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# CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

## Modeling Adaptation in Complex Systems

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**SAND**



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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*

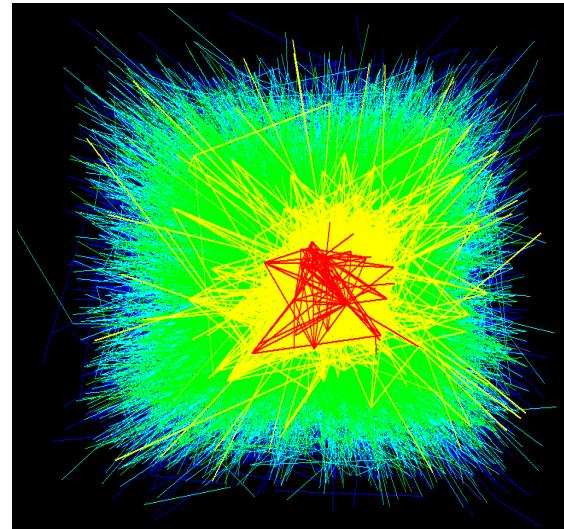
## Brief Biographical Note on Walt Beyeler

- 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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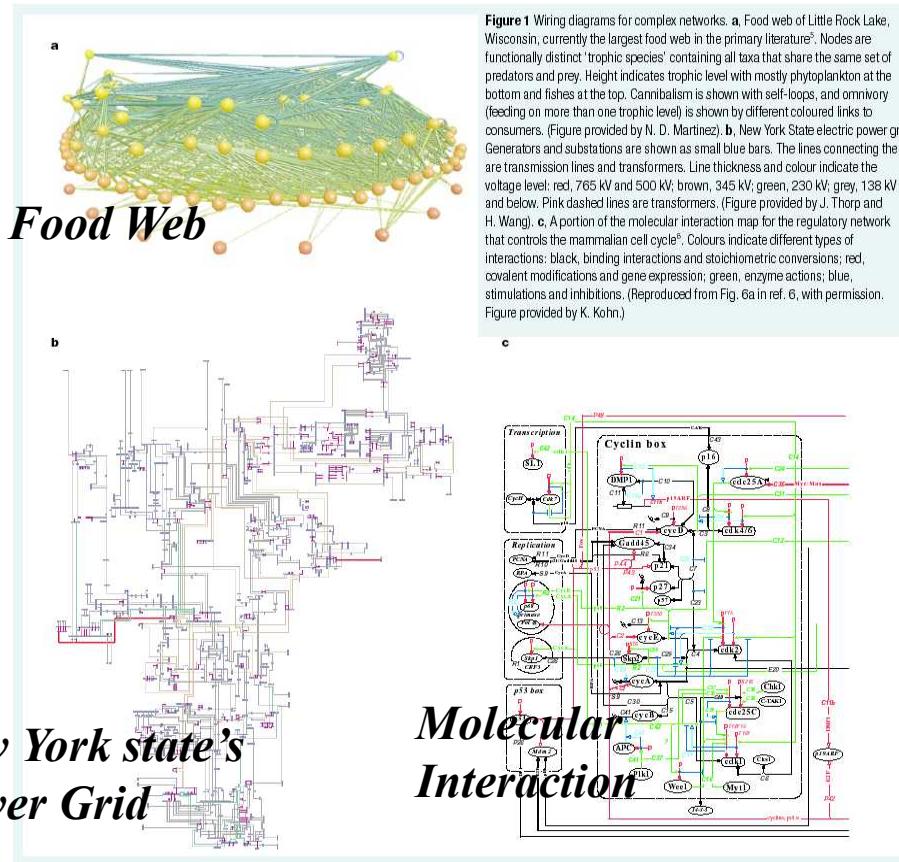
## *Adaptation and Complex Systems*



*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?



New York state's  
Power Grid

Molecular  
Interaction



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

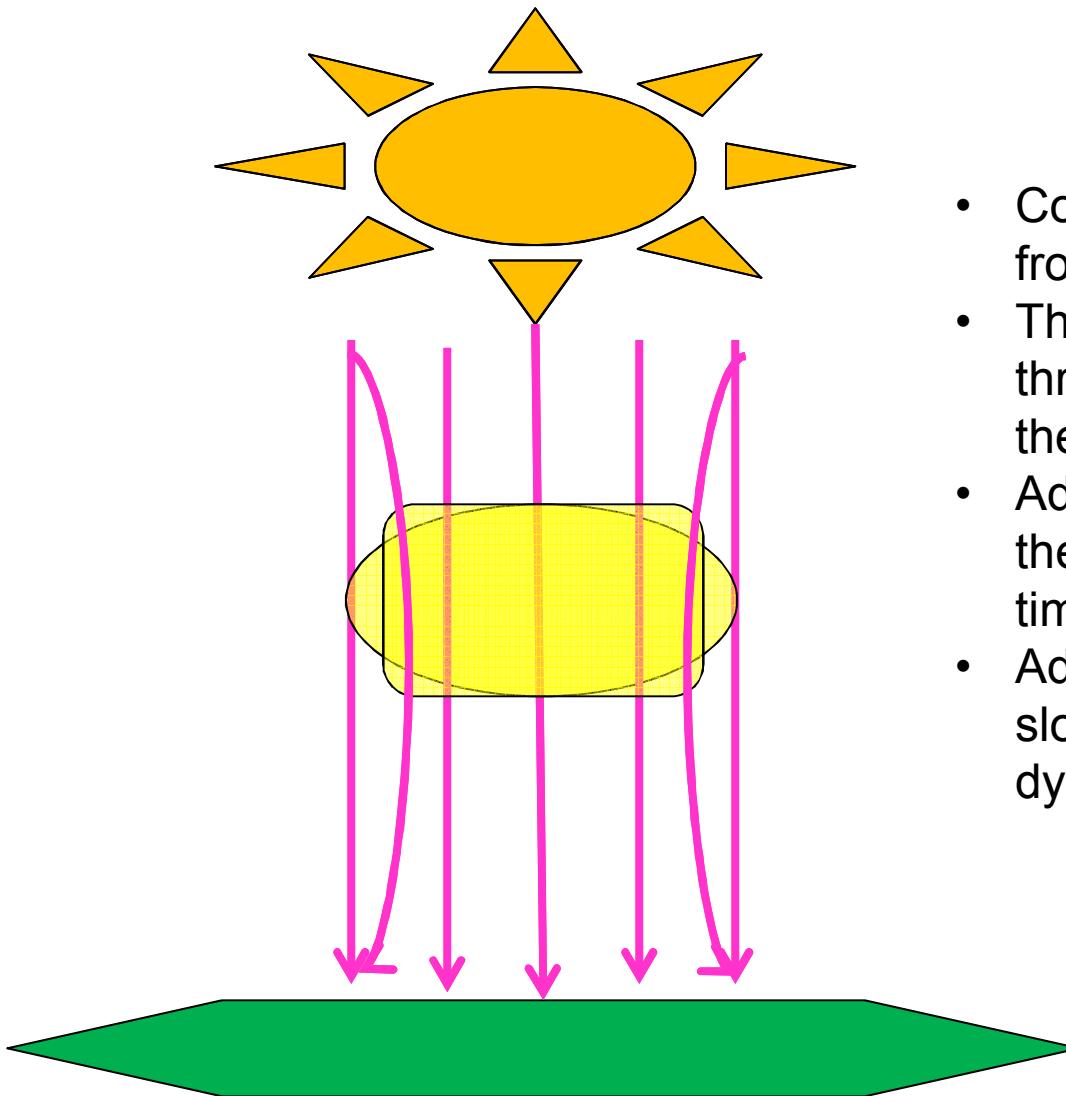
# Complex Systems

- 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

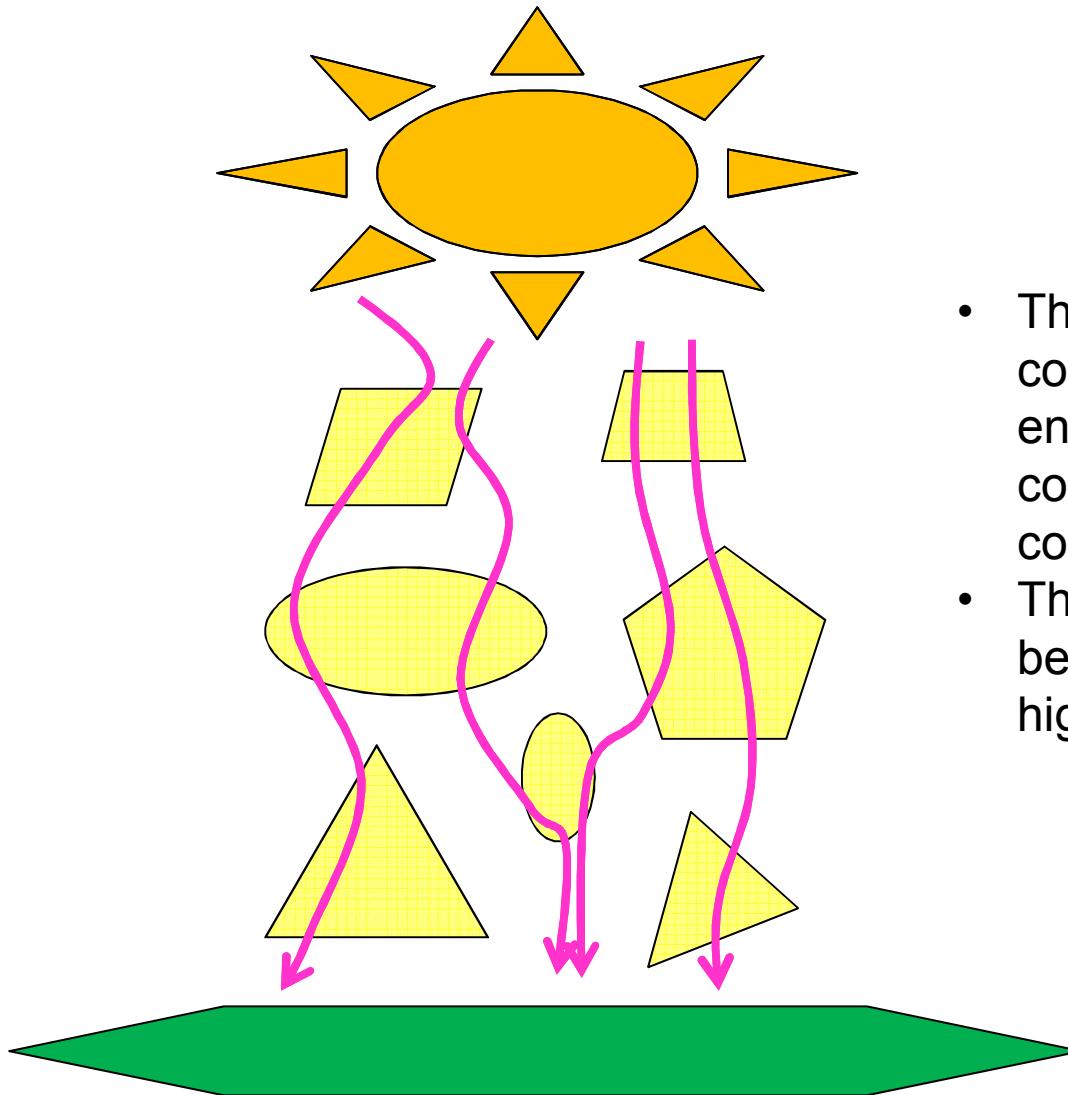
- Definition 0 – A change in a system in response to a change in its environment
  - .... Getting hit by a car?
- Definition 1 – A change that makes a system perform better in its environment
  - .... What if it's a lucky guess?
- Definition 2 – A change that makes a system perform better and that is 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

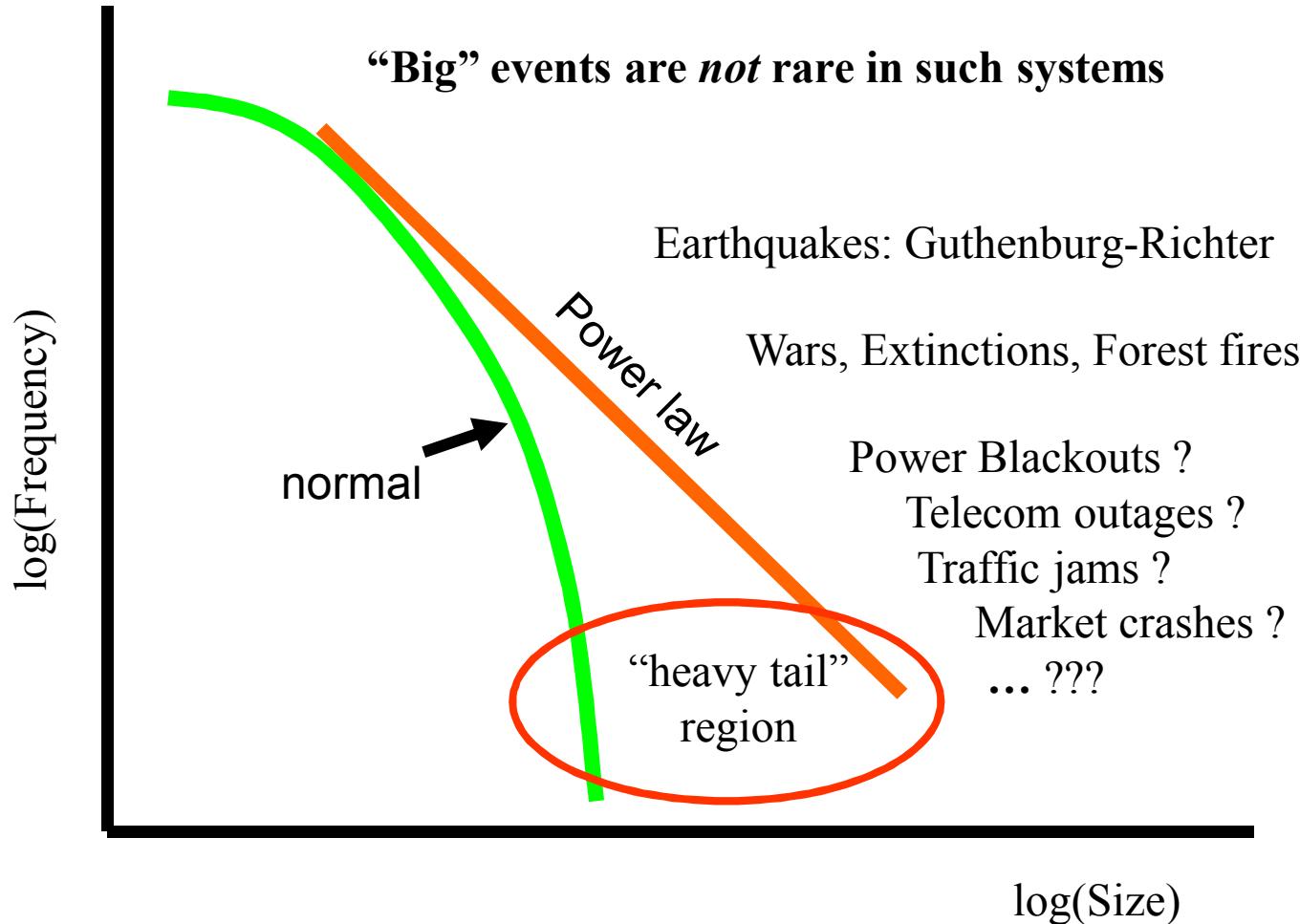


- The environment may consist of other adapting entities, creating a mesh of cooperative and competitive relationships
- These relationships might become reified in some higher-order structure

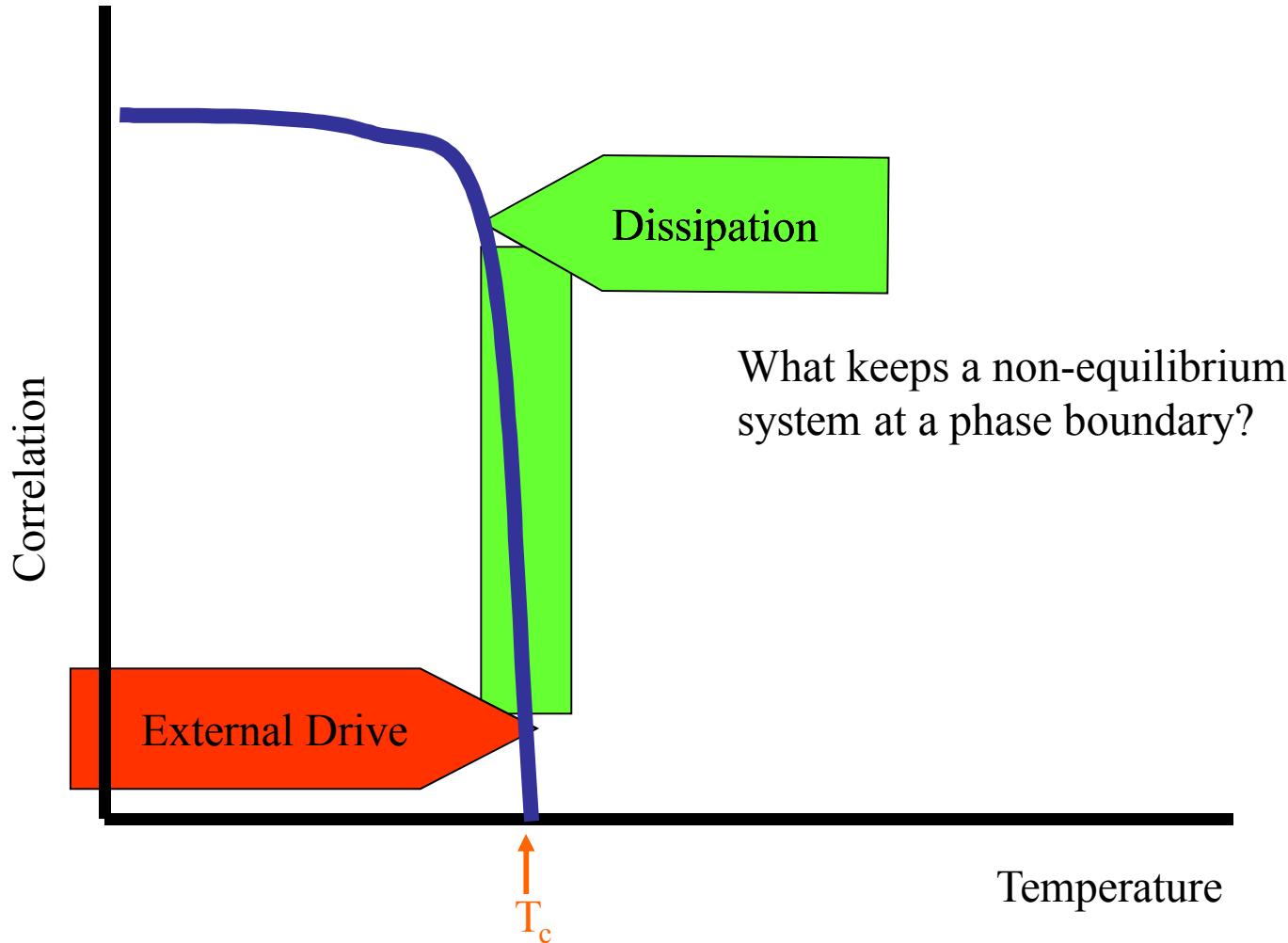
# Why Should You Care

- 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

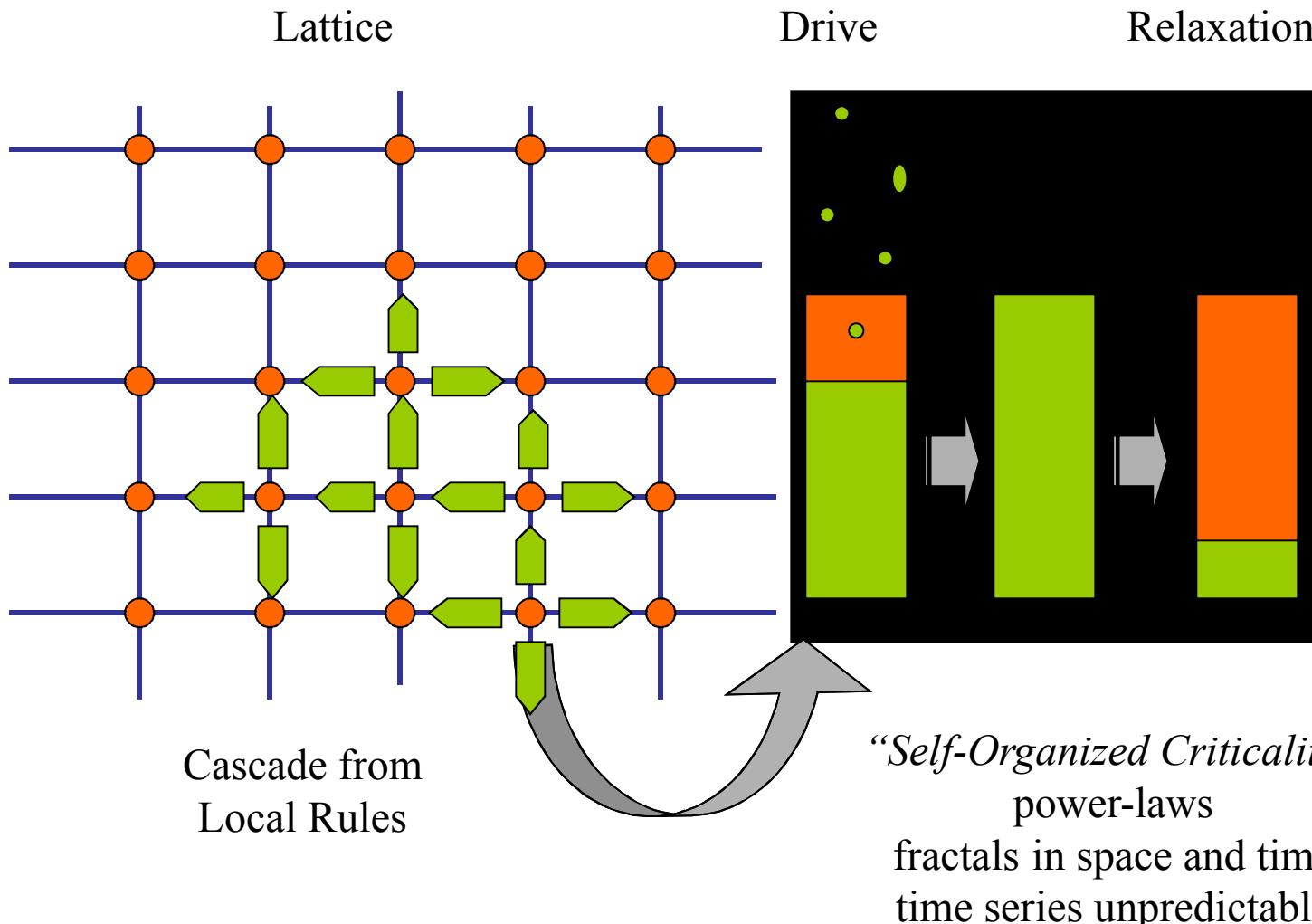


# Complex Behavior and Phase Transitions



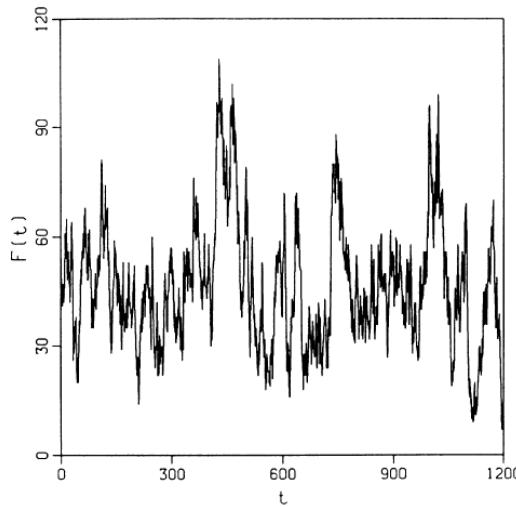
# Self-tuning Systems

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

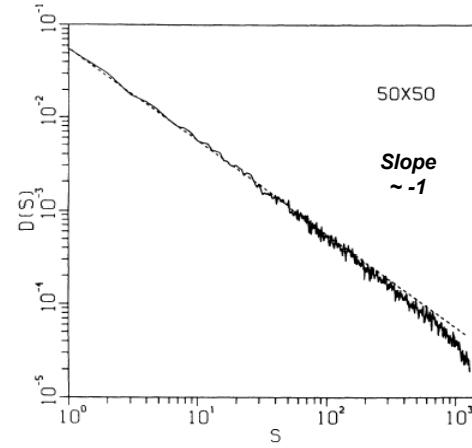


# BTW Results

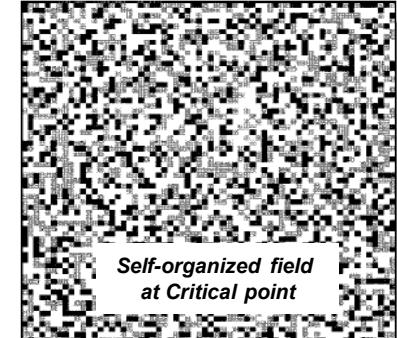
*“Self-Organized Criticality”*  
power-laws  
fractals in space and time  
time series unpredictable



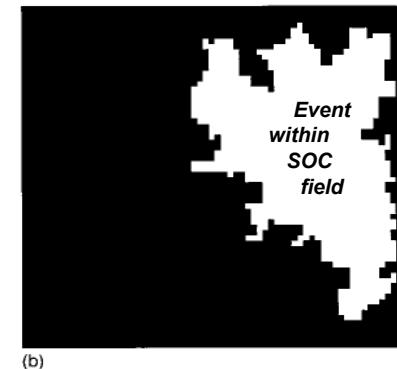
**Time Series of Events**



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



(a)



(b)

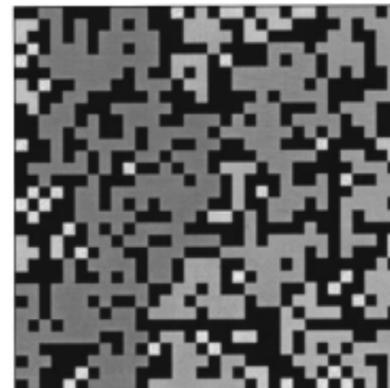
**Cascade Behavior**

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

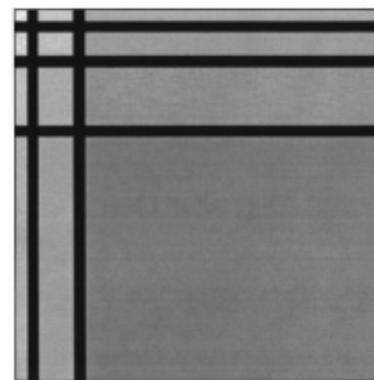
Simple forest fire example

- Robust yet Fragile
- Structure
- Power laws

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

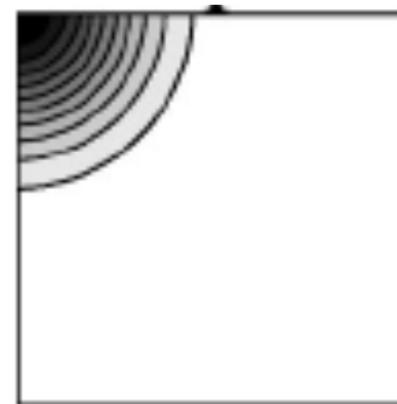


b)  $\rho=0.85, Y=0.75$

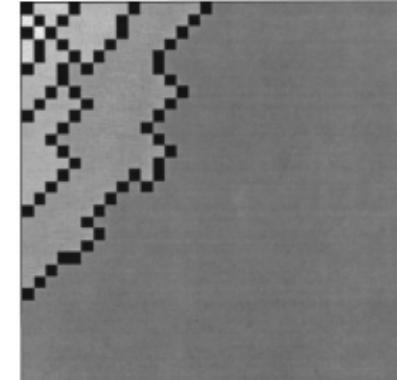


designed

External spark distribution

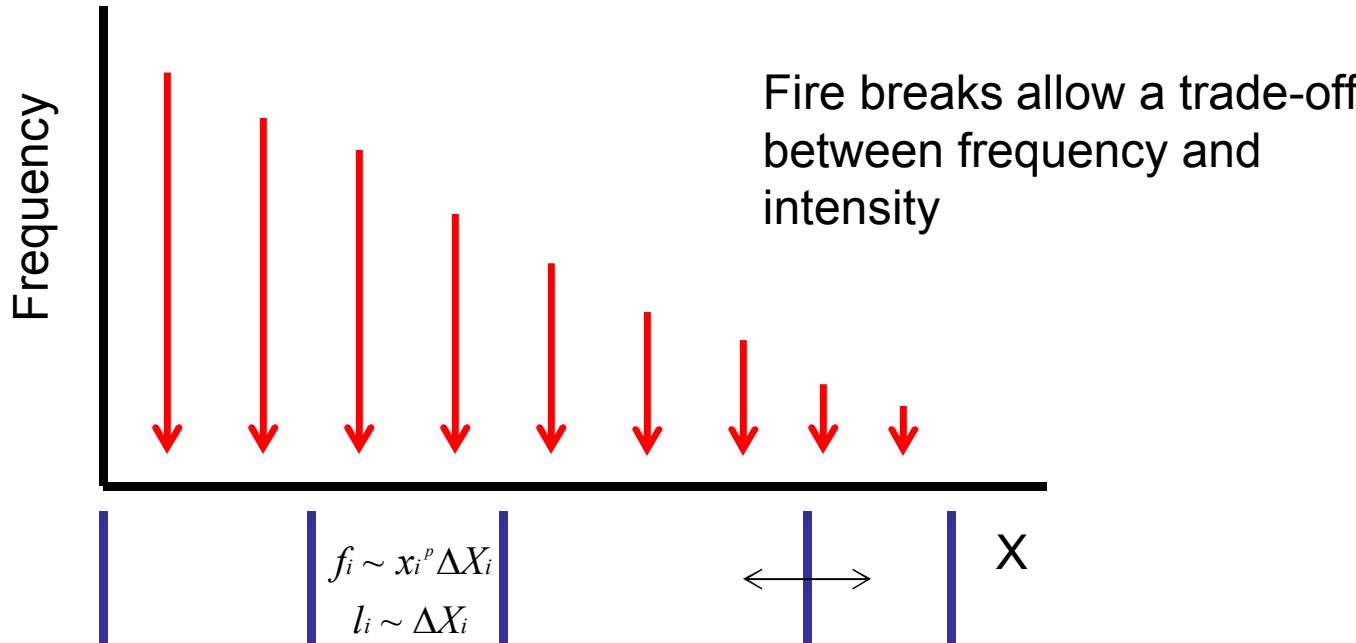


c)  $\rho=0.93, Y=0.93$



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

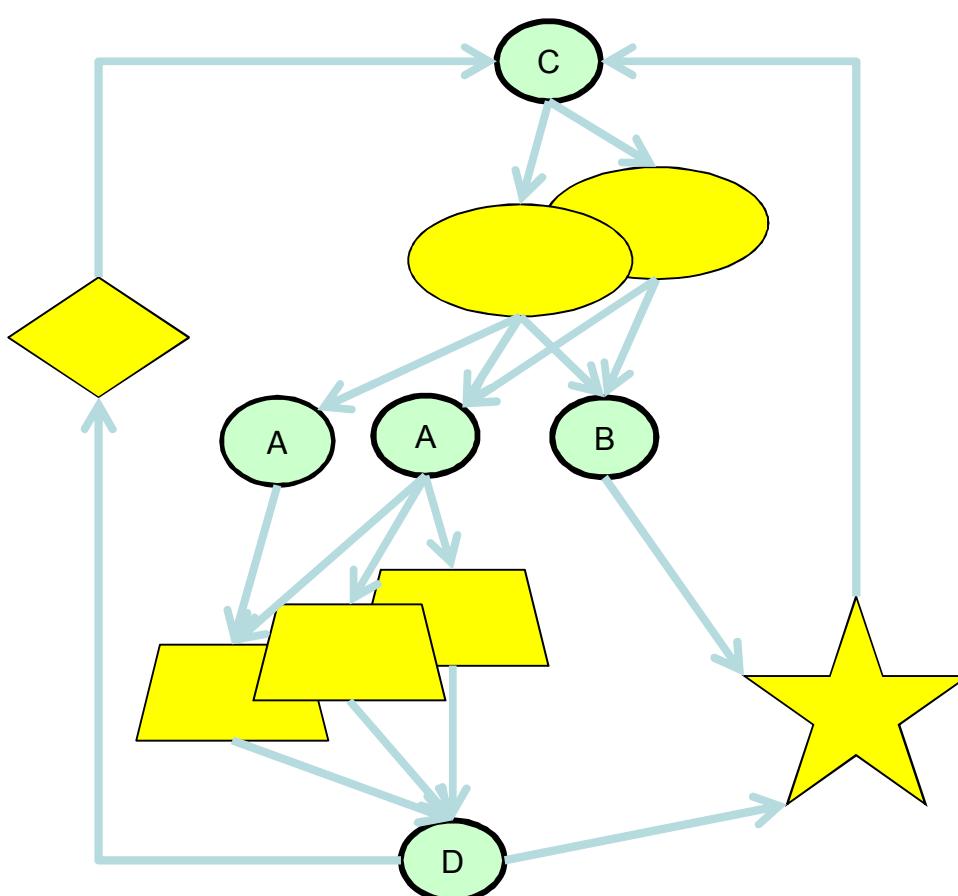
Spider webs designed for rare but life-saving catches  
Samuel Venner and Jerome Casas  
Proc. R. Soc. B (2005) 272, 1587–1592  
Adaptation to the Edge of Chaos in the Self-Adjusting Logistic Map  
Paul Melby, Jorg Eaidel, Nicholas Weber, Alfred Hubler  
PRL, Vol 84 No 26, p5991
- Relationships among components

Spontaneous Emergence of Complex Optimal Networks through Evolutionary Adaptation  
Venkat Venkatasubramanian, Santhojoji 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

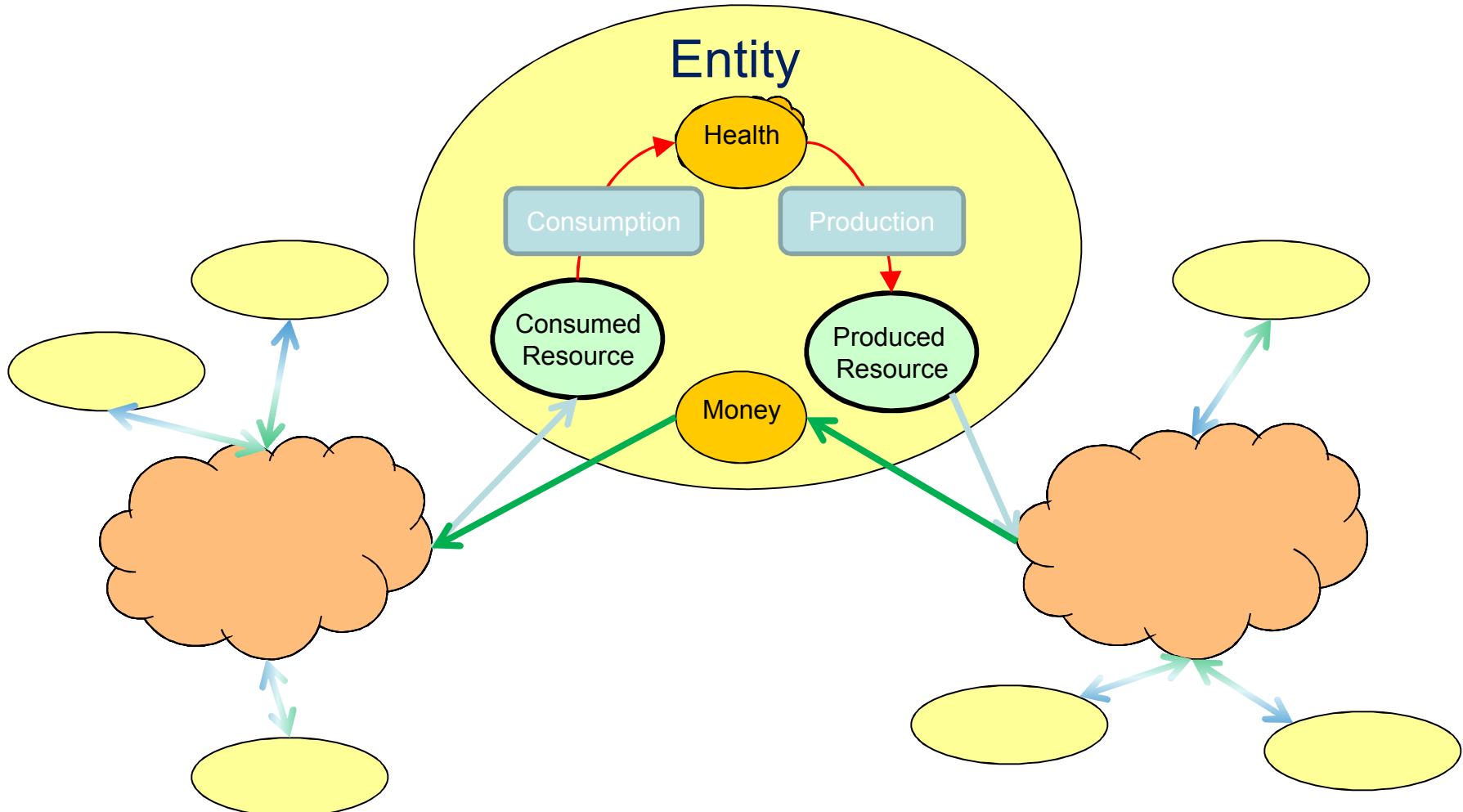


- Resource consumption and production by entities
- Resource exchange among entities
- Change in entities' state as they respond to resource availability
- Change in entity size or capacity
- Change in connection patterns among entities
- Change in the kinds of entities in the system

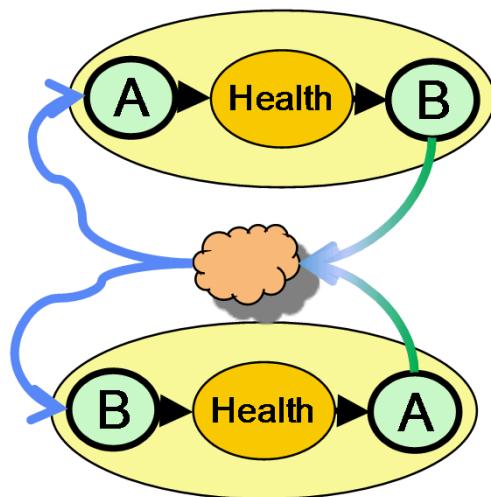
- Only some of these might be relevant for a particular problem. Time constants generally increase from top to bottom, so that slow processes can be considered “frozen”.
- The framework allows us to include all of these processes, and to set time constants so that the dynamics interact

# Basic Elements



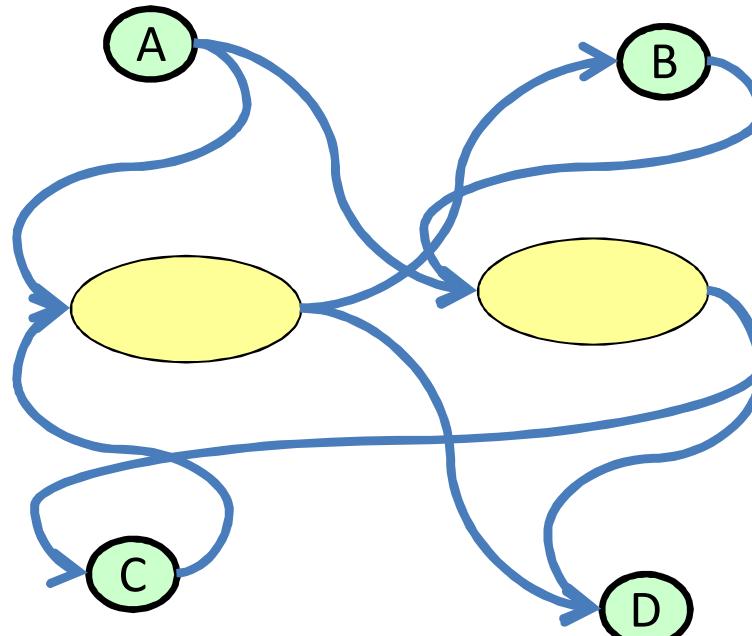
# Exploring Simple Patterns of Interaction

## Complete Interdependency



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

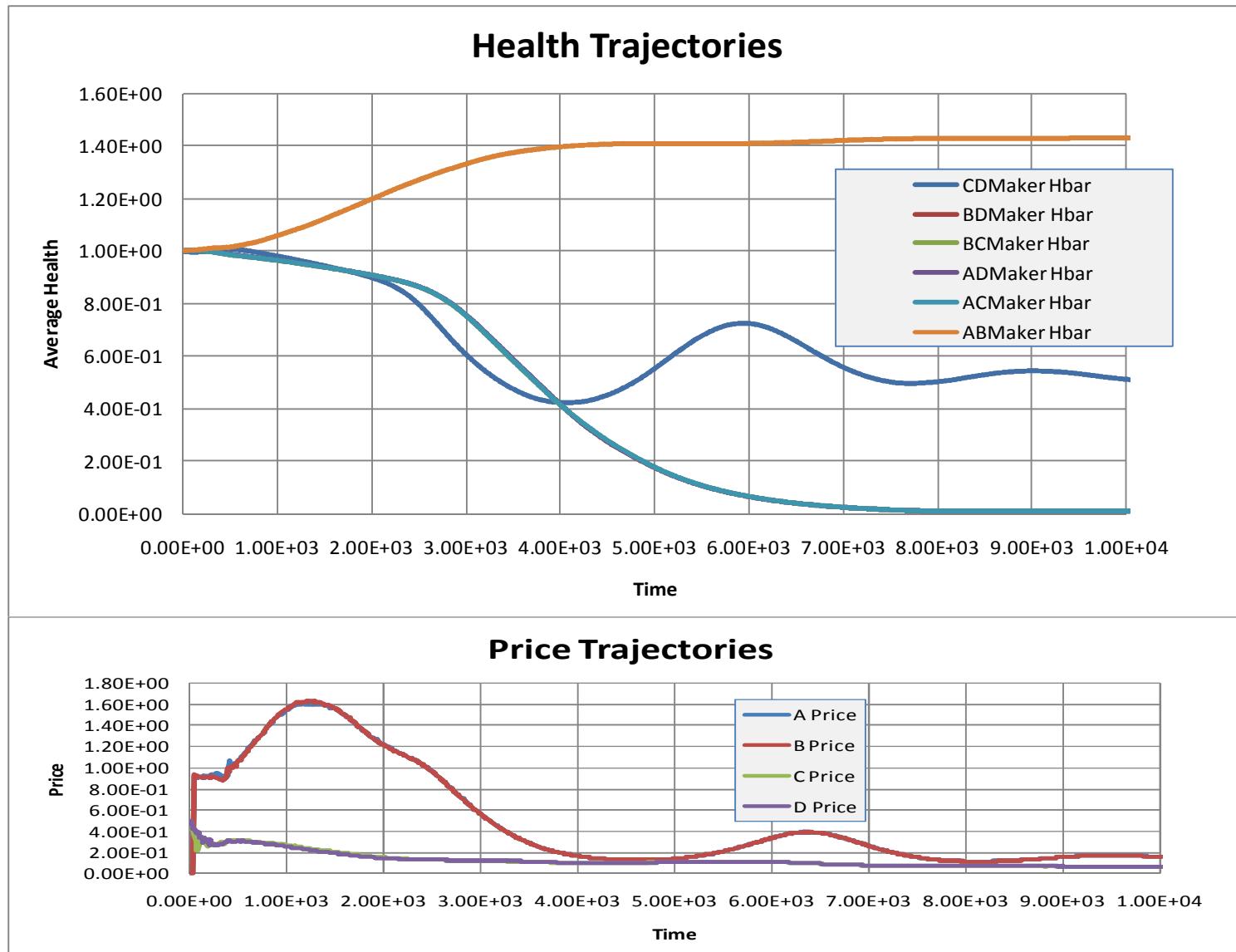
Using four resources minimally allows for  
input substitution and output specialization



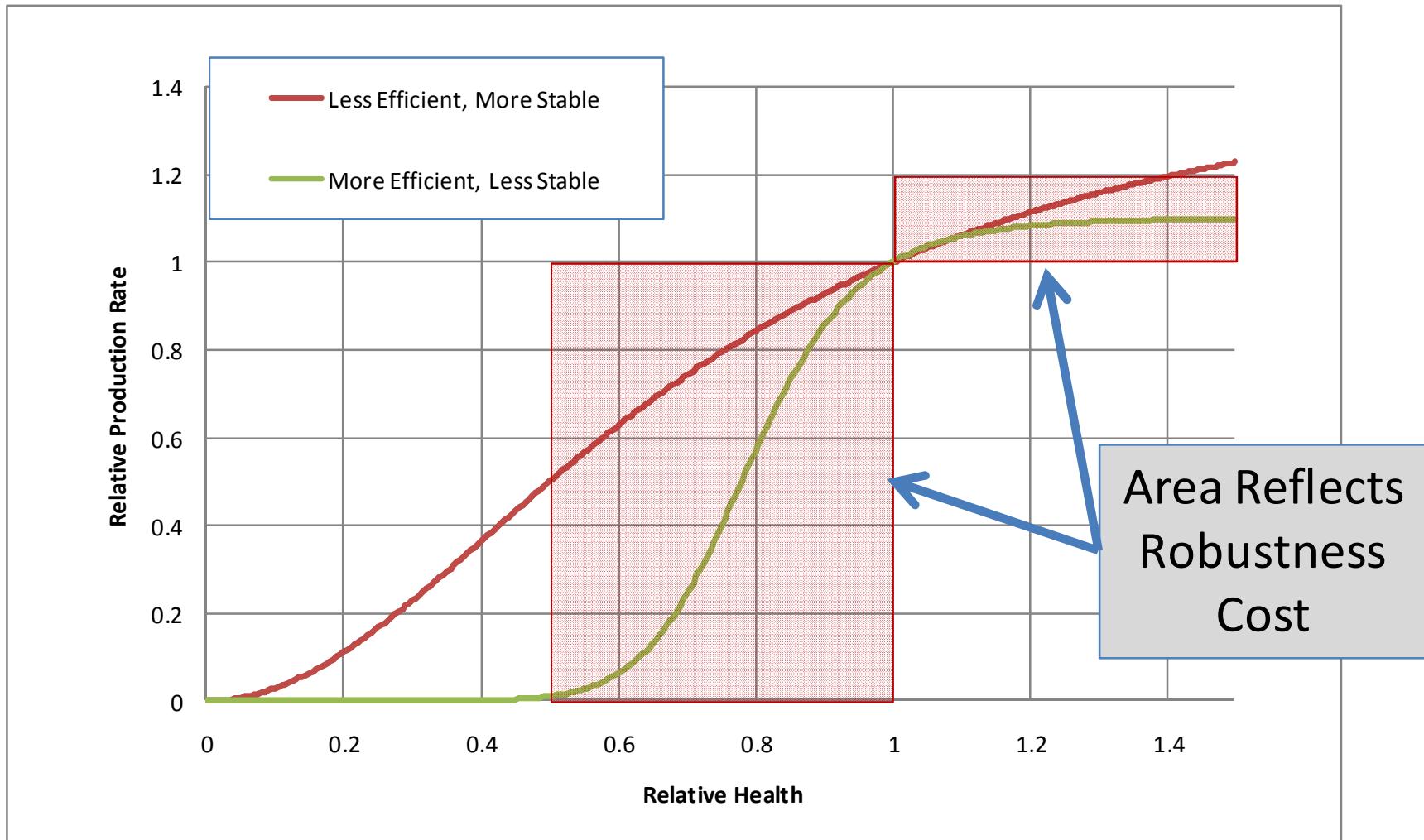
What happens when one type  
is especially productive?

Six distinct  
input/output  
patterns are  
possible

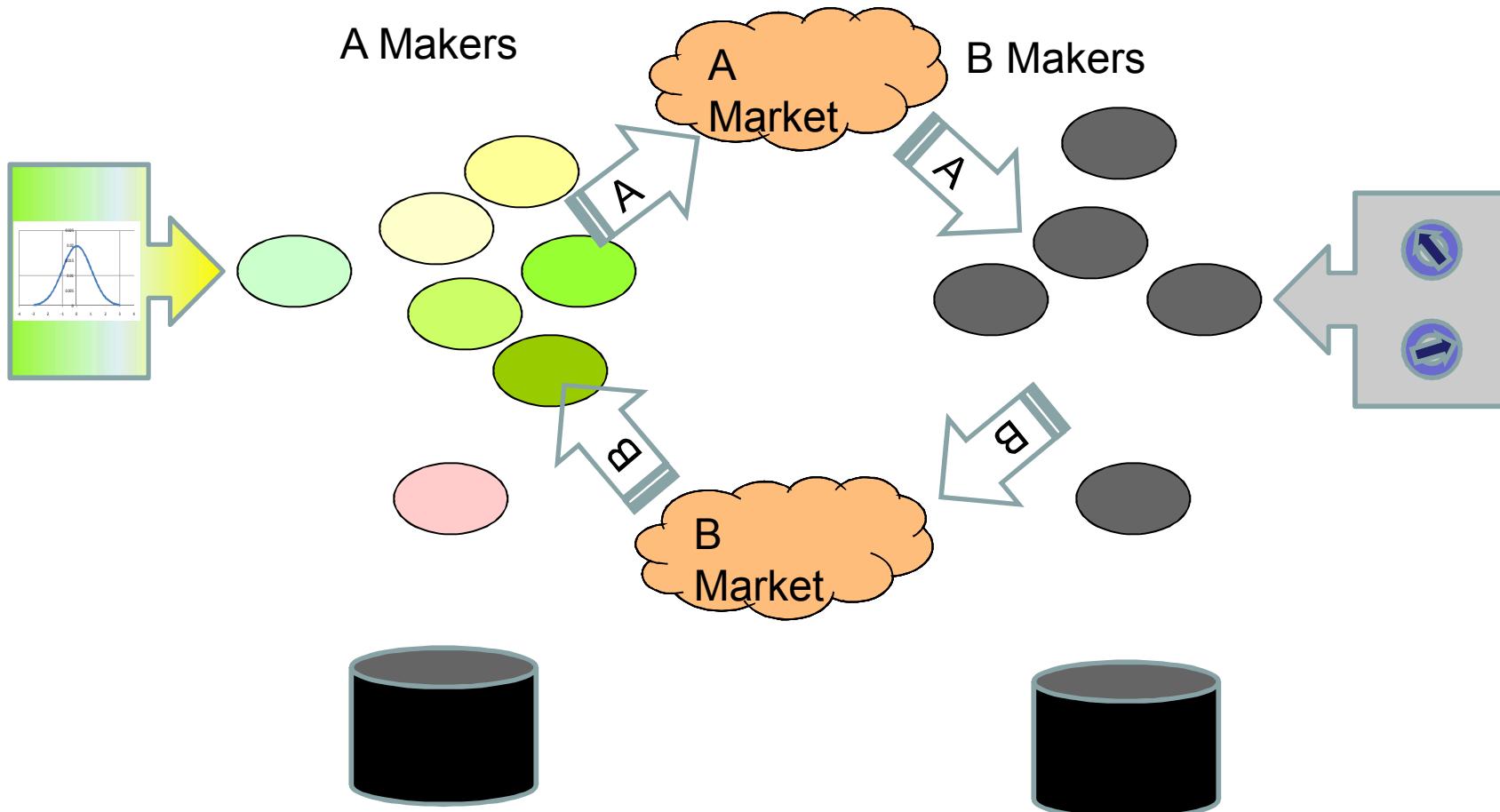
# Competitive Exclusion



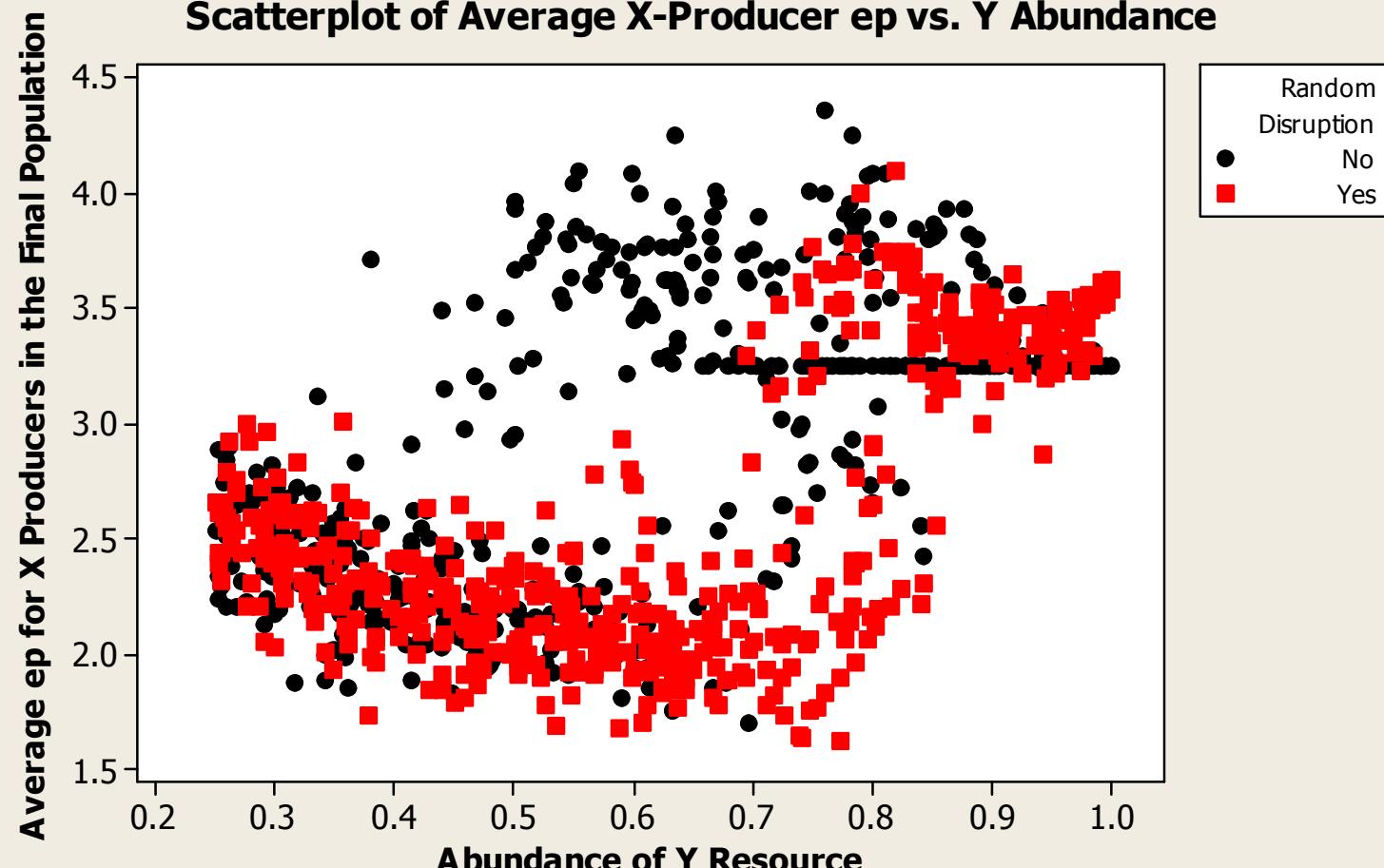
# Robustness/Efficiency Tradeoff



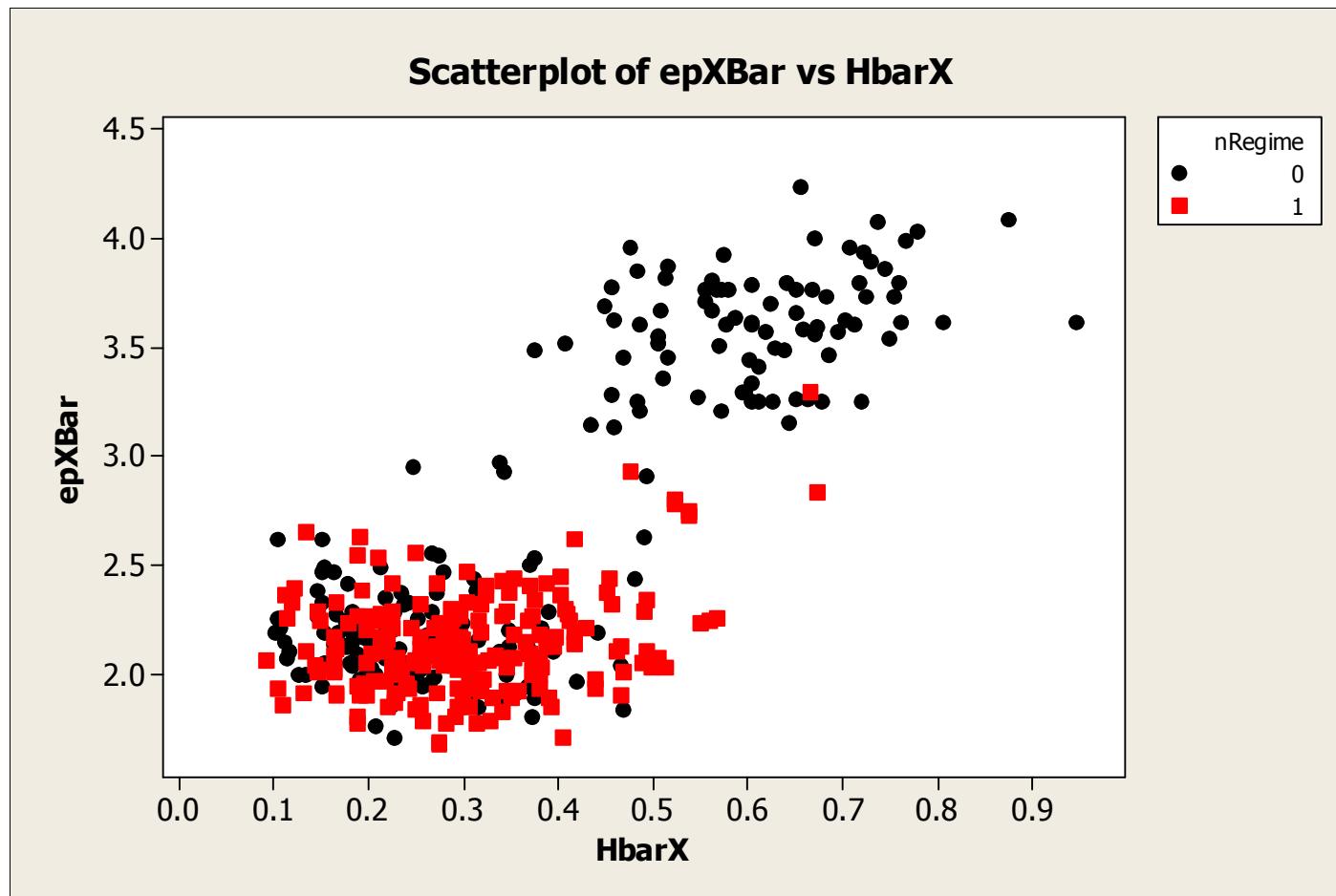
# Robustness/Efficiency Configuration



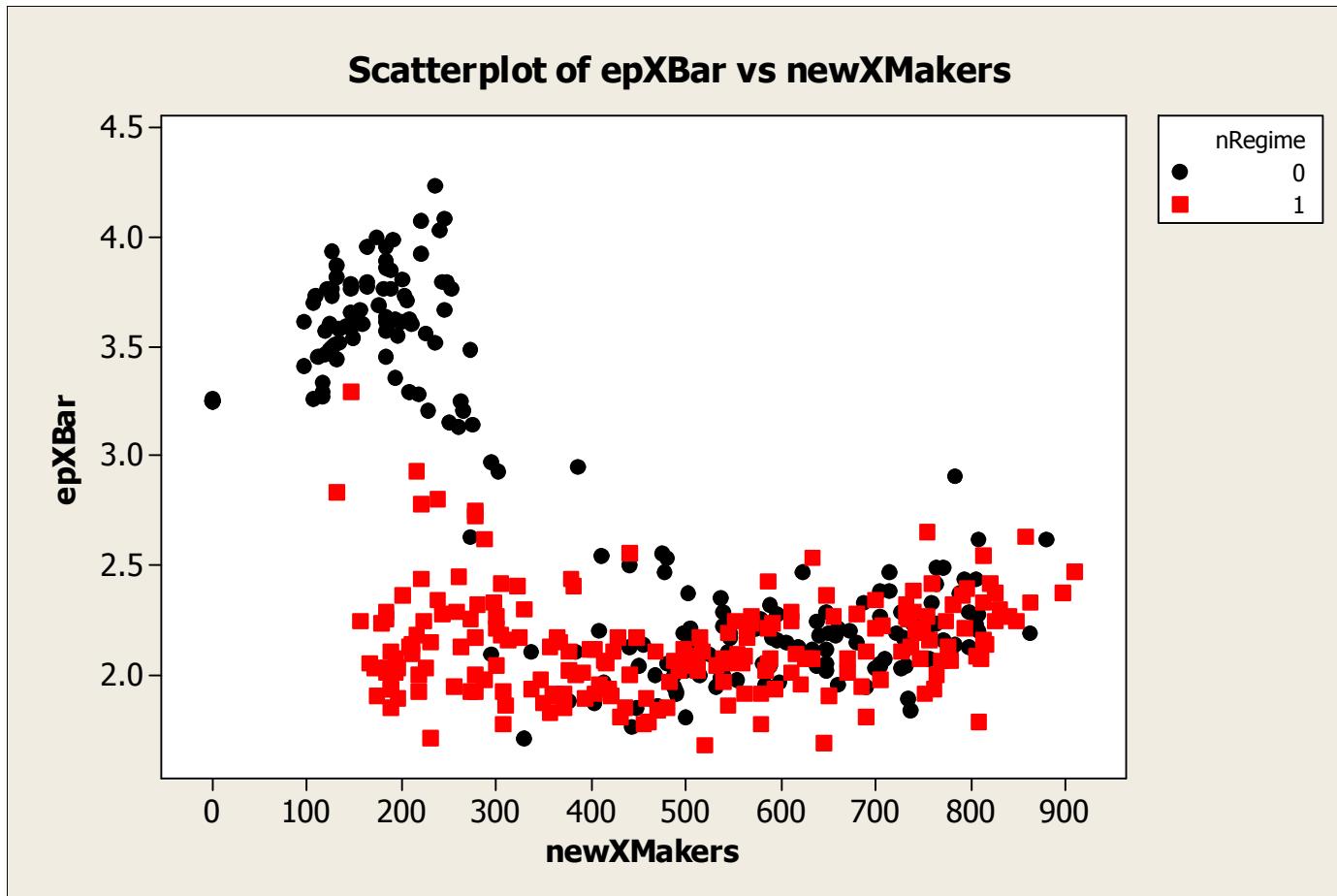
# Robustness/Efficiency Tradeoff



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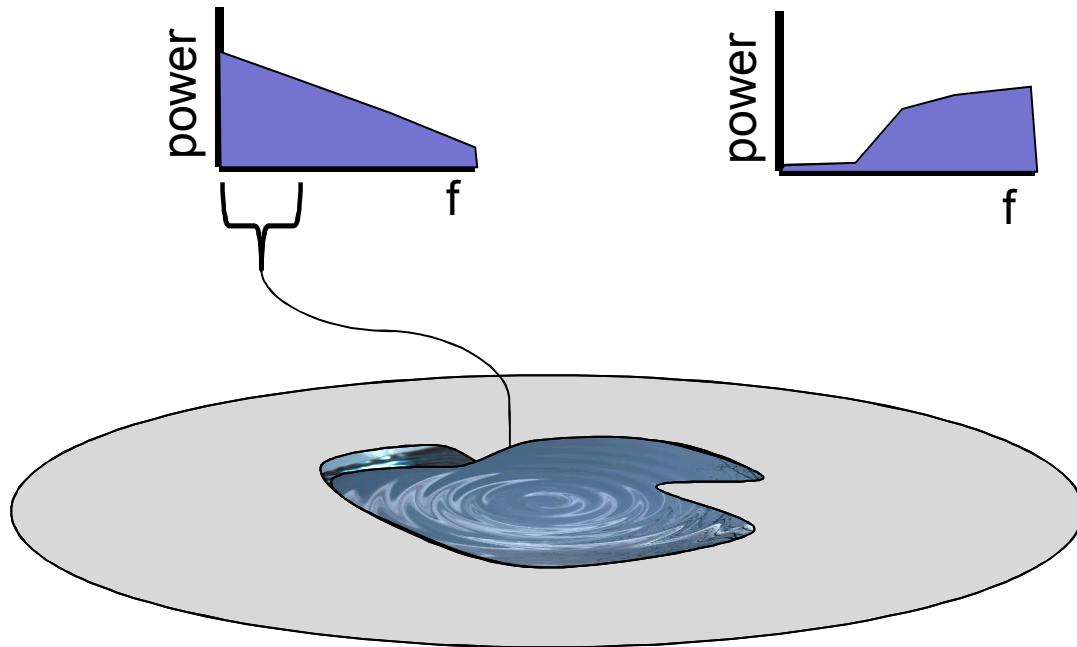


# Robustness/Efficiency Tradeoff



# 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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