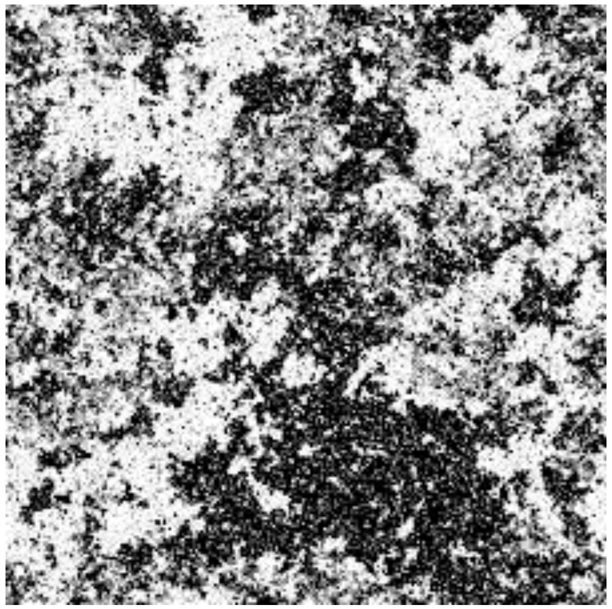
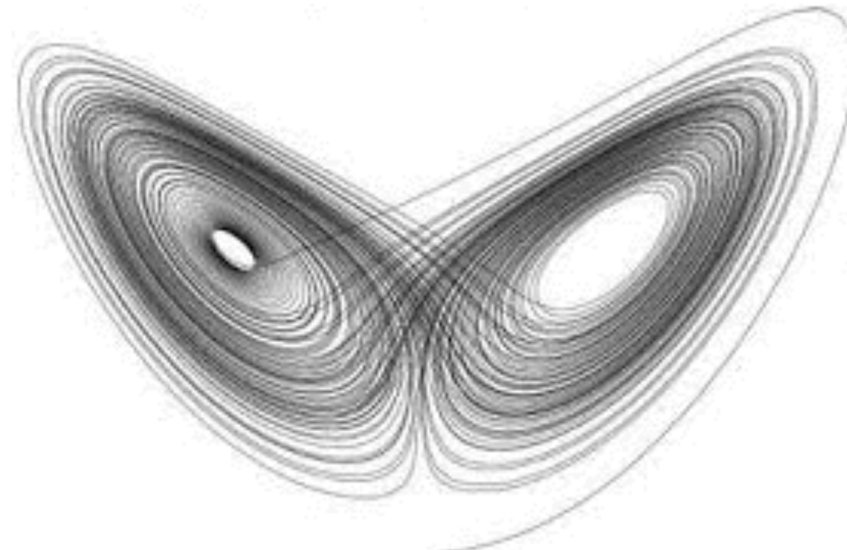
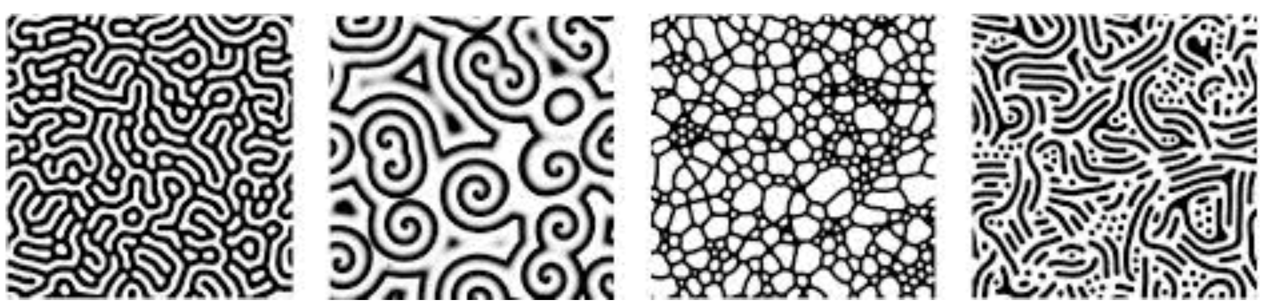
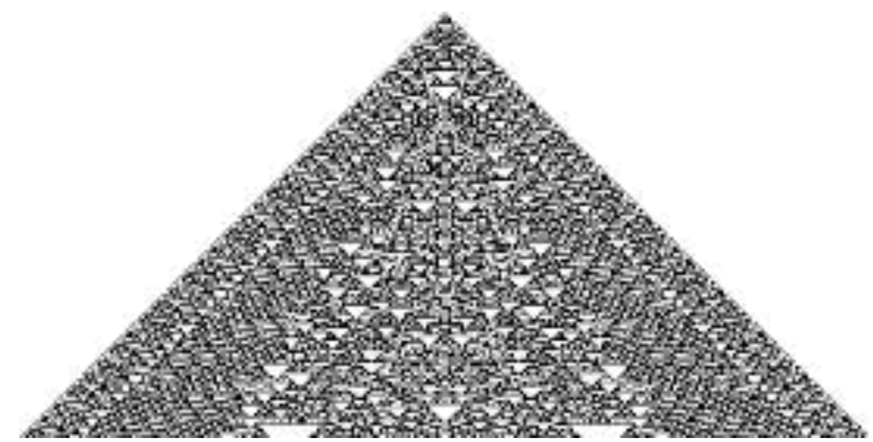
Computational Physics and Complexity (PHY 315)









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Introduction to Complex Systems

What are Complex Systems?

The natural world is dominated by complicated processes

YET

these processes give rise to simply describable behaviors.

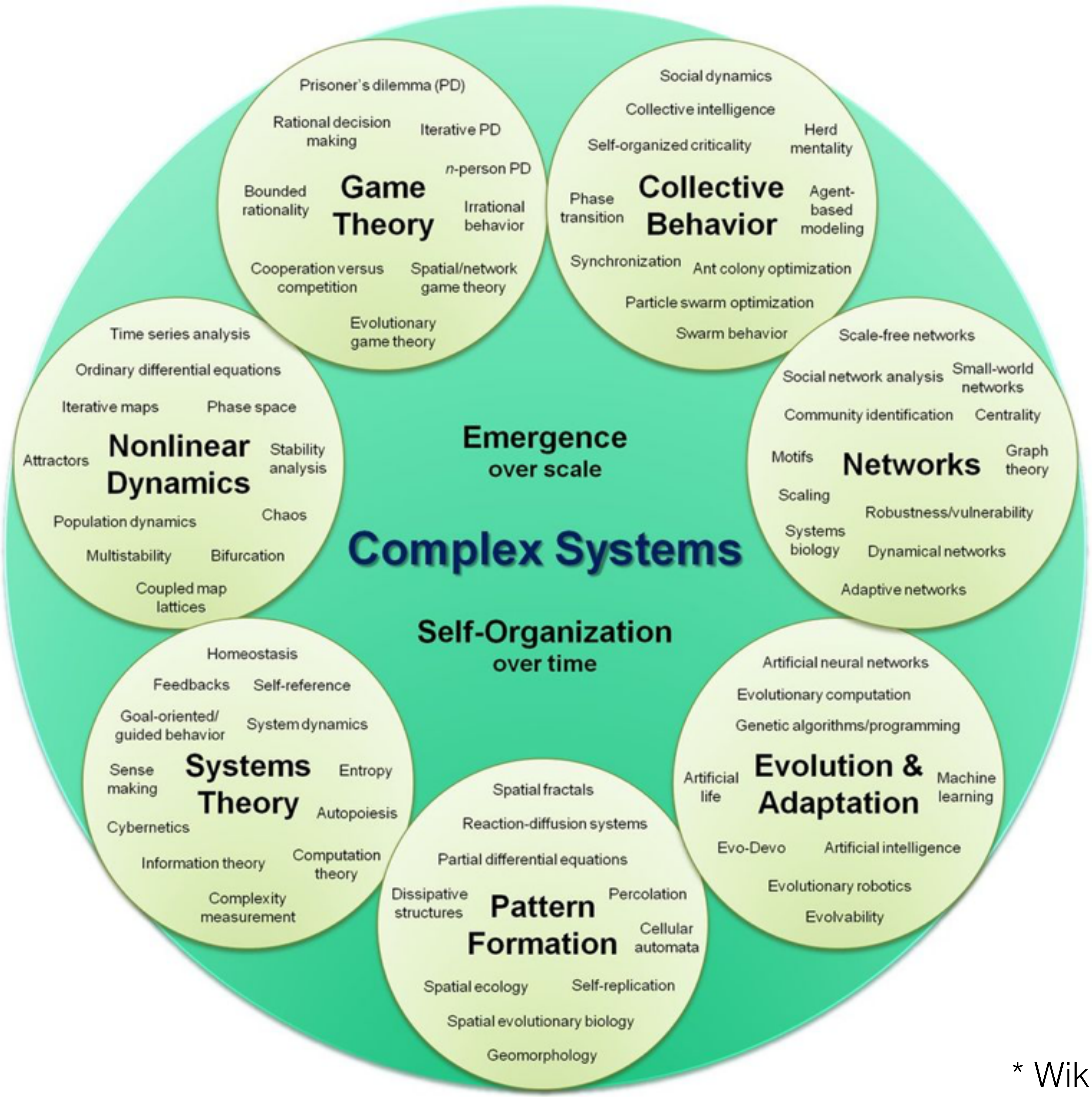
What are Complex Systems?

- **Networks of many components**
- **Components have nonlinear interactions**
- **Scale separation**
- **Show emergent structure**
- **Look both simple and complicated**

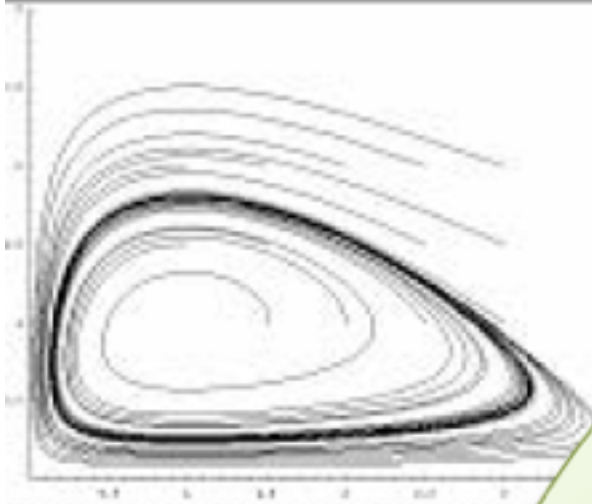
What are Non Complex Systems?

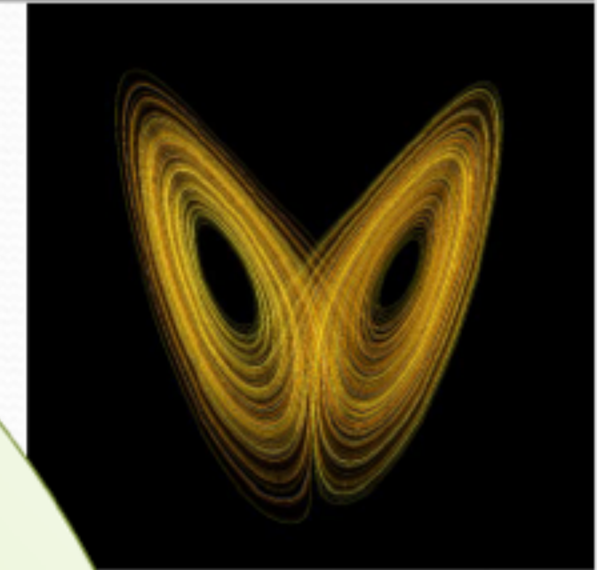
- Collection of independent parts
  - ➡ Ideal gas, random coin tosses
  - ➡ Statistical mechanics works
- Collection of strongly linked parts with no degrees of freedom
  - ➡ Rigid body
  - ➡ Classical mechanics works

REAL SYSTEMS ARE SOMEWHERE IN-BETWEEN



* Wikipedia view





Time series analysis

Ordinary differential equations

Iterative maps

Phase space

Attractors

Nonlinear Dynamics

Stability analysis

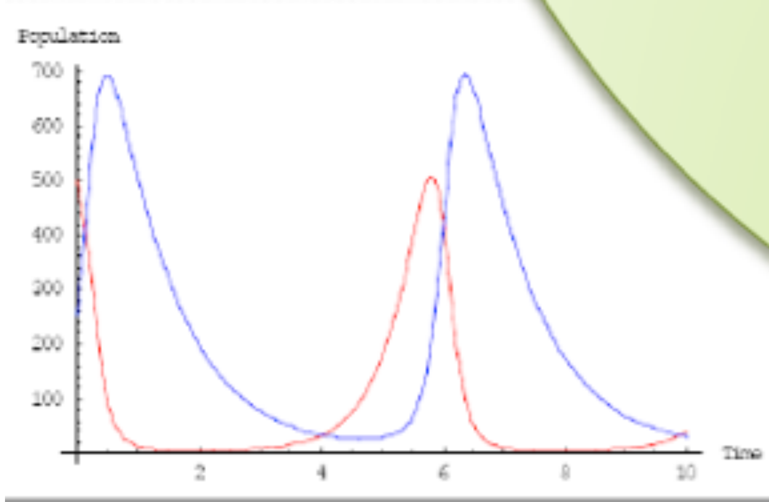
Chaos

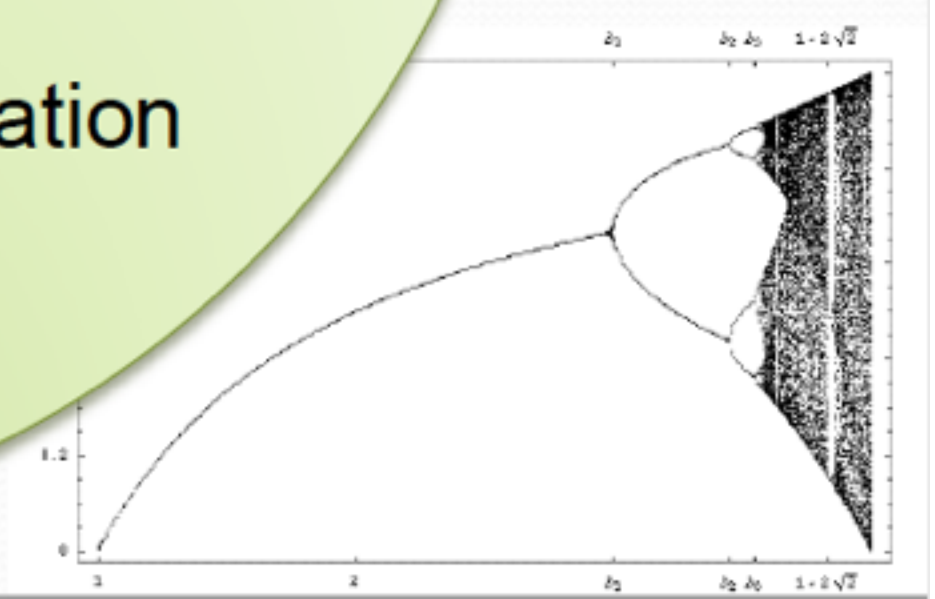
Population dynamics

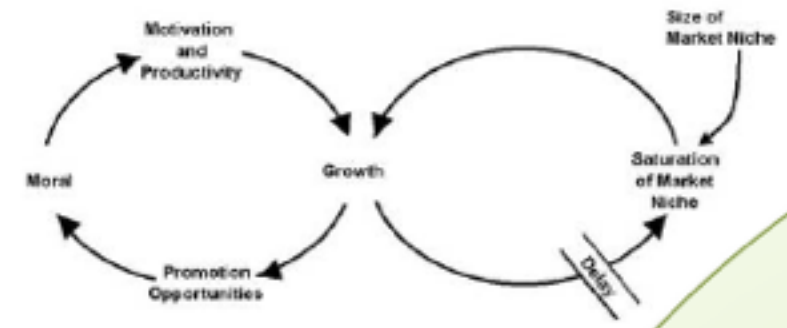
Multistability

Bifurcation

Coupled map lattices







Homeostasis

Feedbacks

Self-reference

Goal-oriented/
guided behavior

System dynamics

Sense
making

Systems Theory

Entropy

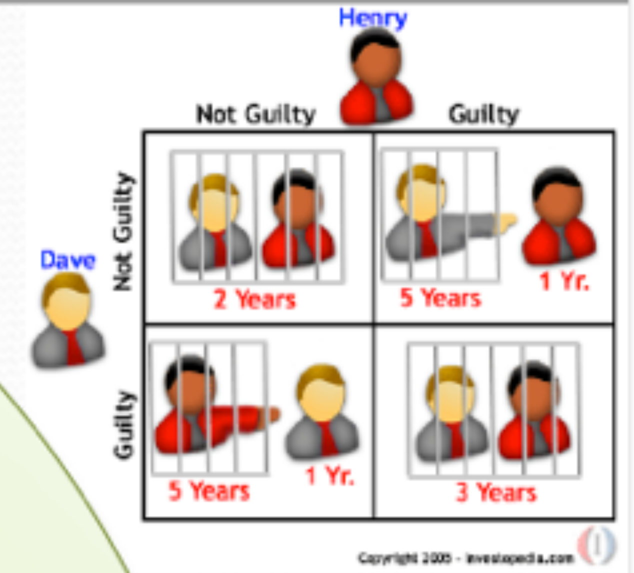
Autopoiesis

Cybernetics

Information theory

Computation
theory

Complexity
measurement



Prisoner's dilemma (PD)

Rational decision making

Iterative PD

n-person PD

Bounded rationality

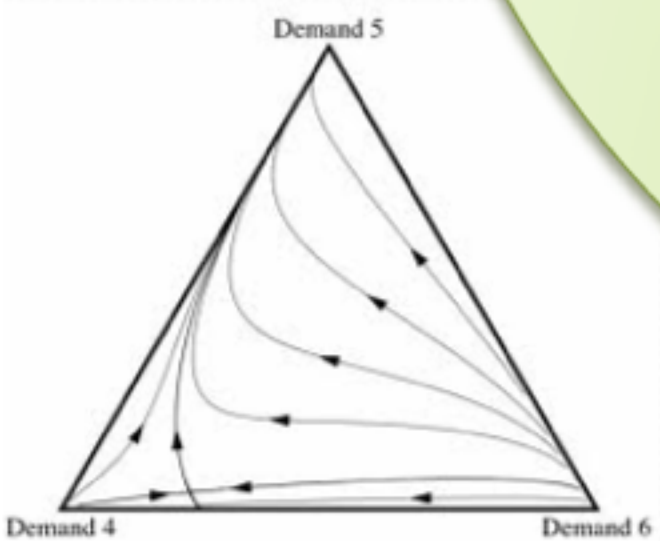
Game Theory

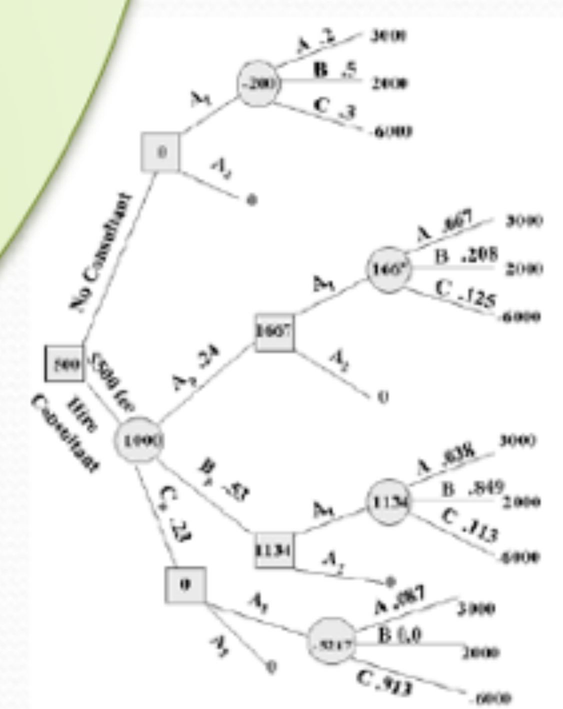
Irrational behavior

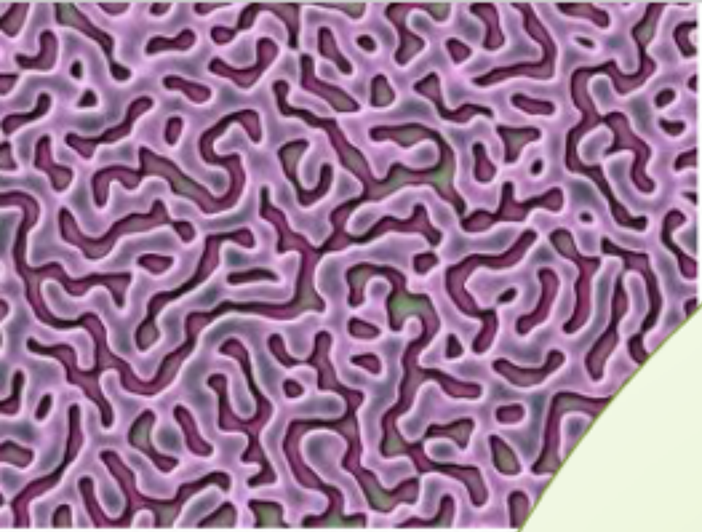
Cooperation versus competition

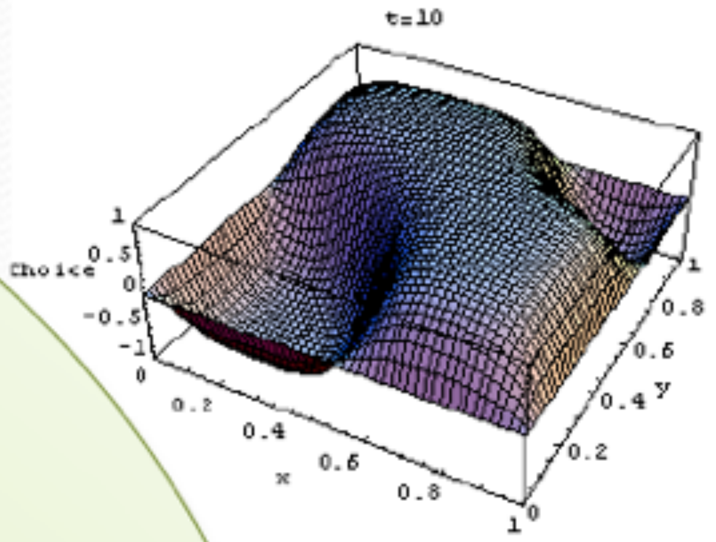
Spatial/network game theory

Evolutionary game theory









Pattern Formation

Spatial fractals

Reaction-diffusion systems

Partial differential equations

Dissipative structures

Percolation

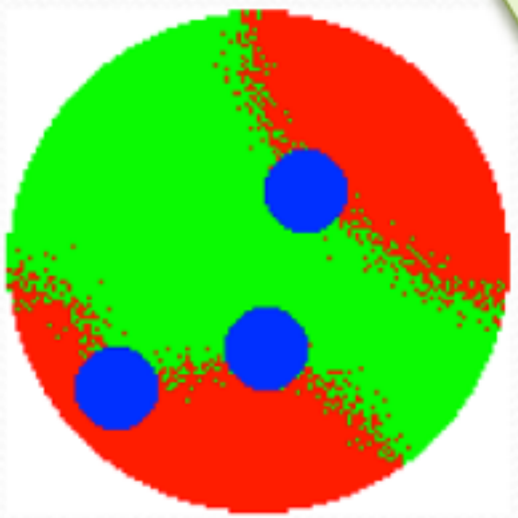
Cellular automata

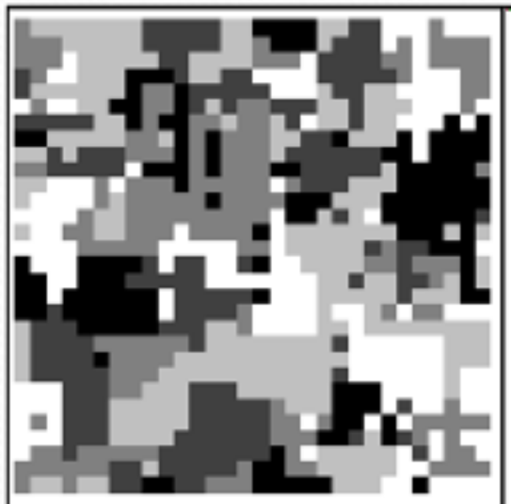
Spatial ecology

Self-replication

Spatial evolutionary biology

Geomorphology





Social dynamics

Collective intelligence

Self-organized criticality

Herd mentality

Collective Behavior

Phase transition

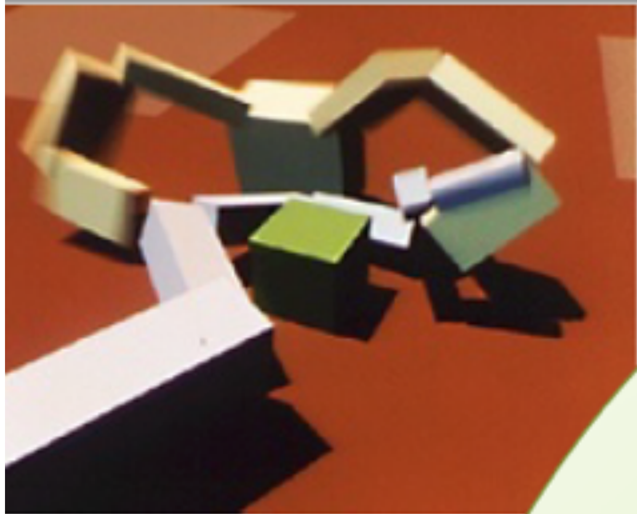
Agent-based modeling

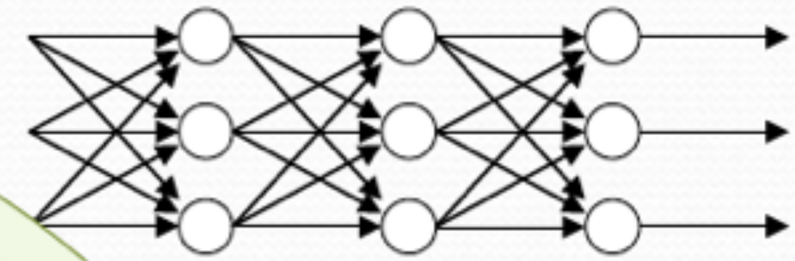
Synchronization

Ant colony optimization

Particle swarm optimization

Swarm behavior





Artificial neural networks

Evolutionary computation

Genetic algorithms/programming

Artificial life

Evolution & Adaptation

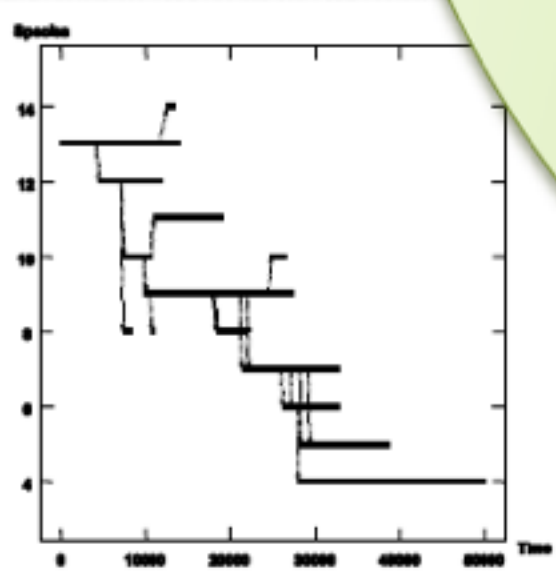
Machine learning

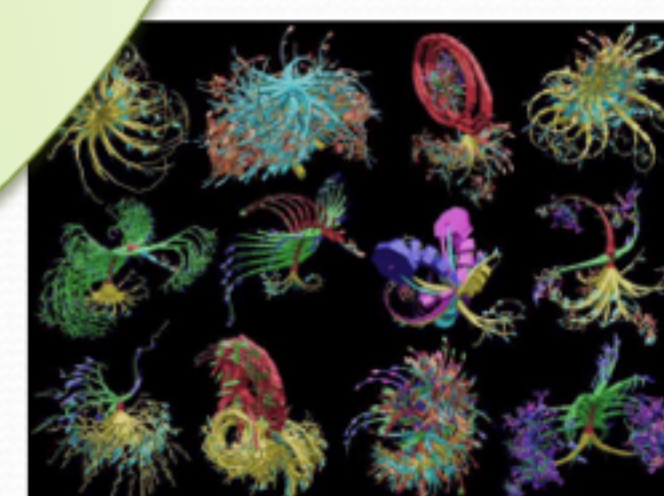
Evo-Devo

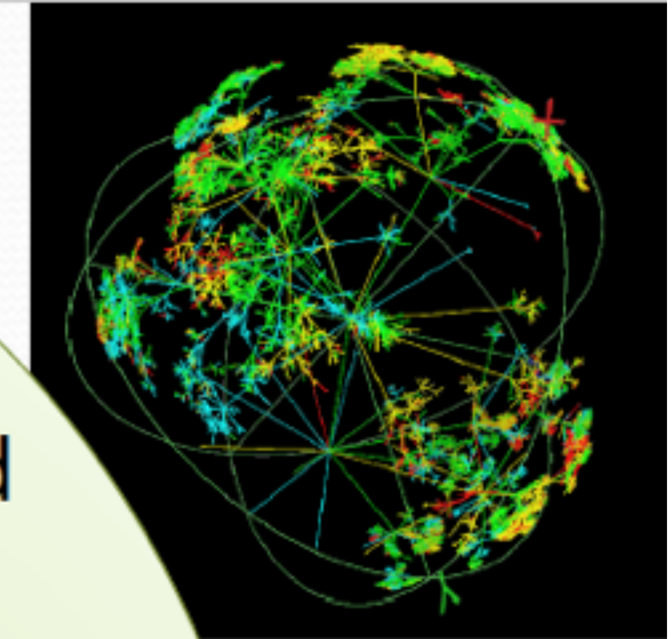
Artificial intelligence

Evolutionary robotics

Evolvability







Scale-free networks

Social network analysis

Small-world networks

Community identification

Centrality

Motifs

Networks

Graph theory

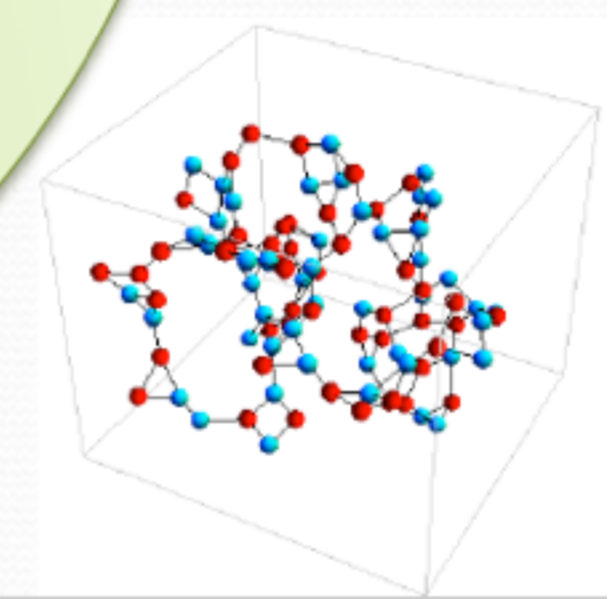
Scaling

Robustness/vulnerability

Systems biology

Dynamical networks

Adaptive networks



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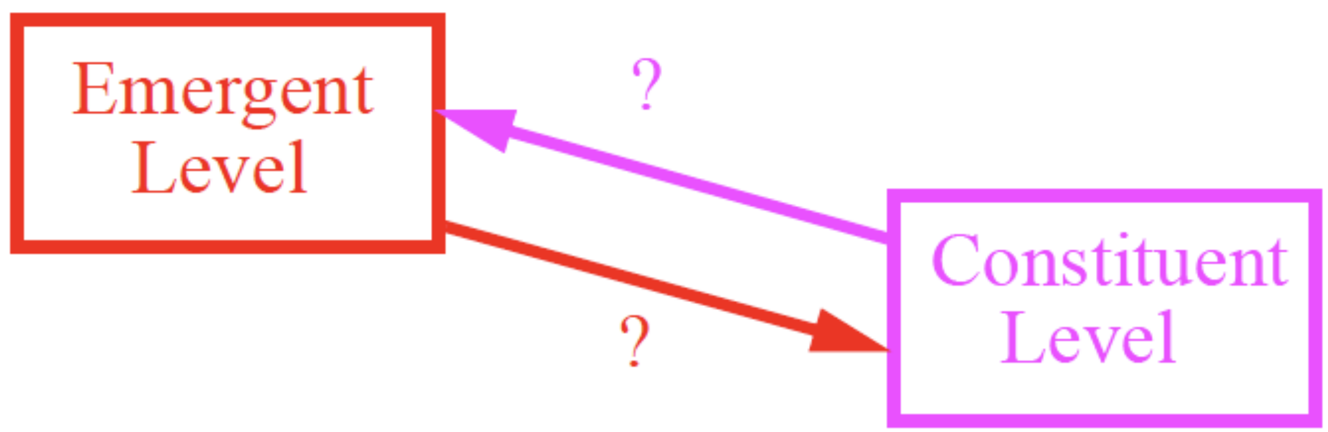
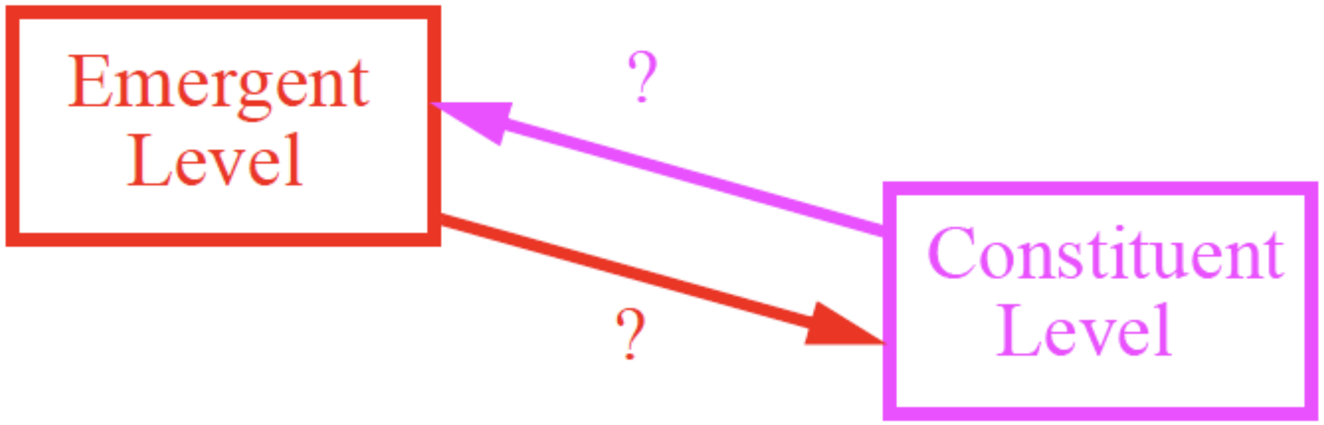
What are Complex Systems?

- Complexity involves two or more levels of description (variables) and levels of behavior (dynamics)



- Self organization connects the constituent level to the emergent level and slaving connects the emergent level to the constituent level

What are Complex Systems?



Describe the emergent and constituent levels?

Hypothesize about the self-organization that occurs.

How is slaving working in these examples?

Models

Some Laws of Science...

- $F = ma$
- $F = Gm_1m_2 / r^2$
- $PV = NRT$
- $V = IR$
- $E = mc^2$
- Conservation of energy, momentum, etc...

...and how they came about

- Observe Nature
- Develop a hypothesis that explains observations
- Make some predictions using hypothesis
- Carry out experiments to see if predictions are correct
  - ➡ If correct, hypothesis is proven
  - ➡ If not, you have to develop another hypothesis

?really?

For example...

- Observe phenomenon P
- Develop a hypothesis H that explains P (i.e. $H \rightarrow P$)
- You predict another phenomenon Q using H (i.e. $H \rightarrow Q$)
- Conduct experiments to see Q
  - ➡ What if Q is actually observed?
  - ➡ What is not Q is observed?

For example...

- If not Q is observed, H is easily disproved
  - ➡ $(H \rightarrow Q)$ implies $(\text{not } Q \rightarrow \text{not } H)$
- If Q is observed, we are not yet sure whether H by itself is right or not
  - ➡ Maybe H needs additional conditions like K
  - ➡ Maybe another hypothesis R could also explain P and Q (and possibly more)

- Laws are at best "well-tested hypothesis" or in other words, they are MODELS

Models

- $F = ma$
- $F = Gm_1m_2 / r^2$

Valid only in Newtonian mechanics

- $PV = NRT$
- $V = IR$

Applicable only to ideal gases

- $E = mc^2$

Seems legit, BUT there may be other ways to explain

- Conservation of energy, momentum, etc…

Model

A simplified representation of a system (either conceptual, verbal, diagrammatic, physical, or formal)

Creating Models

Modeling Steps

1. **Observe the system of interest**
2. **Reflect on possible rules that might cause the system’s dynamical behavior**
3. **Derive predictions from those rules and compare them with the reality**
4. **Repeat the above to modify the rules until you are “satisfied”**

Modeling Steps

1. Observe the system of interest
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Exercise

- **Create a mathematical model of the following observed behavior:**

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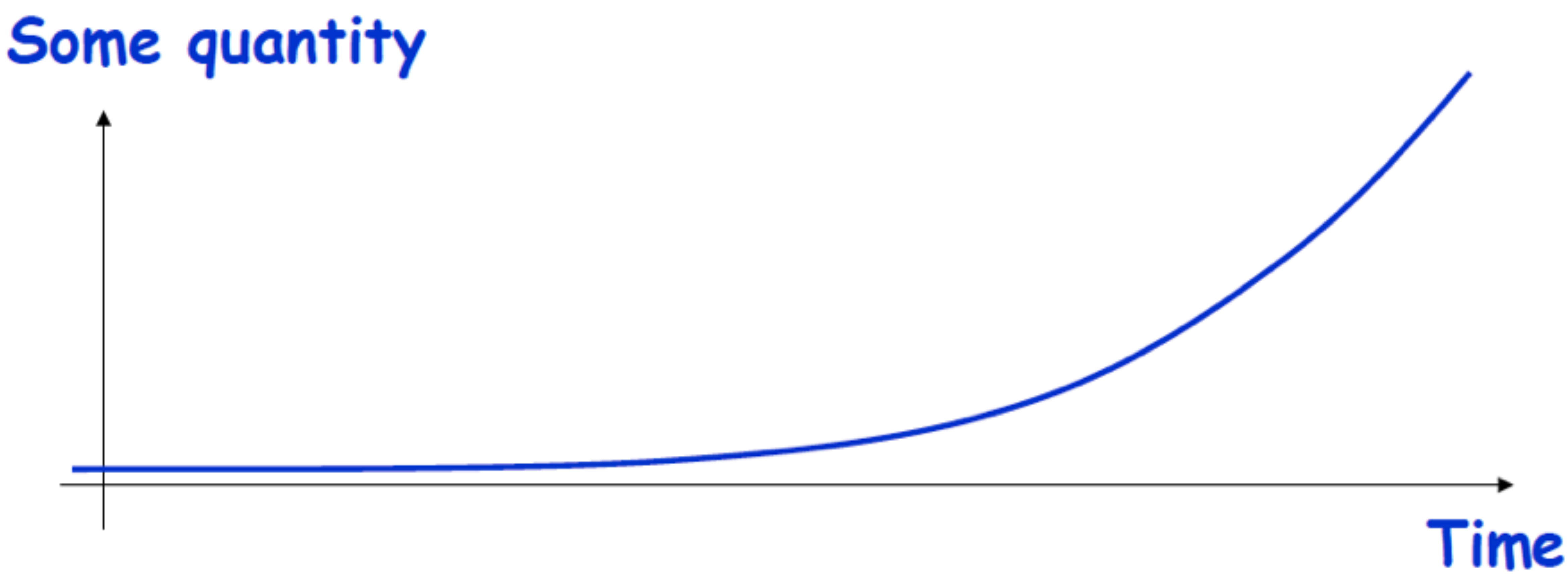

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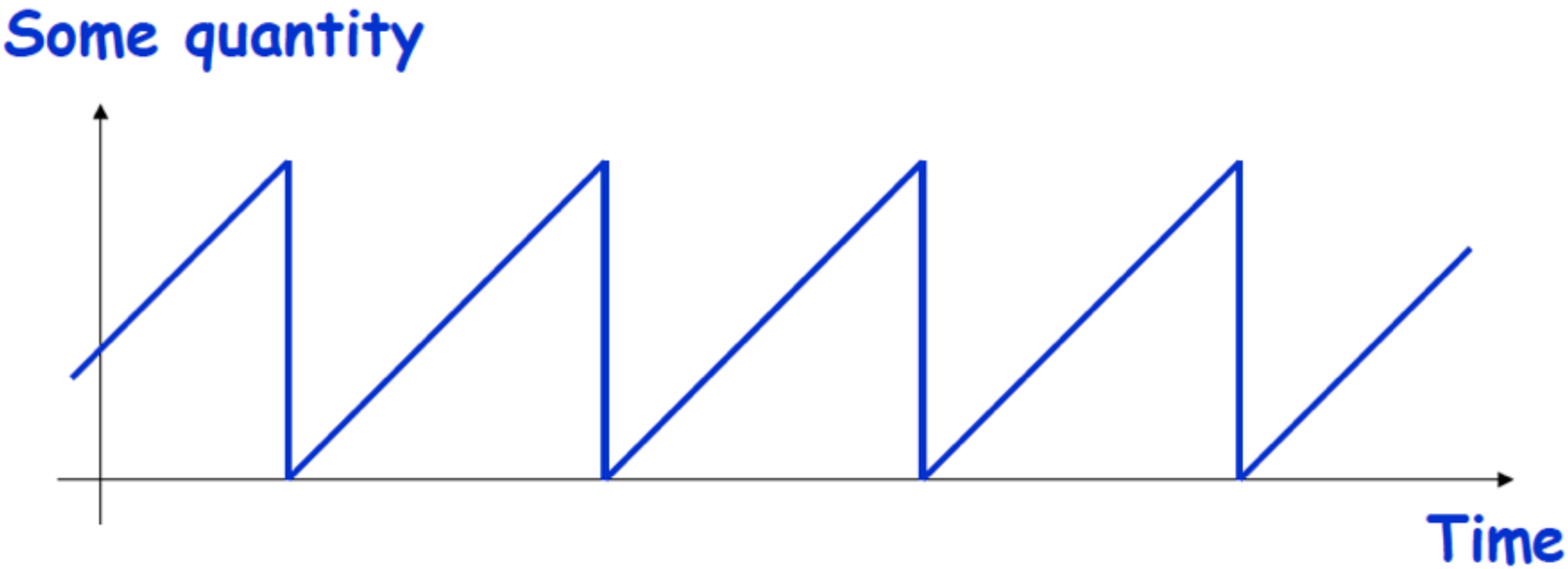

Exercise

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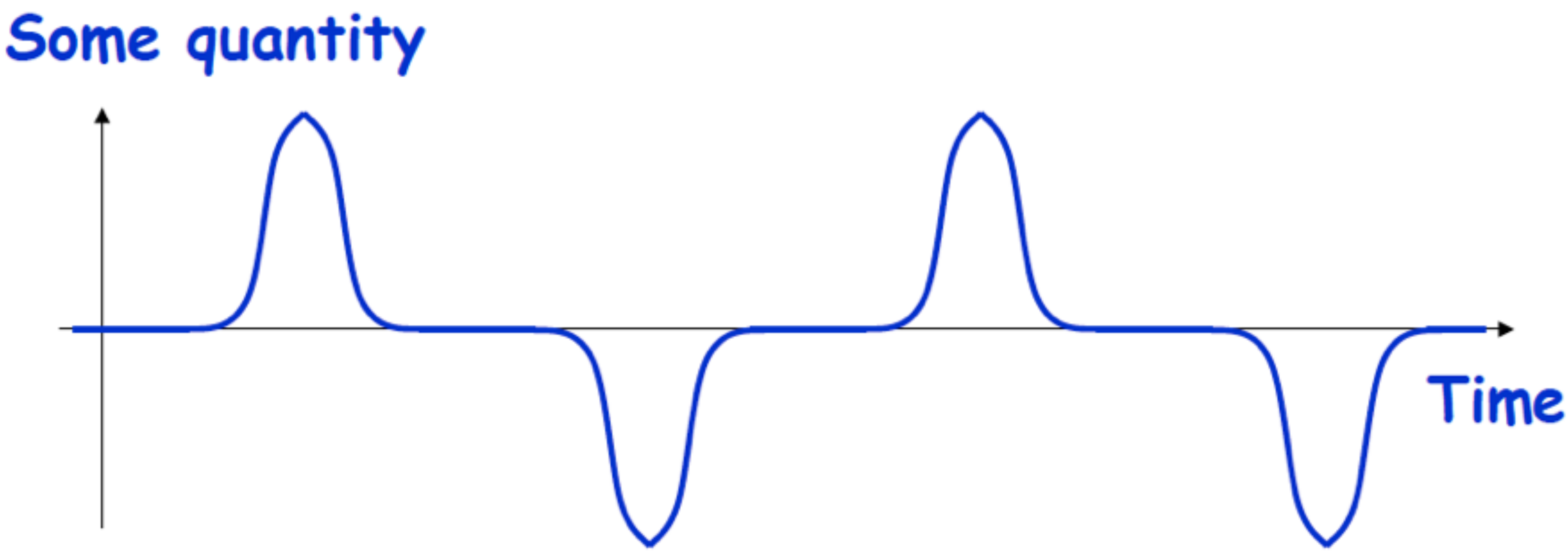

Challenges in modeling complex systems

- **Network**
- **Nonlinear**
- **Self-organization**
- **Emergence**

Difficult (if not impossible) to handle with traditional "reductionism" approaches

Tools for developing models

- General programming languages
  - ➡ C, C++, Java, Python, R, Fortran, etc…
- Free simulation software packages
  - ➡ StarLogo, NetLogo, Repast, etc…
- Commercially available applications
  - ➡ MATLAB, Mathematica, etc…