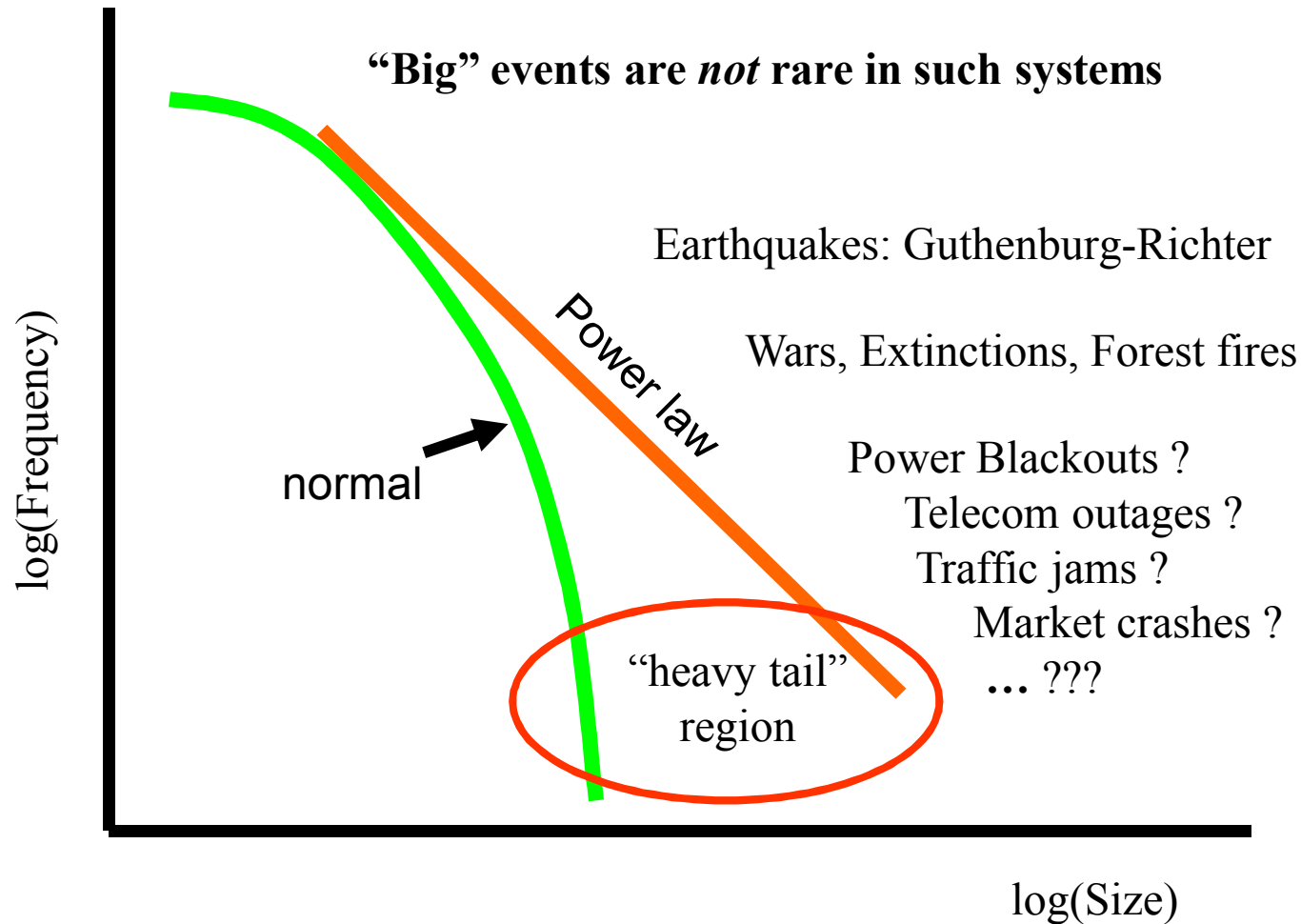


- The environment may consist of other adapting entities, creating a mesh of cooperative and competitive relationships
- These relationships might become reified in some higher-order structure

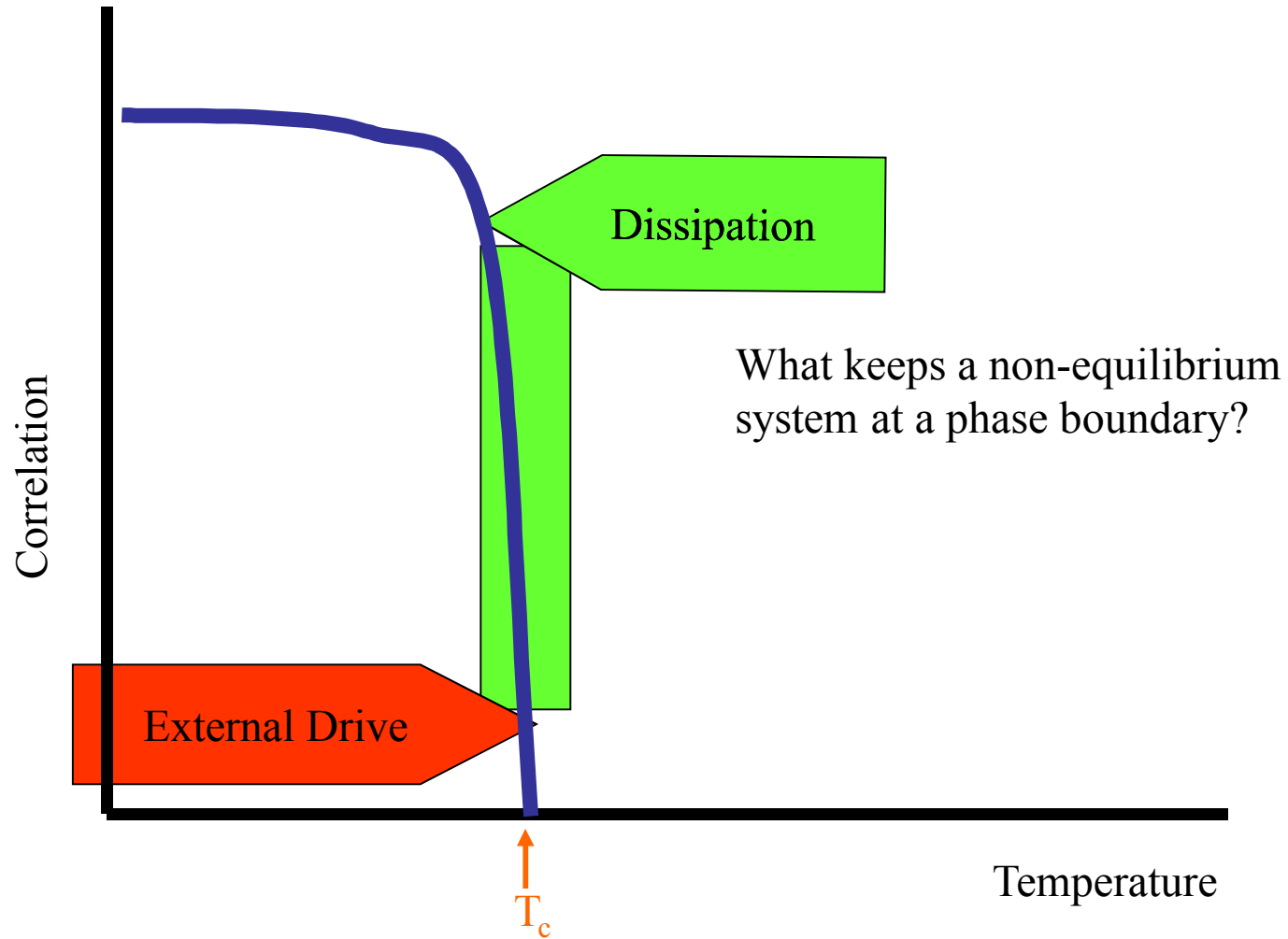
# Why Should You Care

- 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

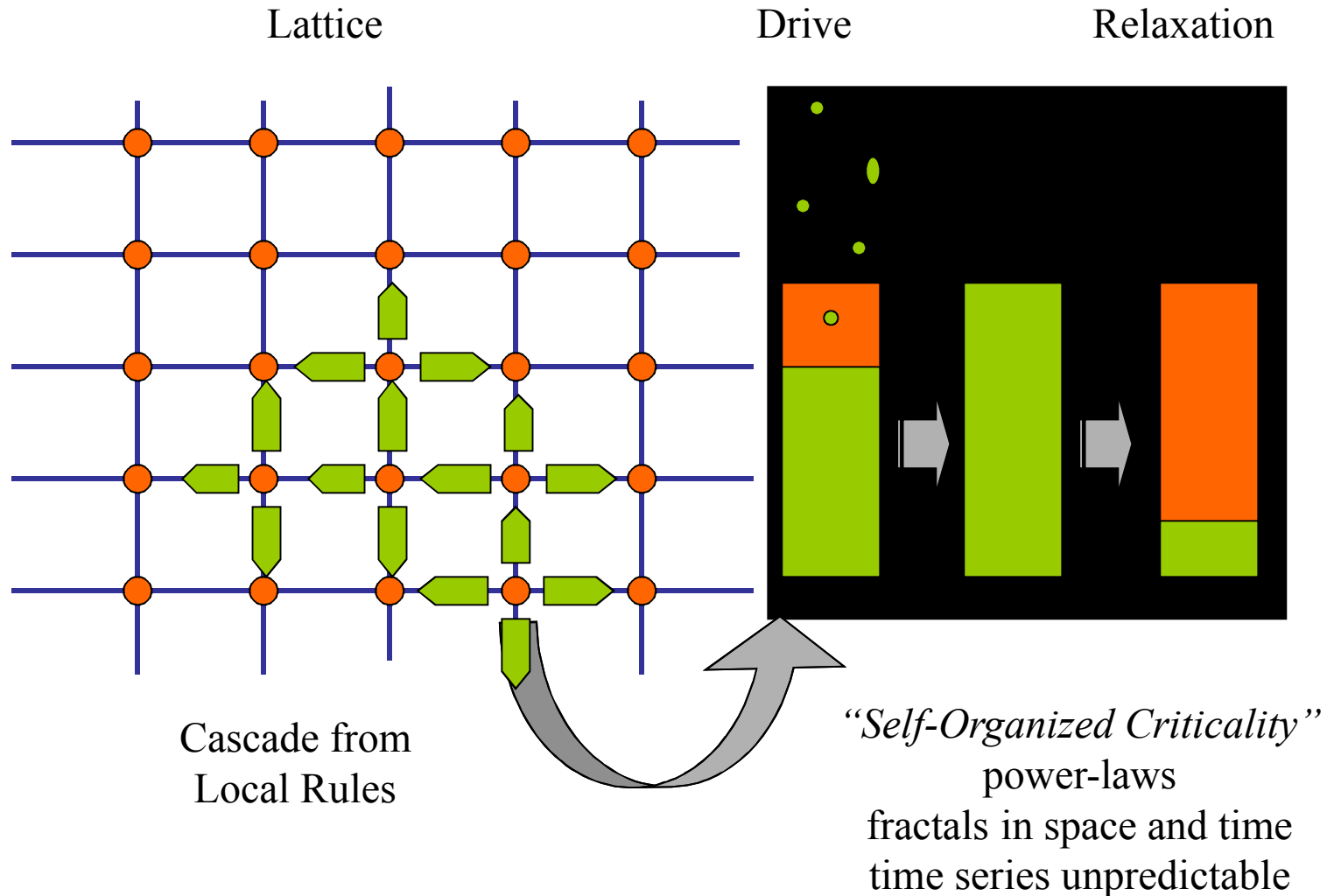


# Complex Behavior and Phase Transitions



# Self-tuning Systems

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



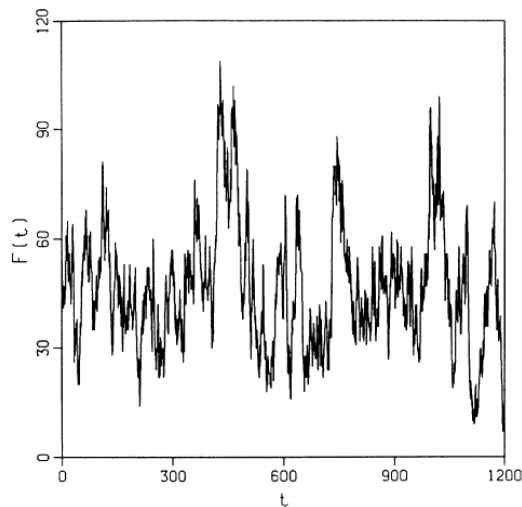
# BTW Results

*“Self-Organized Criticality”*

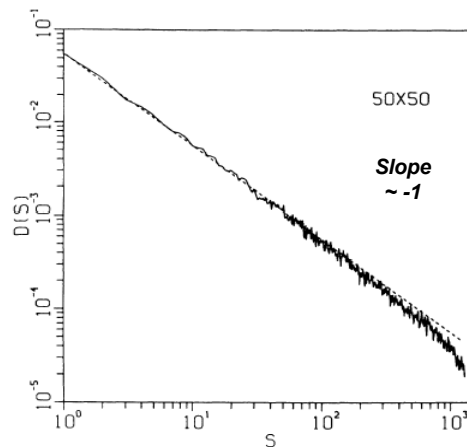
power-laws

fractals in space and time

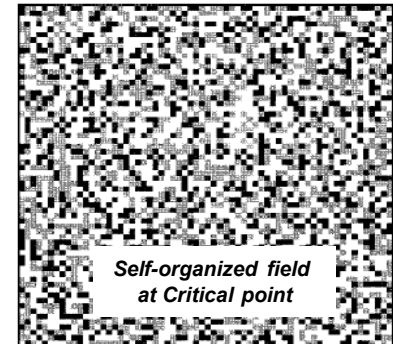
time series unpredictable



***Time Series of Events***



***Power-Law Behavior  
(Frequency vs. Size)***



(a)



(b)

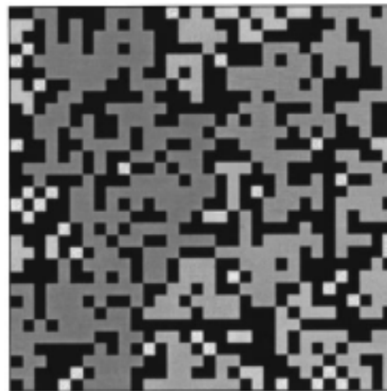
***Cascade Behavior***

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

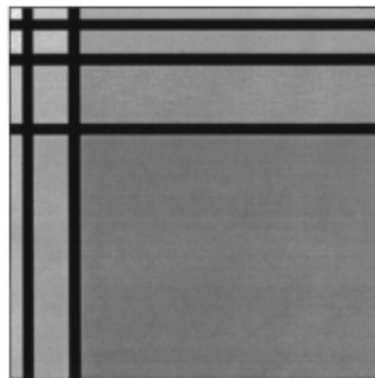
Simple forest fire  
example

- Robust yet Fragile
- Structure
- Power laws

a)  $\rho=0.55, Y=0.49$

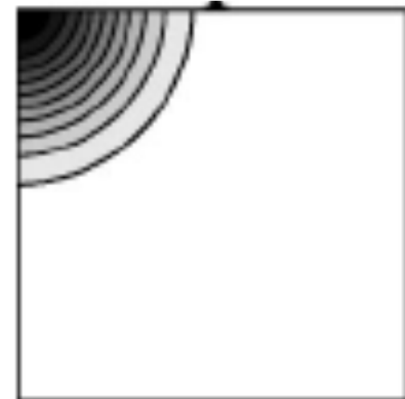


b)  $\rho=0.85, Y=0.75$

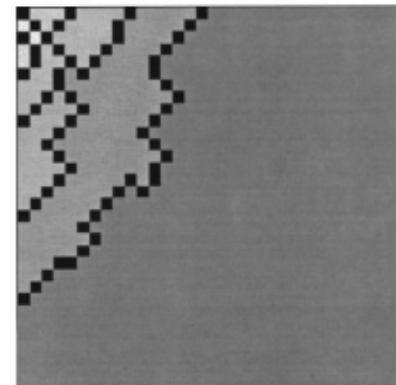


designed

External spark distribution

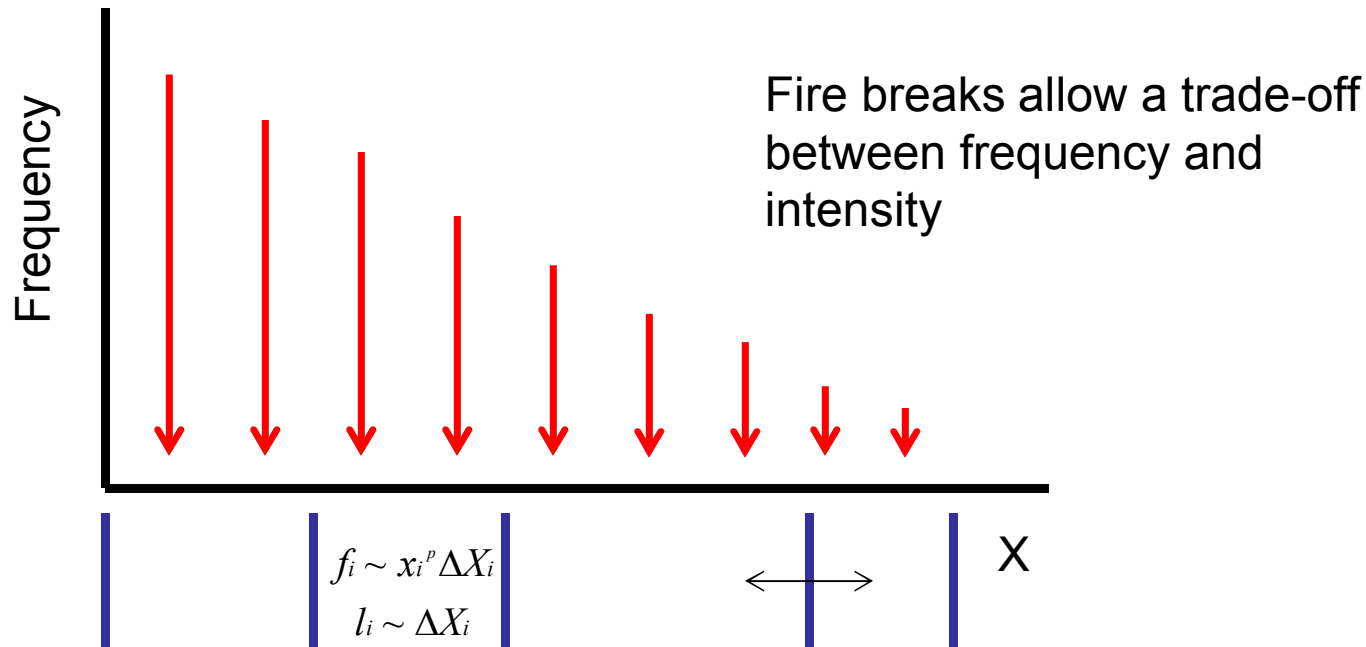


c)  $\rho=0.93, Y=0.93$



adapted

# How Adaptation Produces Complex Behavior in Carson and Doyle



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

Minimization requires that each event has the same expected cost



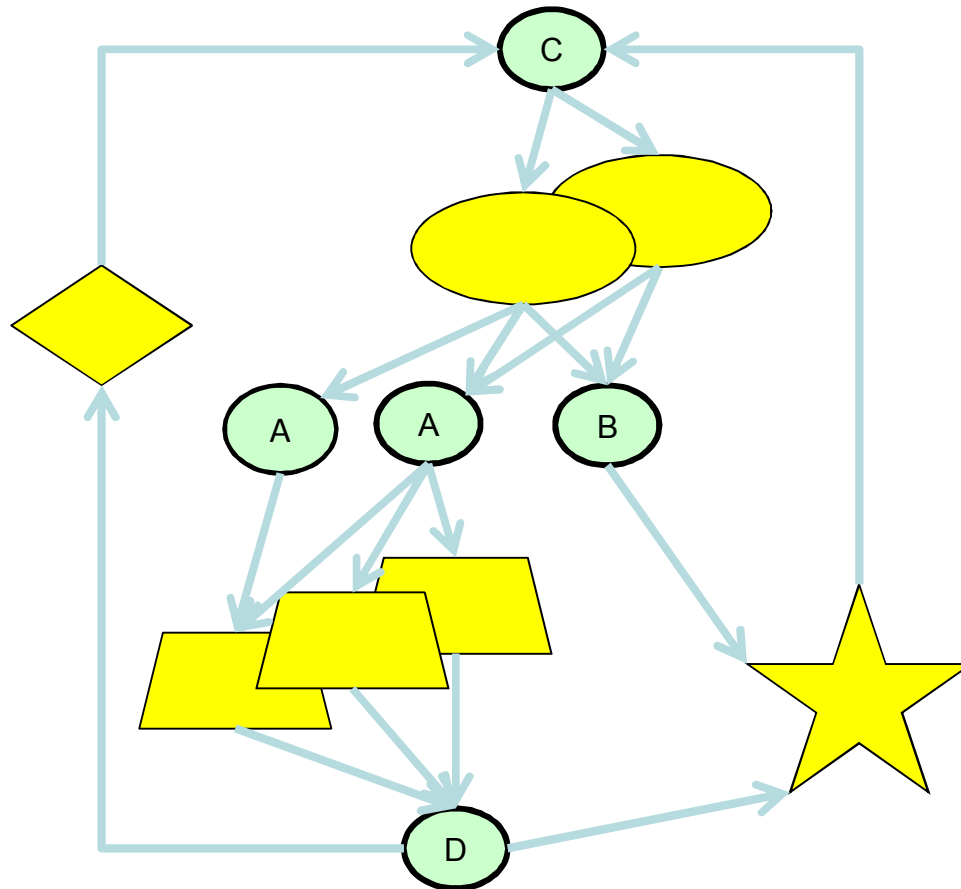
# Mechanisms of Adaptation

- 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

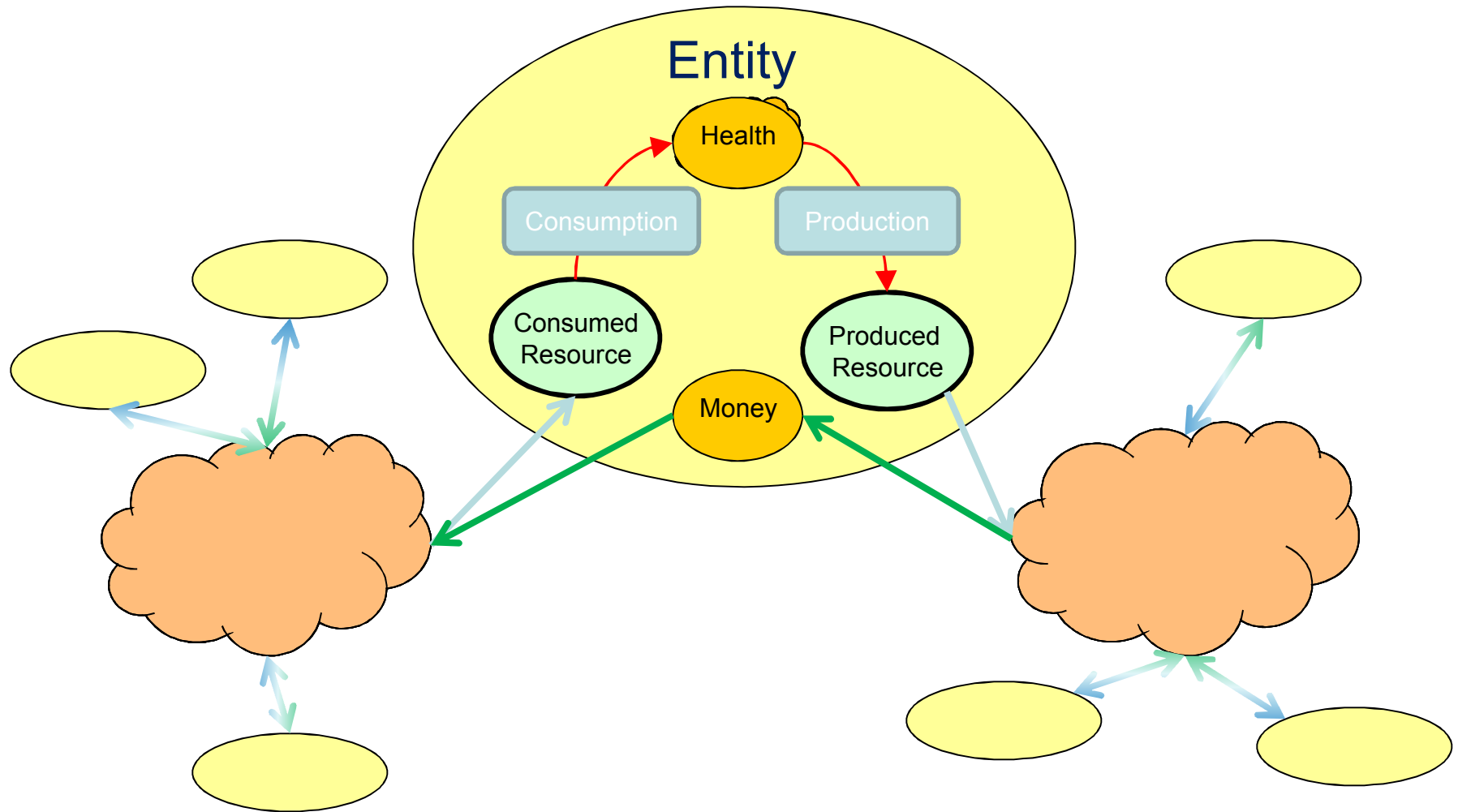
- Consider the diverse problems we confront involving systems composed of adapting interacting components (infrastructures, ecosystems, producers of goods and services...)
- Find the most basic features and processes that are common to all systems, and that dictate their ability to function as individuals 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



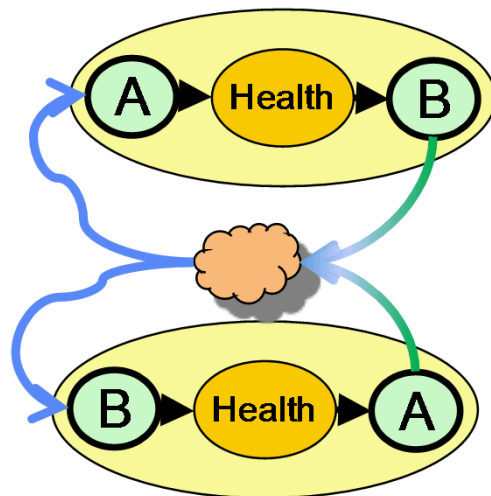
- Resource consumption and production by entities
  - Resource exchange among entities
  - Change in entities' state as they respond to resource availability
  - Change in entity size or capacity
  - Change in connection patterns among entities
  - Change in the kinds of entities in the system
- 
- Only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



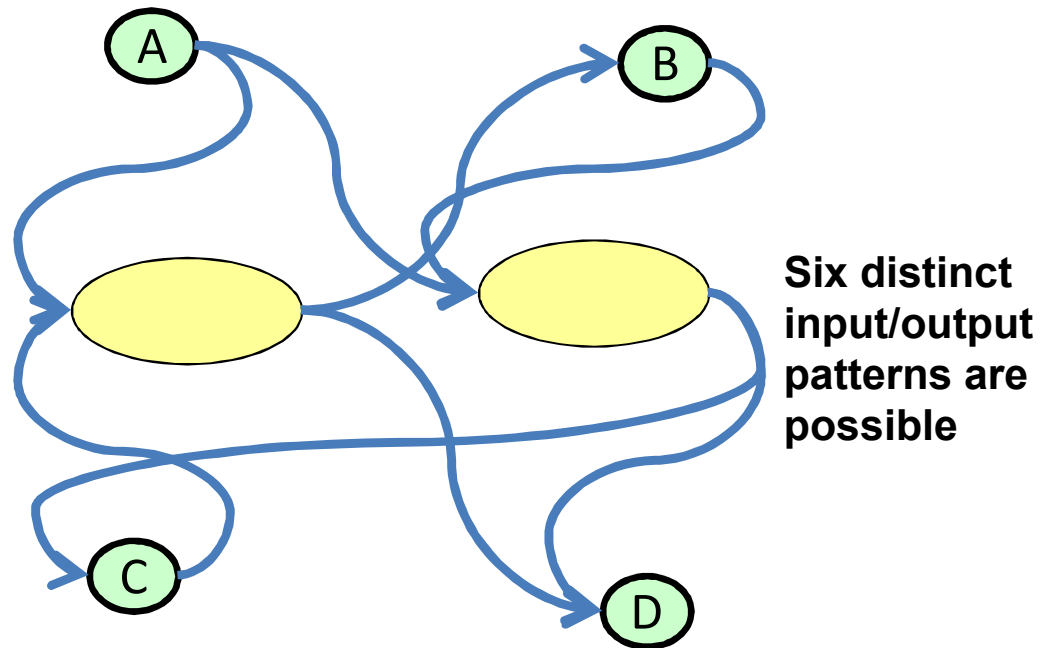
# Exploring Simple Patterns of Interaction

## 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

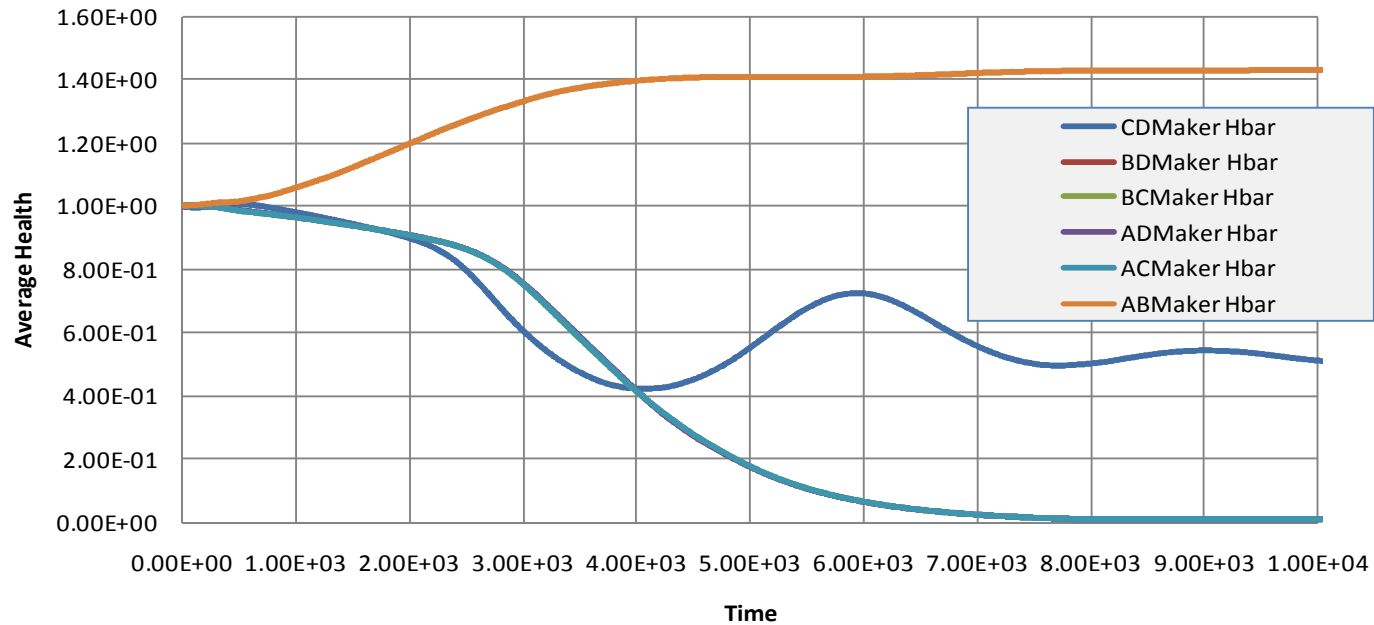


Six distinct  
input/output  
patterns are  
possible

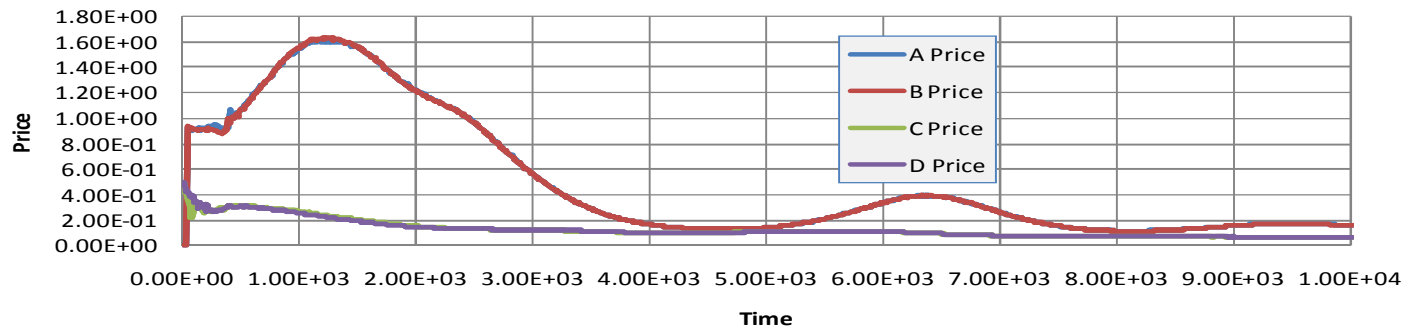
What happens when one type  
is especially productive?

# Competitive Exclusion

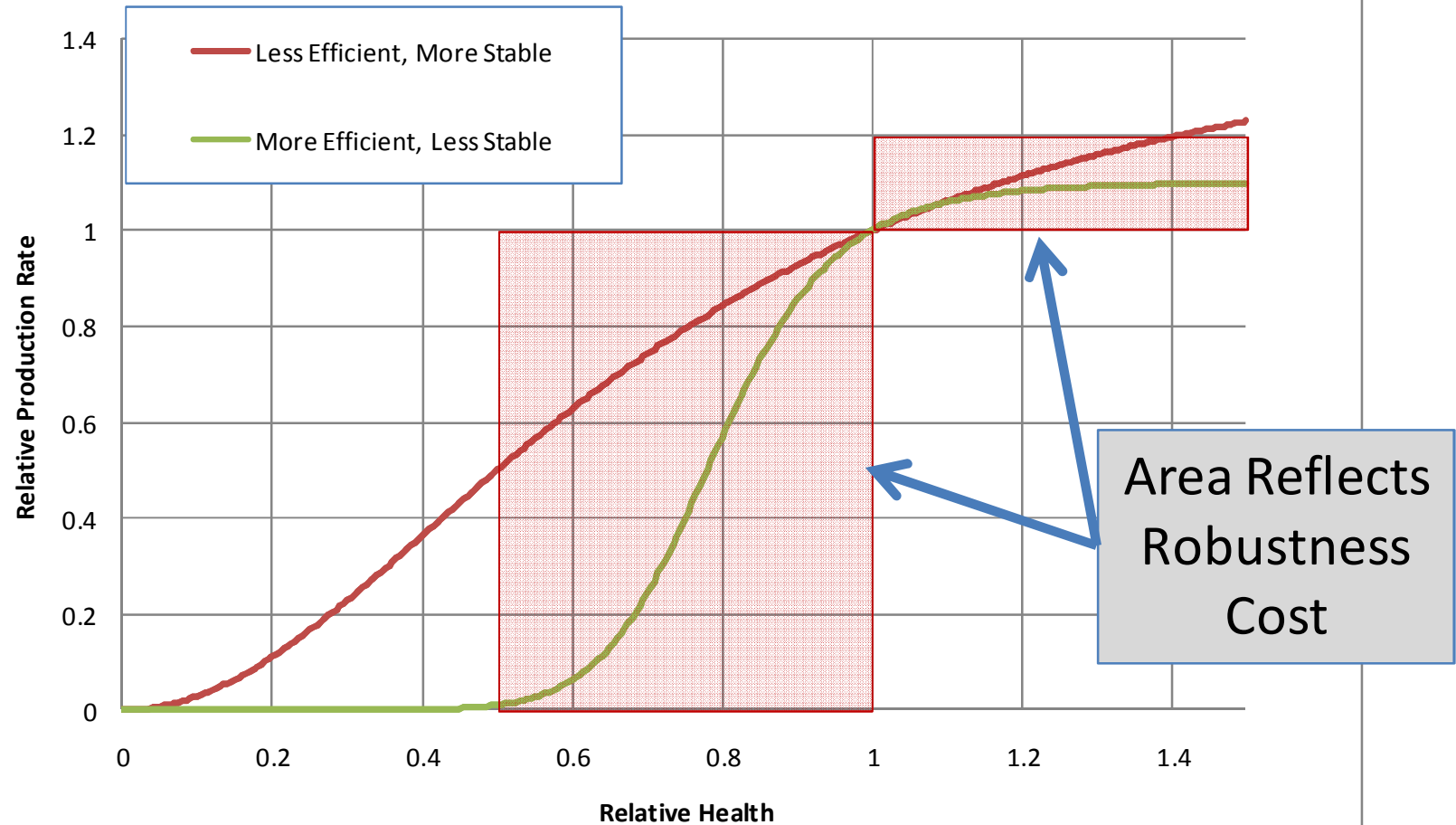
## Health Trajectories



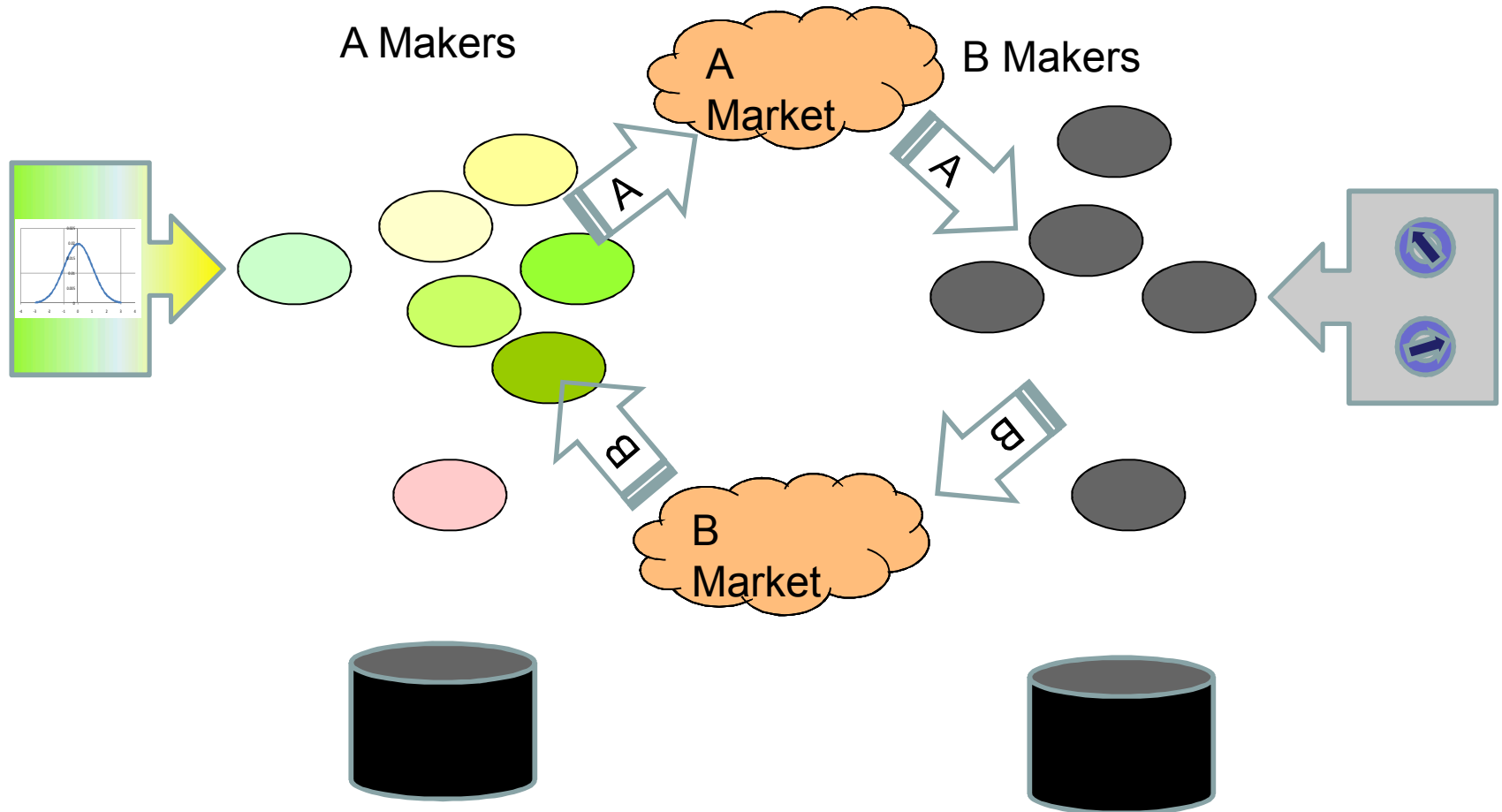
## Price Trajectories



# Robustness/Efficiency Tradeoff

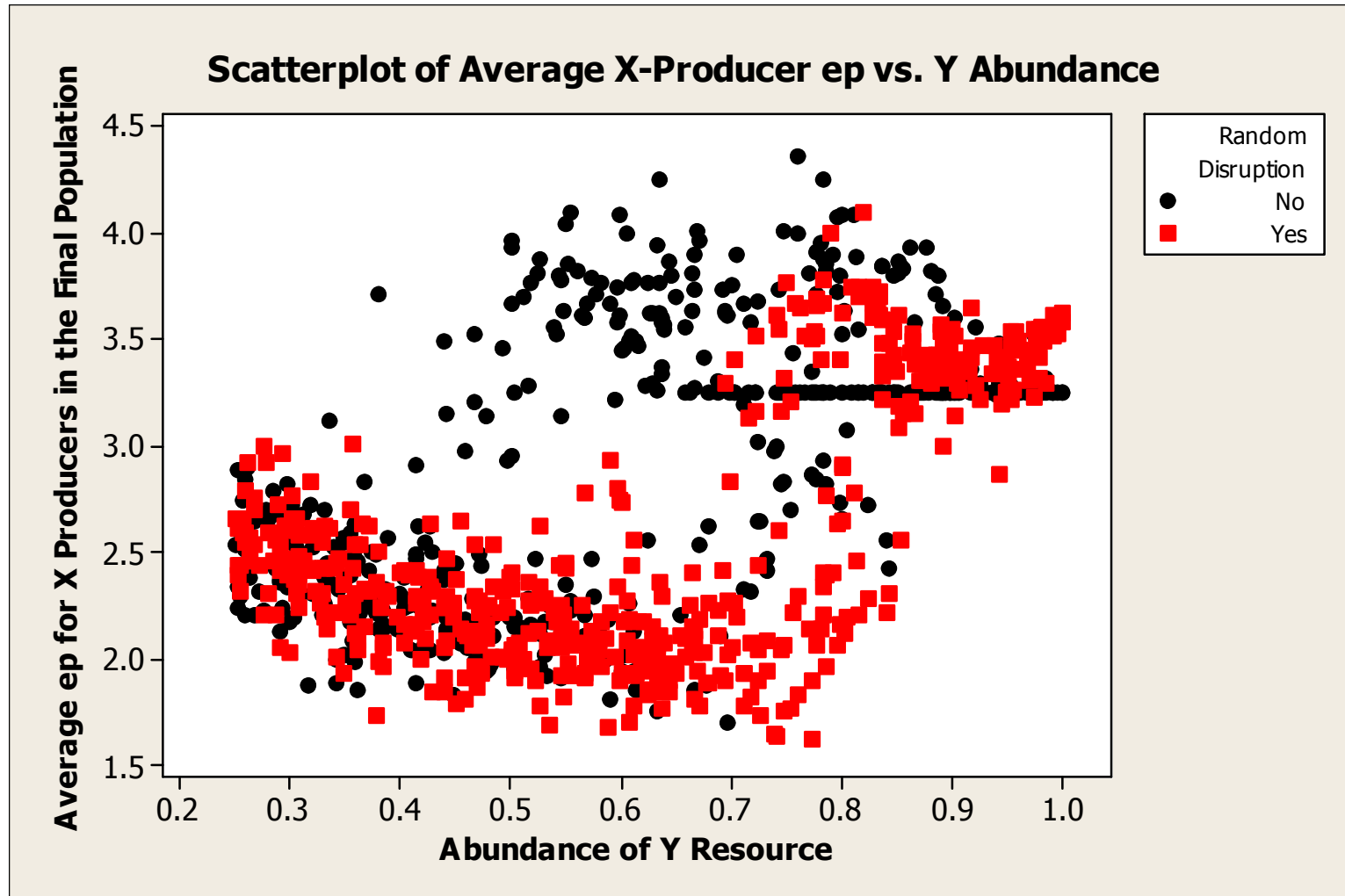


# Robustness/Efficiency Configuration

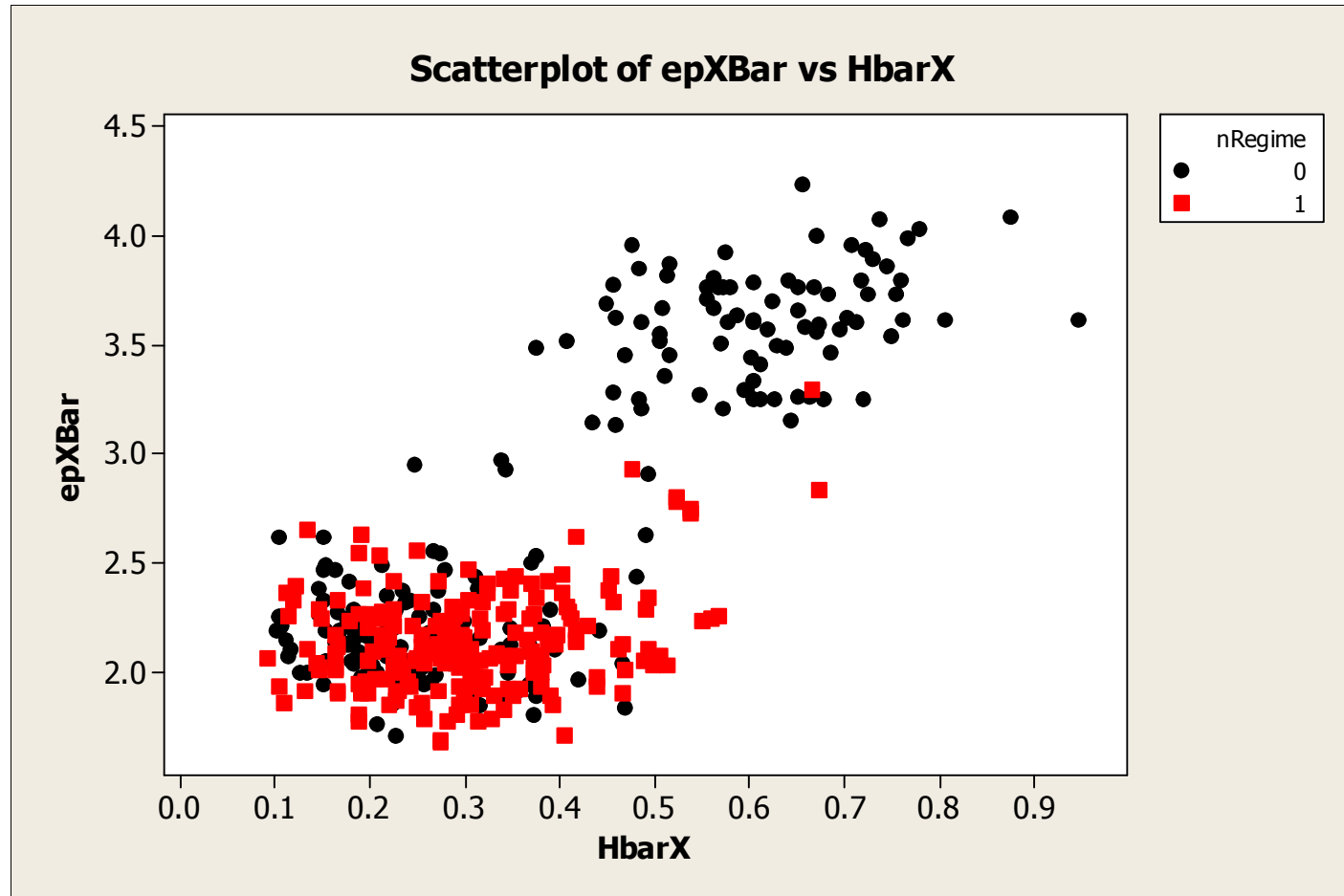




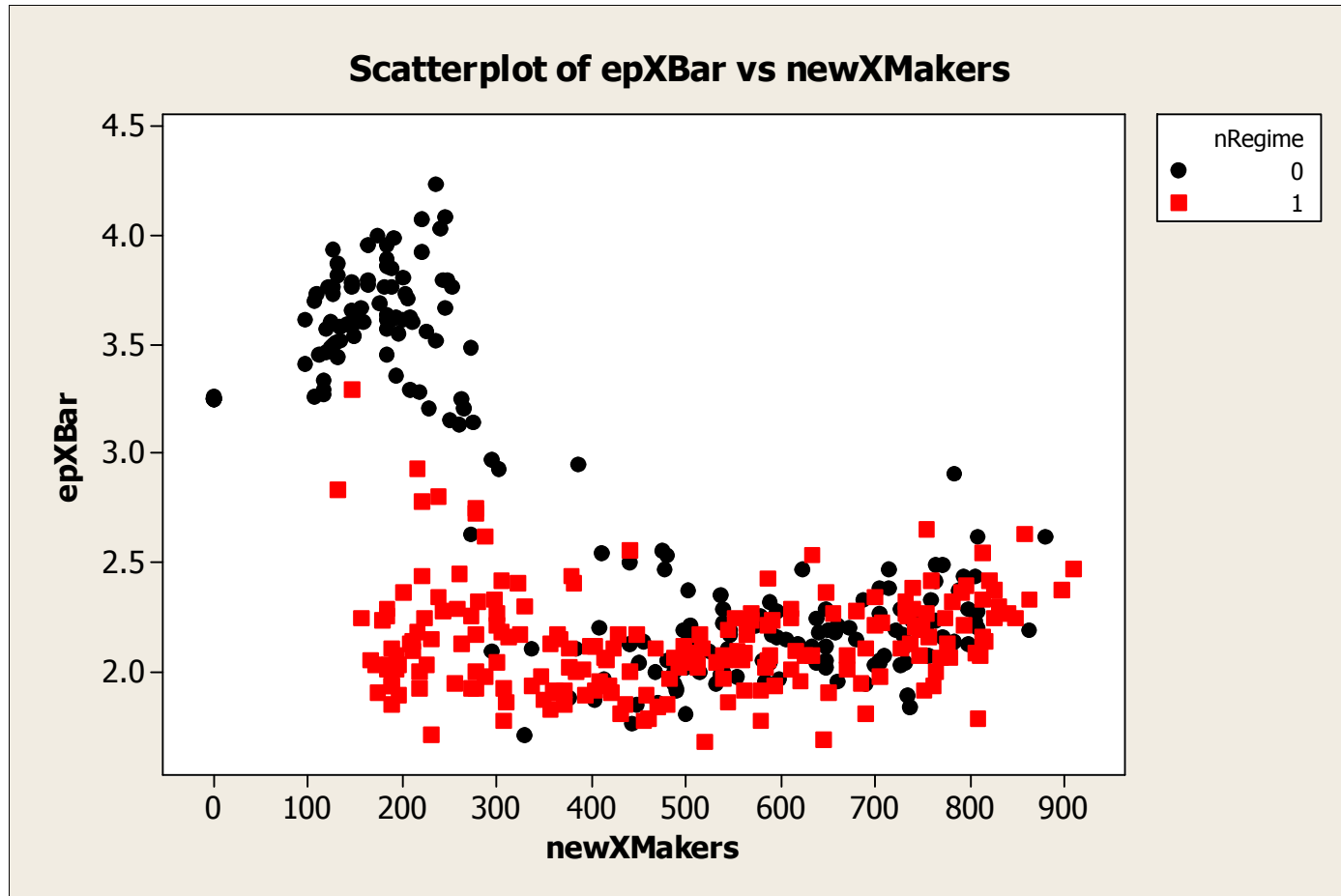
# Robustness/Efficiency Tradeoff



# Robustness/Efficiency Tradeoff

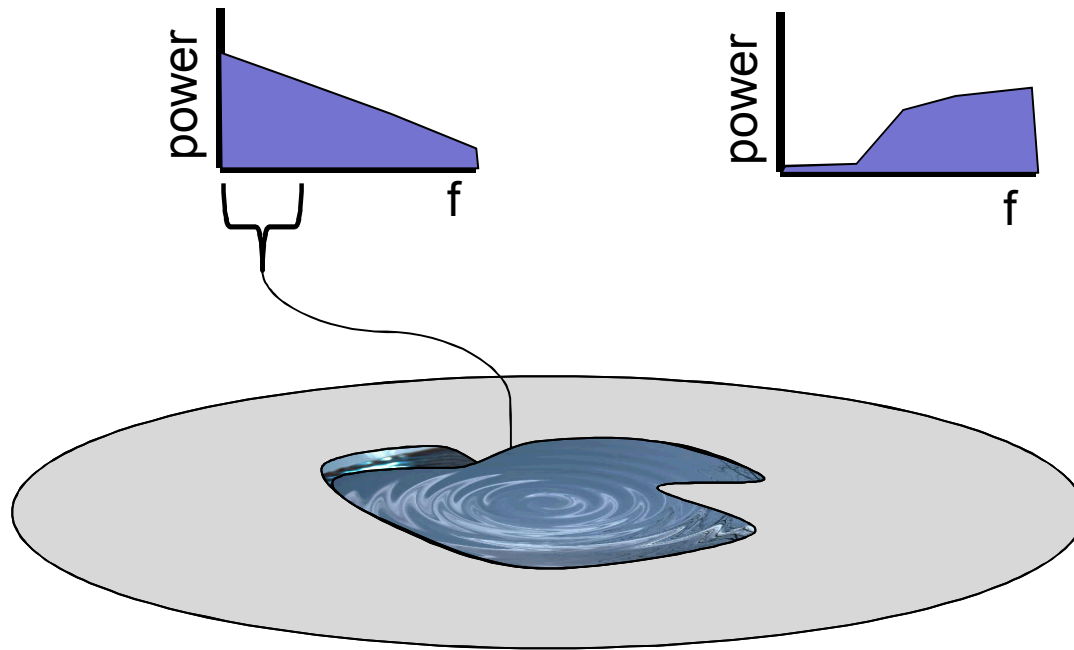


# Robustness/Efficiency Tradeoff



# 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

Walt Beyeler

Organization 6924, R&D Science and Engineering

Sandia National Laboratories

Albuquerque NM 87185-1138

[webeyel@sandia.gov](mailto:webeyel@sandia.gov)

<http://www.sandia.gov/CasosEngineering/>