Complex Systems Theory

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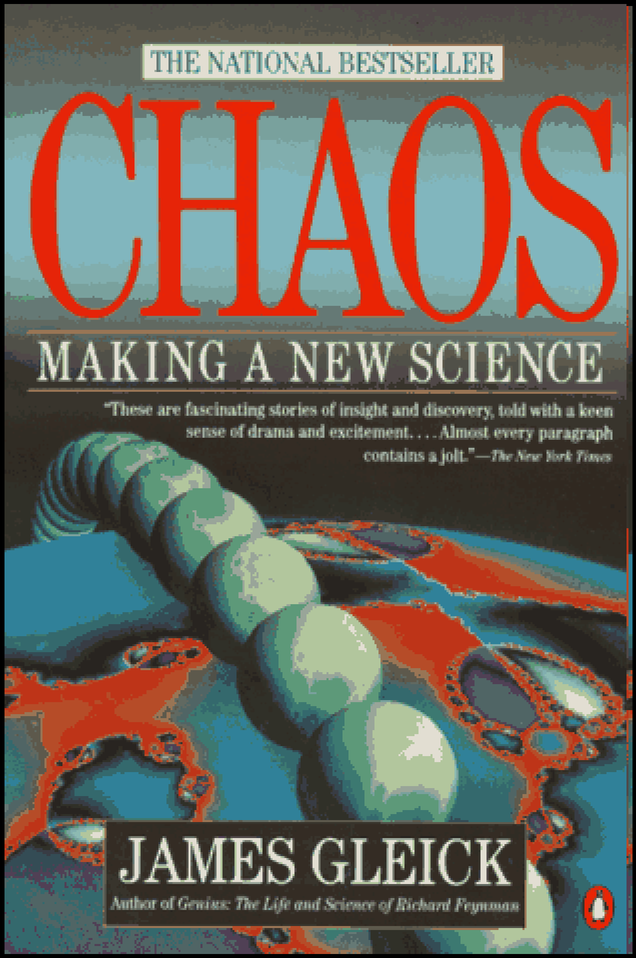
Or,

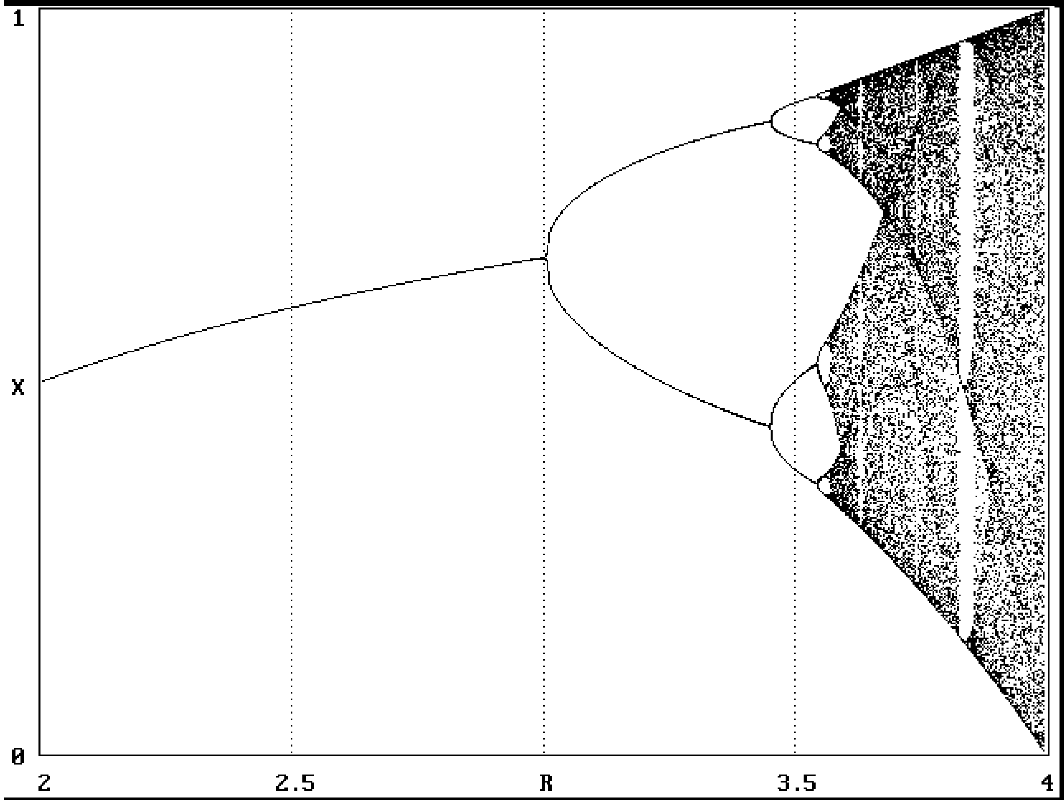
Just because a system is complex, does not make it a complex system.

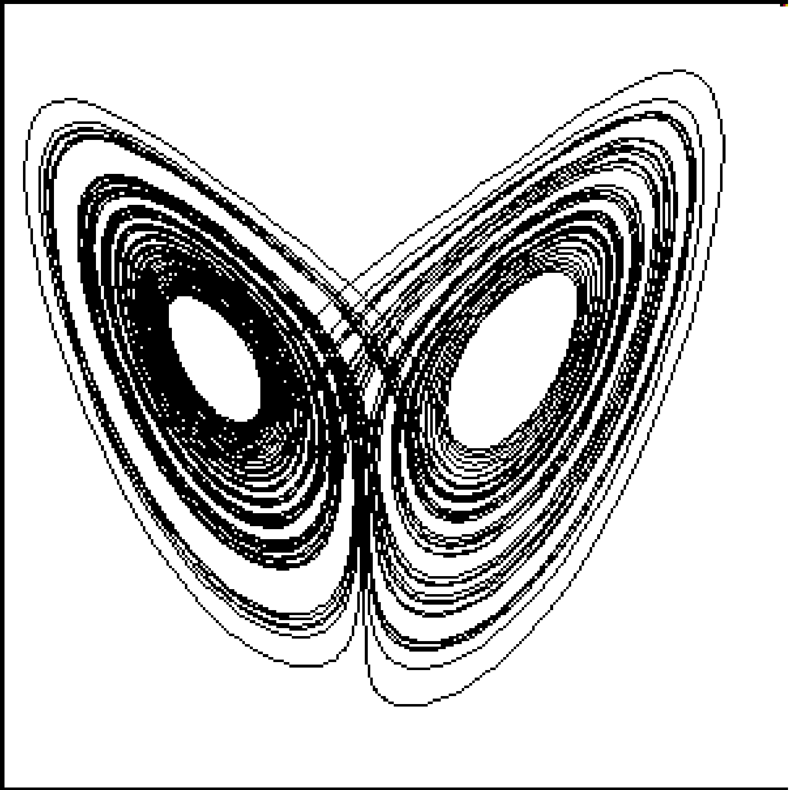
The source and growth of an idea – personal beginnings

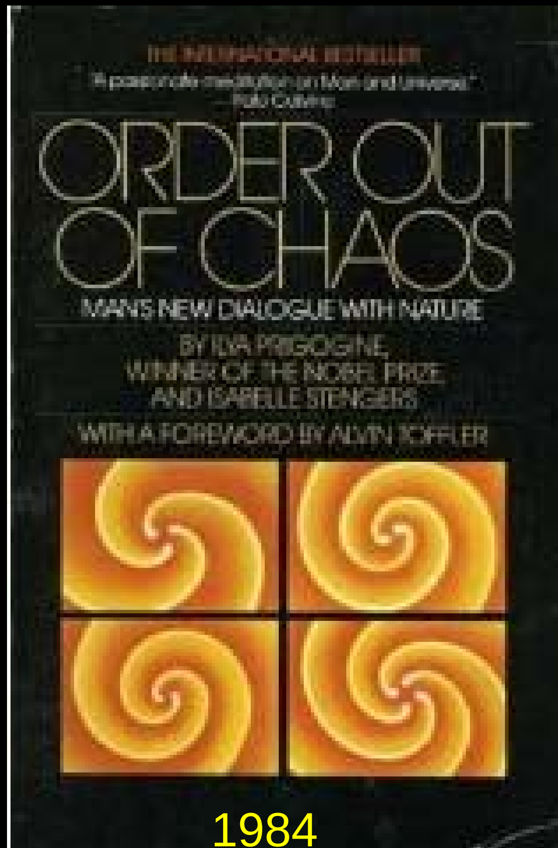


1987

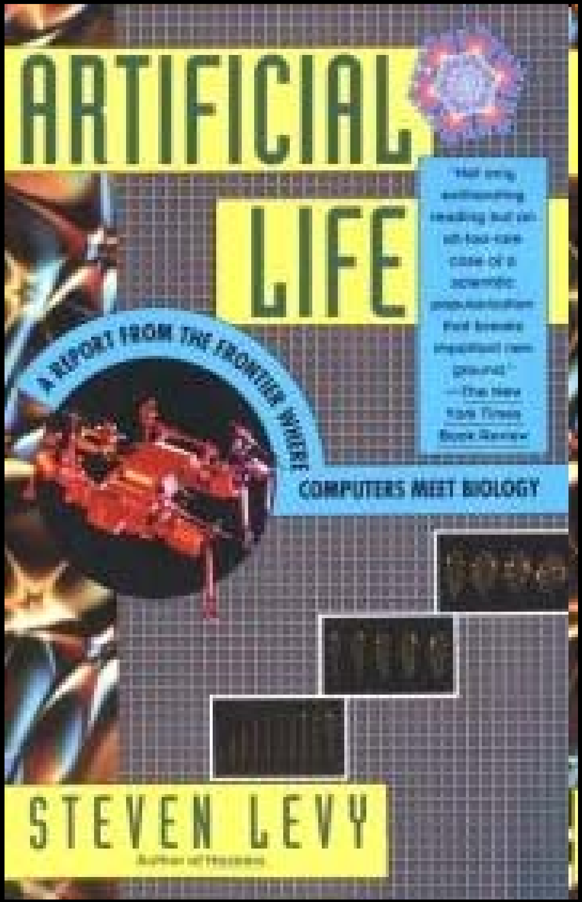
Bifurcation Diagram and Strange Attractors







Non-Equilibrium Thermodynamics And Dissipative Structures


ARTIFICIAL
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A REPORT FROM THE FRONTIER WHERE
COMPUTERS MEET BIOLOGY
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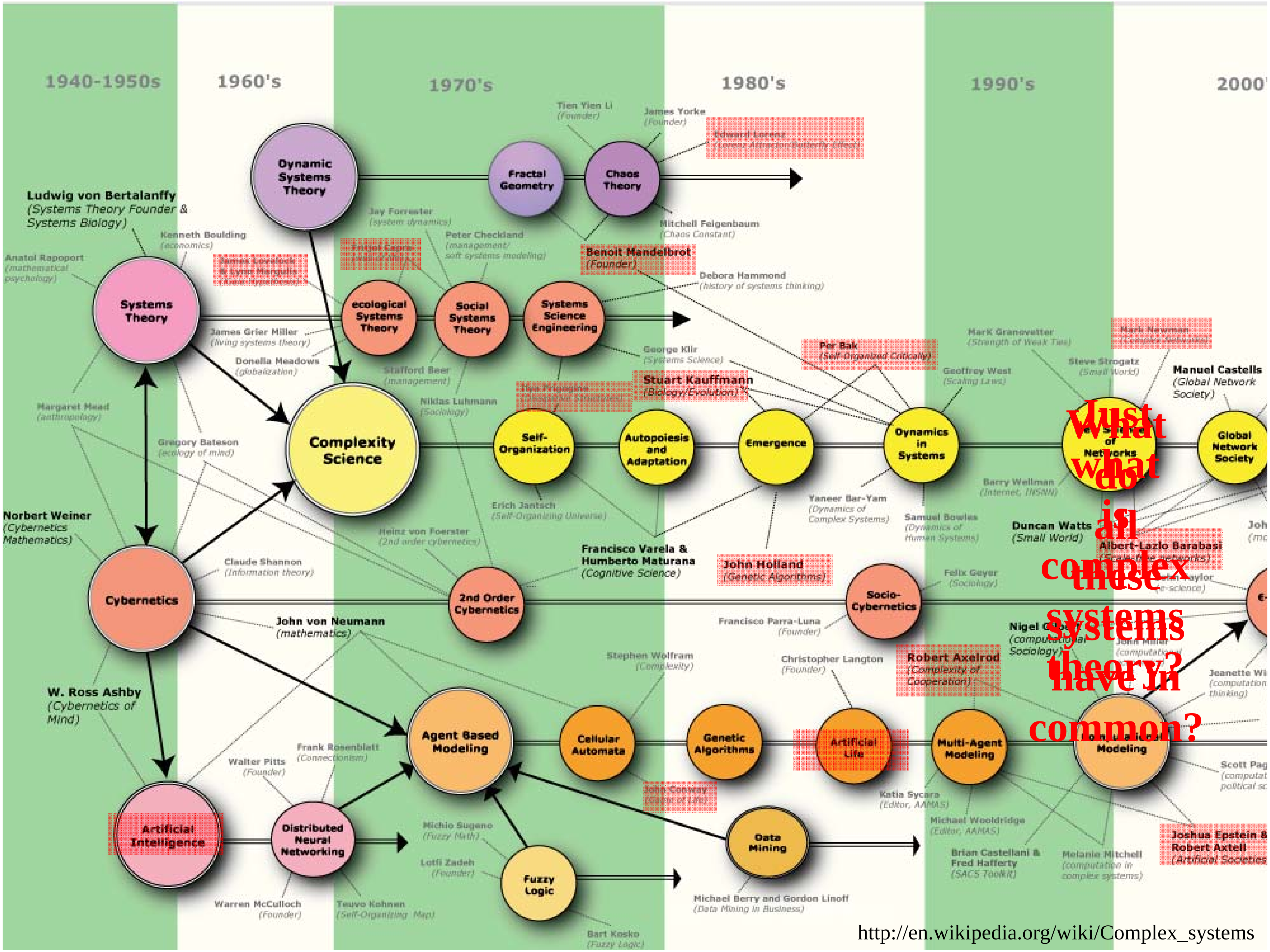
1993



http://en.wikipedia.org/wiki/Complex_systems

Impediments to Teaching Complex Systems

1. Confusion over the terms “complex” and “system.”

Humpty Dumpty

"When I use a word it means exactly what I want it to mean, neither more nor less"

The term "system" has become a buzz word today. But, what does it mean for something to be a system?

Buzzz

It's . . . the system,

Buzzz

You can't beat . . . the system,

Buzzz

You haf'ta play . . . the system,

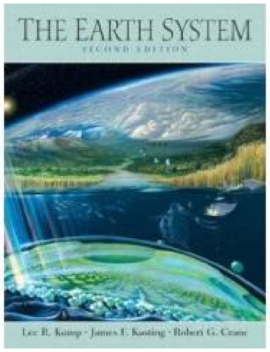
Buzzz

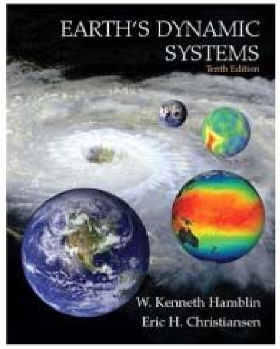
Or, more specifically (for us). . .

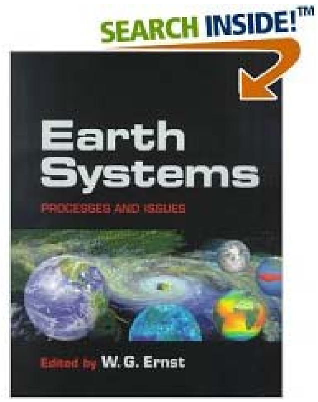
Buzzz

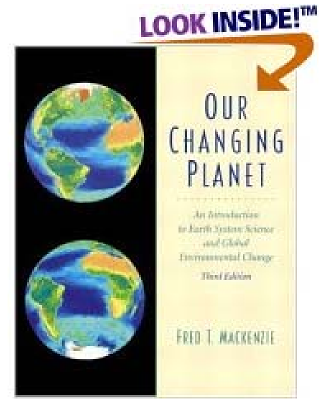
Or, more specifically (for us). . .

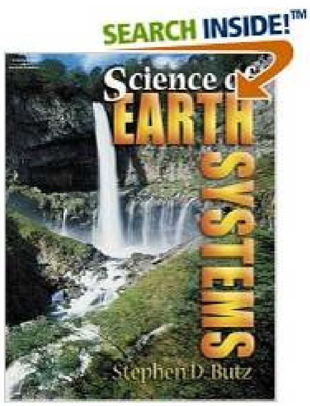
The Earth is a System . . .

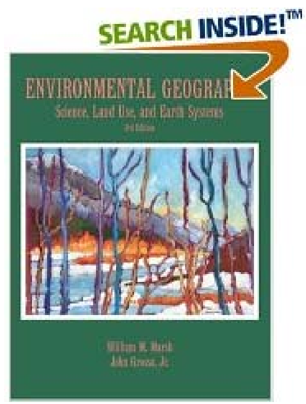


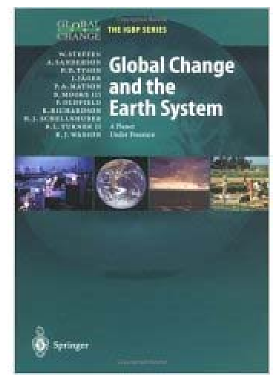












But, what does it mean to say the Earth is a System? Is it similar to or different from . . . a school system, the Federal Reserve System, the Global Positioning System, an operating system, or the solar system.

What is a System?

Clarification One

Preliminary Dictionary Definitions

6. A set of objects or phenomena grouped together for classification or analysis.

(Does not specify whether the objects are or are not related. They could be unrelated.)

What is a System?
Clarification One

Preliminary Dictionary Definitions

6. A set of objects or phenomena grouped together for classification or analysis.

9. The prevailing social order; the establishment. Used with: "You can't beat the system."

Implies something or someone is in control.

What is a System?
Clarification Two

Preliminary Dictionary Definitions

6. A set of objects or phenomena grouped together for classification or analysis.

9. The prevailing social order; the establishment. Used with the: "You can't beat the system."

5. A naturally occurring group of objects or phenomena: the solar system.

Ah, now we are on to something, but does "naturally occurring" mean anything?

Naturally occurring sounds like magic. "It occurs naturally." What does it mean to occur naturally?

More ambiguity . . .

What is a System?
Clarification Three

Final Dictionary Definition

1A. A naturally occurring group of interacting, interrelated, or interdependent elements, forming a complex whole.

Yet, we might ask, “Interacting how?” “Interrelated how?” “Interdependent how?”

- Are the relationships a lucky accident?

  Or Teleological? Or random?

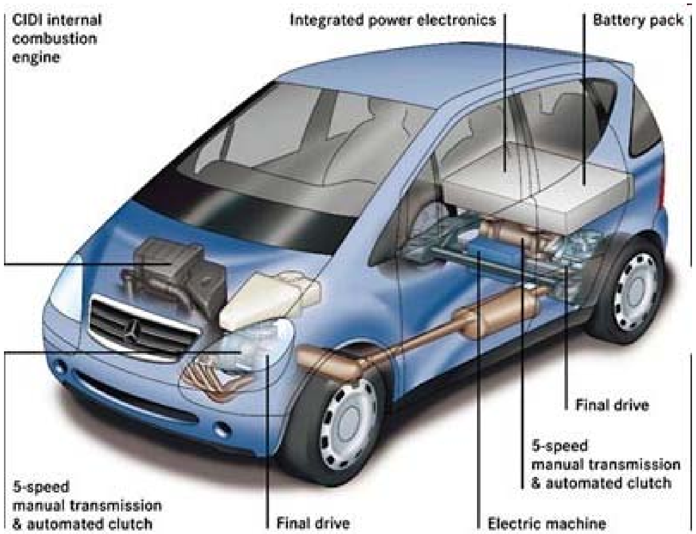
How they became Interacting, Interrelated, and Interdependent is what we are trying to determine. We cannot assume what it is our purpose to discover.

What is a System?
Clarification Three

Final Dictionary Definition

1A. A naturally occurring group of interacting, interrelated, or interdependent elements, forming a complex whole.

And "complex whole?" Is it complex just because it has a bunch of parts?

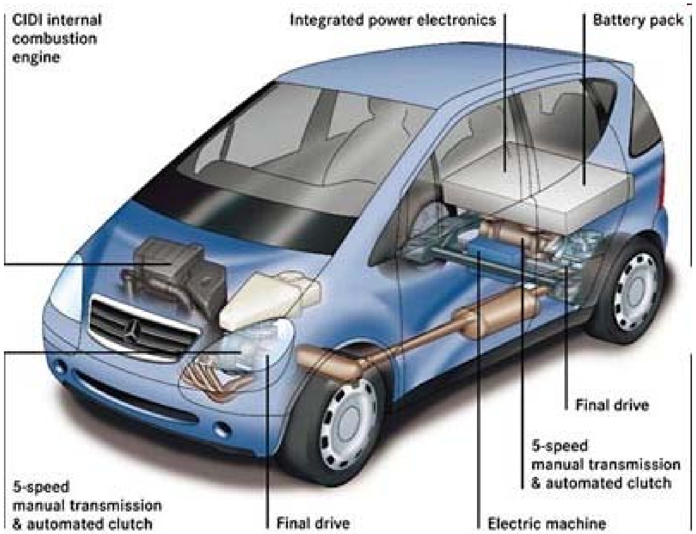


Is a car complex in the same way people are complex?

What is a System?
Clarification Three

Saying a system is complex is not the same thing as saying it is a complex system.

And "complex whole?" Is it complex just because it has a bunch of parts?



Is a car complex in the same way people are complex?

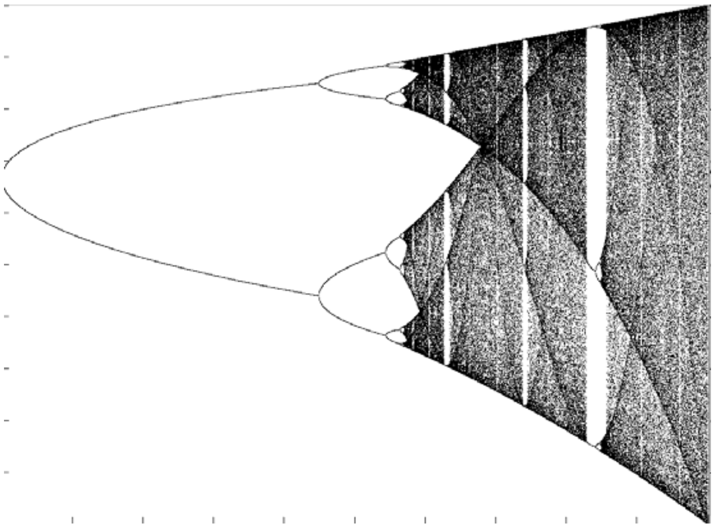
What is a System?
Clarification Three

Final Dictionary Definition

1A. A naturally occurring group of interacting, interrelated, or interdependent elements, forming a complex whole.

And is behavior important?

- What about a bunch of parts that have simple behavior?
- Or, simple parts that have complex behavior?



What is a System?

And, it doesn't help when you look at some of the early definitions for complex systems

"A system in which complex causes produce simple effects." *Cohen and Stewart, The Collapse of Chaos*

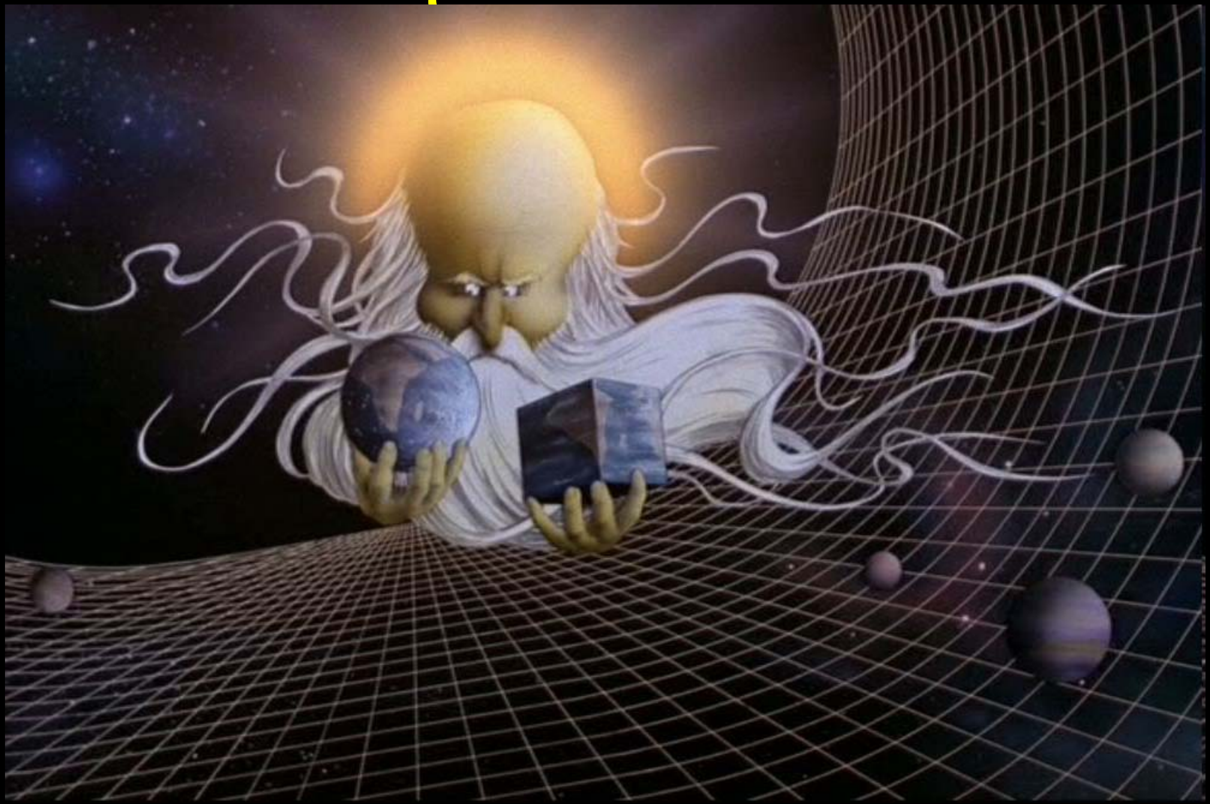
The narrow transition region between order and chaos. *Norman Packard*

A type of dynamical system intermediate between chaotic and fixed behavior. *Lewin*

A system in which the individual components, operating independently, produce order.

That region where the behavior of a system is fluid, dynamic, and able to change easily to new arrangements, patterns, and organizations, but not so fluid that no quazistable patterns can emerge.

And, how did this whole - this system - come into existence in the first place ?



- It is one thing to talk about the behavior of a system that already exists.
- It is something else to ask where and how these systems came into existence in the first place.

Impediments to Teaching Complex Systems

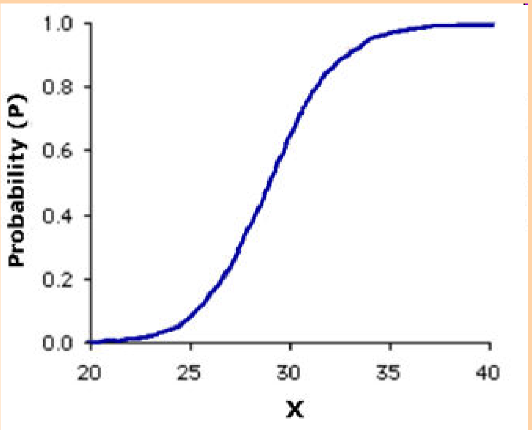
1. Confusion over the terms “complex” and “system.”
2. The dominance of linear/equilibrium thinking and training in our schools.

Chaos Theory

Studies why and how the behavior of simple systems—simple algorithms—becomes more complex and unpredictable as the energy/information the system dissipates increases.

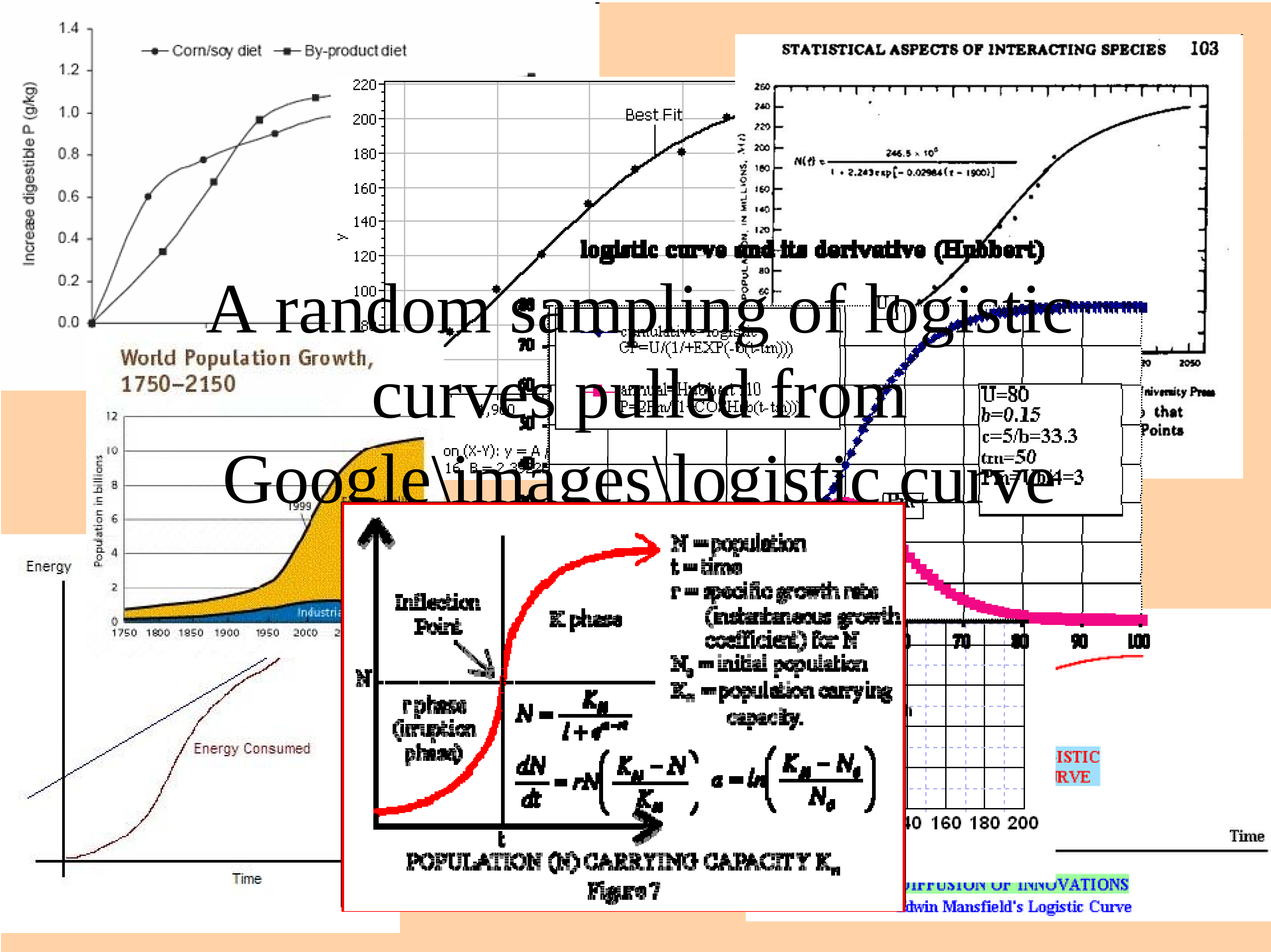
$$X_{next} = rX\,(1-X)$$

The logistic system



System evolves to equilibrium

A random sampling of logistic curves pulled from Google\images\logistic curve



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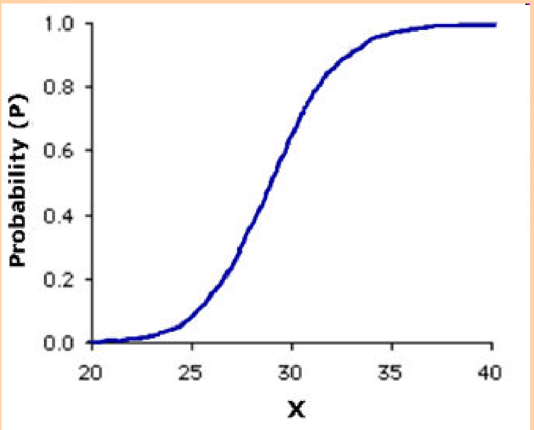
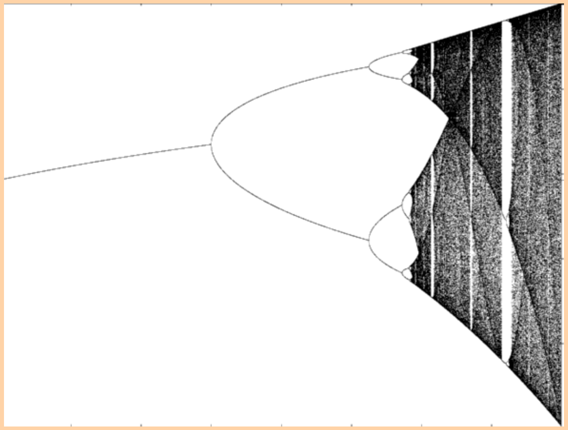
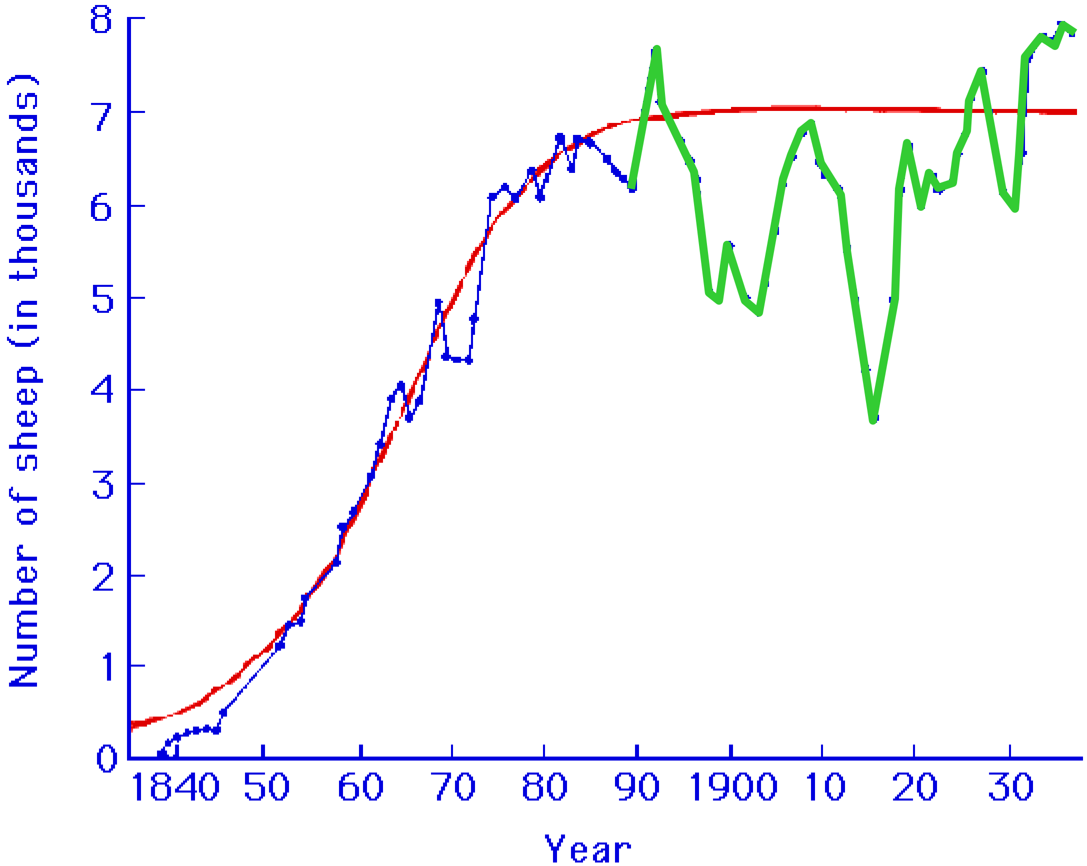


System evolves to equilibrium



System evolves to complexity

Here is a brave attempt to make a real population curve follow a theoretical logistic 'S" shape.



"The exponential growth phase exists because that is when the population has already begun to grow, but not a lot yet, and it rises quickly because there are no limiting factors yet and the resources are in unlimited amounts. The plateau phase begins when the organism hits it's carrying capacity, which is the maximum number of organisms in a population that can be supported by the environment at a certain time, in a certain ecosystem. The transitional phase in between these two phases occurs because this is when the limiting factors in the environment start to limit the increase, slowing the population increase."

Plateau - a land area having a relatively level surface

Plateau - to reach a state or level of little or no growth or decline

http://www.cic-caracas.org/departments/science/Topic4.php

Impediments to Teaching Complex Systems

1. Confusion over the terms "complex" and "system."
2. The dominance of linear/equilibrium thinking and training in our schools.
3. The domination of biological evolutionary theory as the only systematic mechanism for evolutionary change.

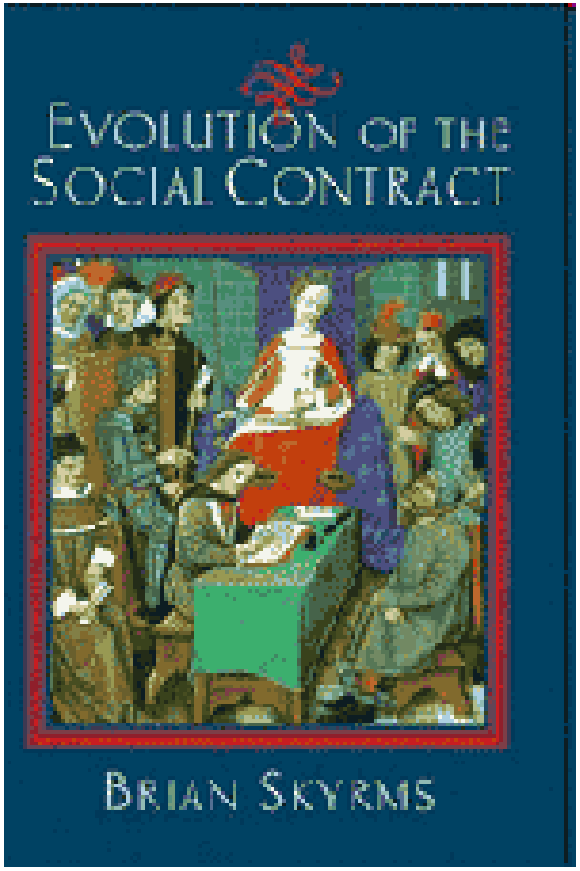
How Do Things Evolve?

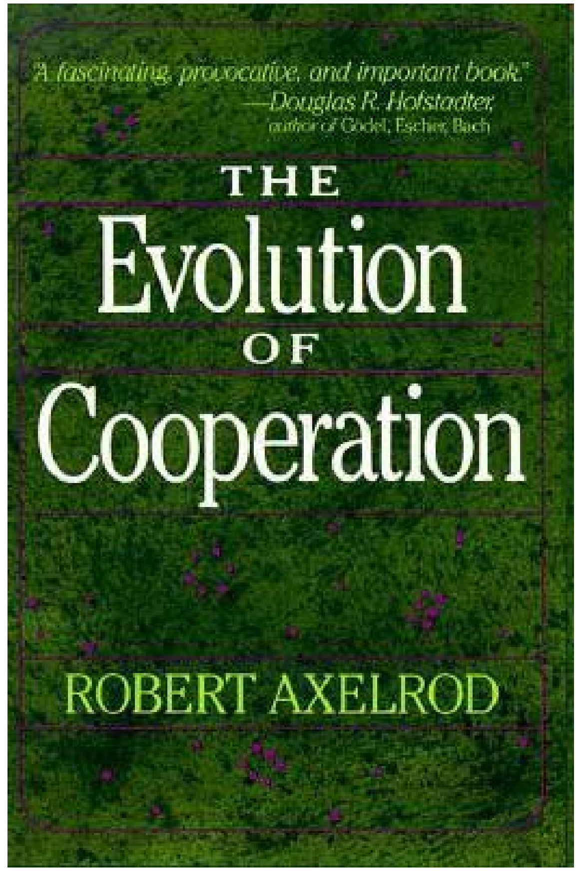
Ask the average person on the street what the theory of evolution is . . .

. . . and they are likely to answer . . .

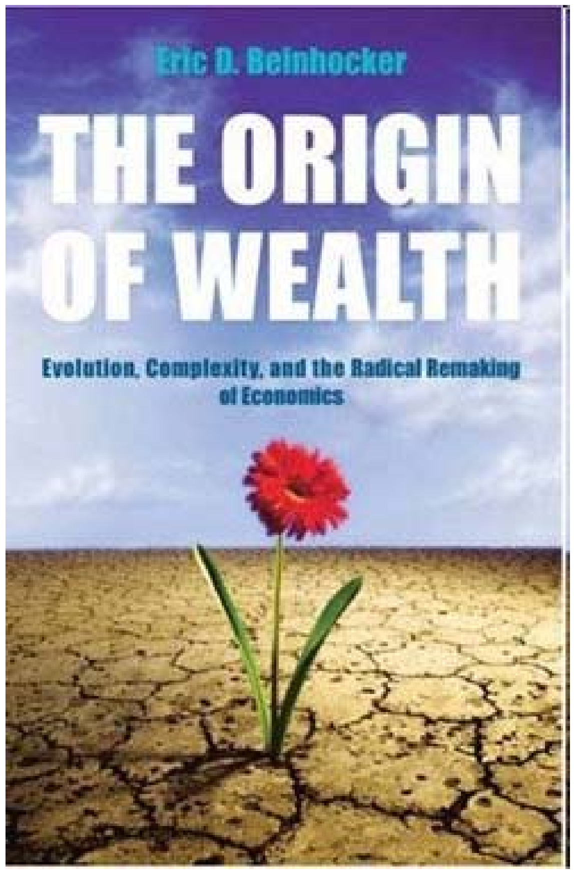
- Natural selection ?
- Darwin’s theory of evolution ?
- Survival of the fittest ?

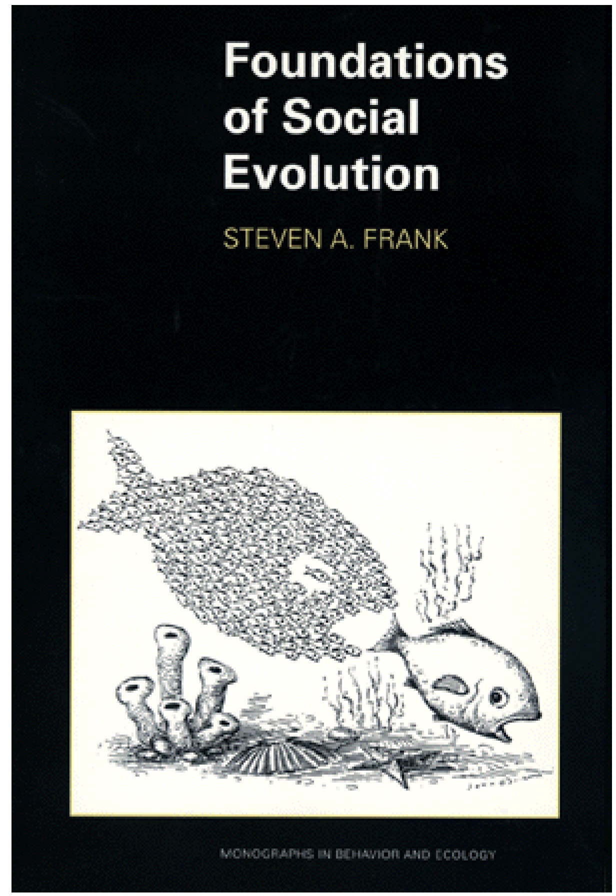
But we acknowledge and take for granted that many systems evolve





But we acknowledge and take for granted that many systems evolve





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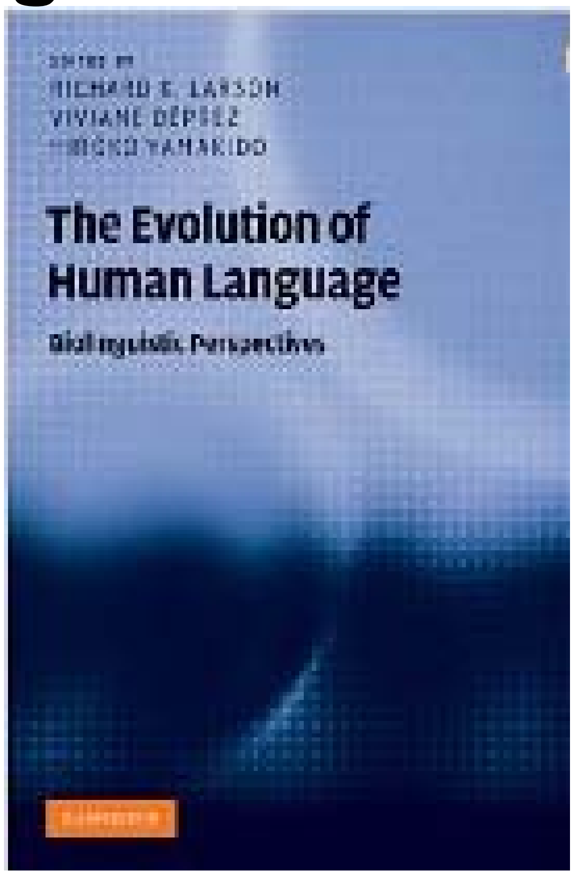

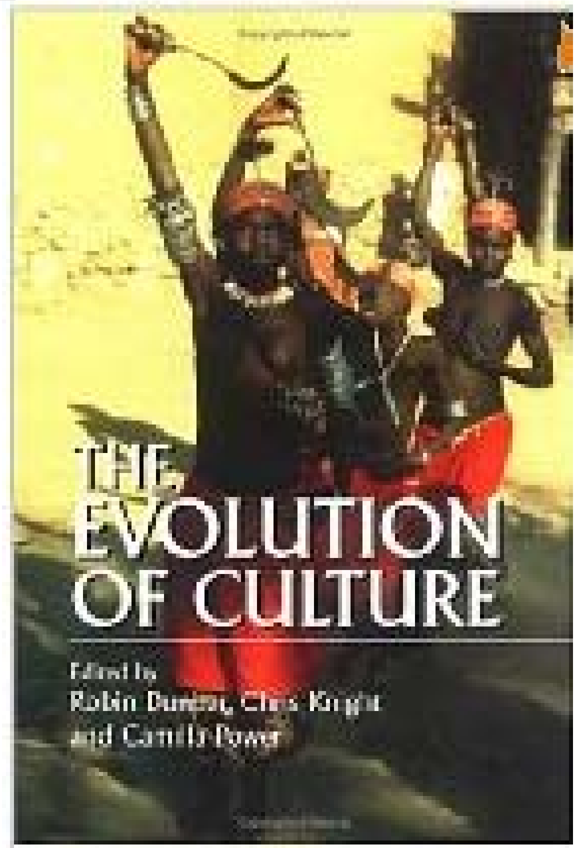

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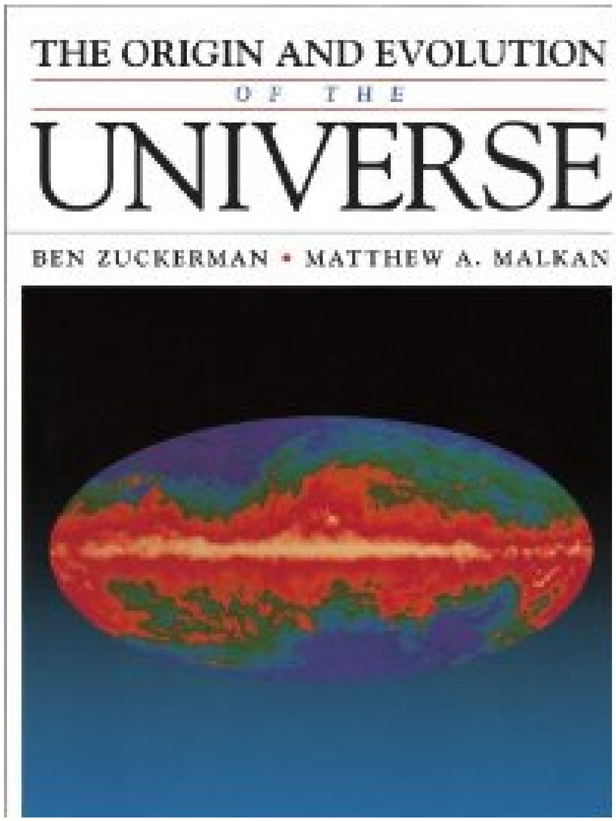
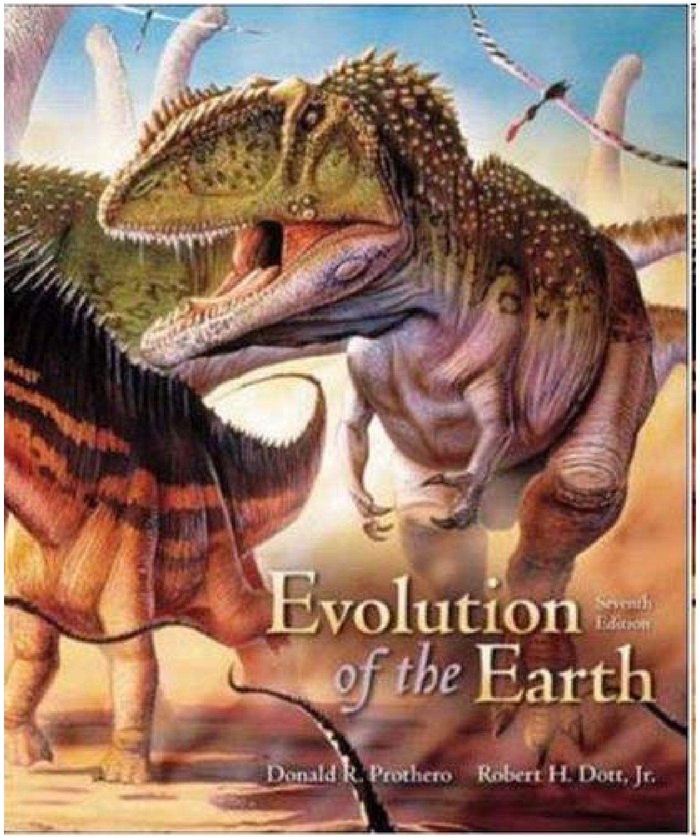




In science it is not proper to talk of processes without positing a theory and mechanisms of why and how those processes take place.

If we define evolution as . . .

Any system that increases in complexity, diversity, order, and/or interconnectedness with time.

Then . . . .

. . . lots of things evolve

All by the same mechanism?

And, what is common to all things that evolve?

Can we assume that biological evolutionary theory is a general theory of evolution ?

Take, for example an economic system.

. . . What in an economic system is equivalent to . . .

- A Gene?
- An individual?
- A species?
- A mutation and genetic recombination?

No !

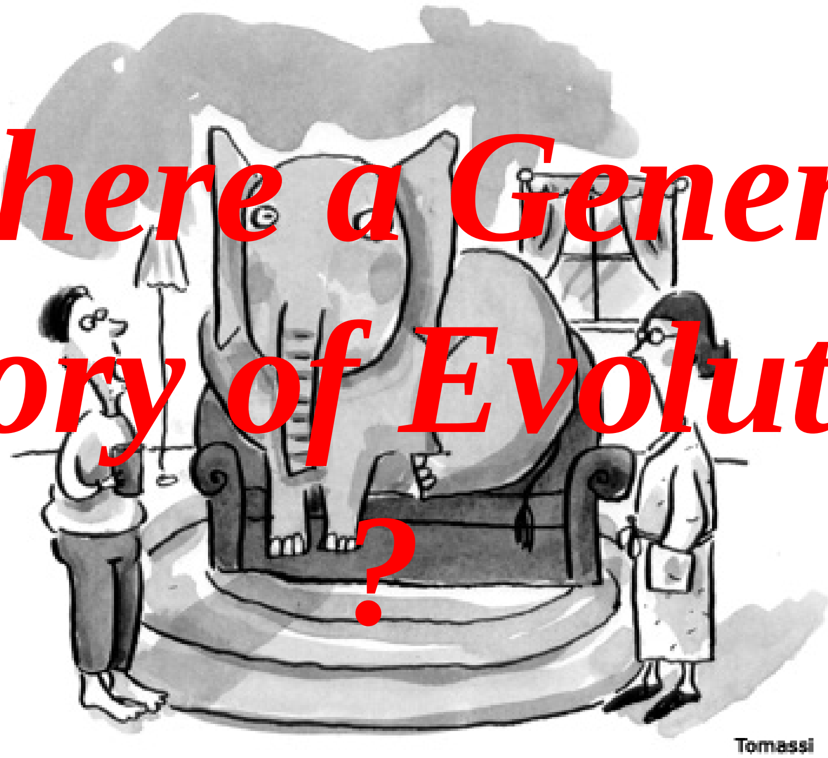
Is it accurate to say economic systems evolve like biological systems?

If biological things evolve and economies evolve . . .

And we cannot make a direct one-for-one comparison of the units and processes between them . . .

Then Darwinian evolutionary theory (the Modern Synthesis) is a *special theory* of evolution, not a general theory. . .

The Elephant in the Room



Is there a General Theory of Evolution ?

How Long Has That Been There ?

The expression "elephant in the room" refers to a situation where something major is going on, it's on everyone's mind and impossible to ignore -- like an elephant in the room. But nobody talks about the "elephant" because nobody knows what to do about it

This is where . . .

Chaos Theory

Complex Systems Theory

. . . comes in.

Complex Systems Theory

Chaos Theory

. . . studies how systems with many "agents" that are already at high energy/information dissipation interact and behave.

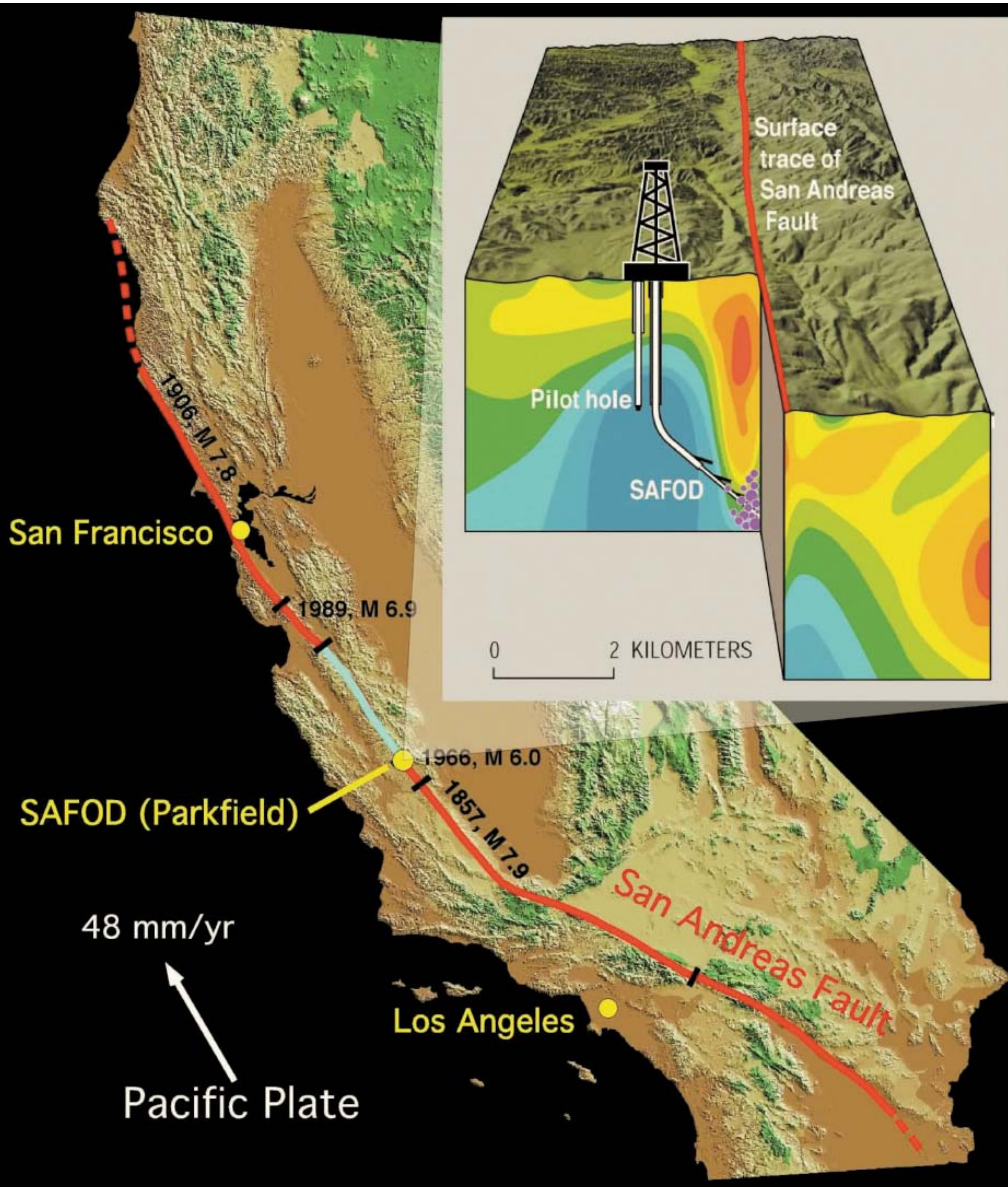
Agent:

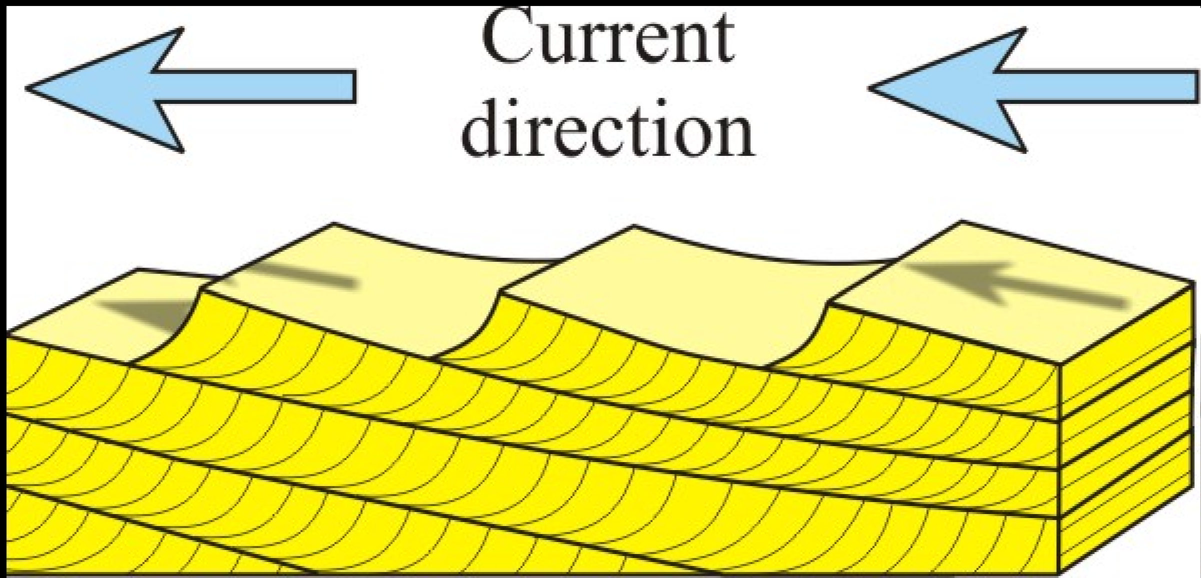
the individual units that are interacting, like . . .

Complex systems theory (or complexity theory) studies how systems with many "agents" that are already at high energy/information flow interact and behave.

Complex systems theory (or complexity theory) studies how systems with many "agents" that are already at high energy/information flow interact and behave.

Units of friction along a fault zone

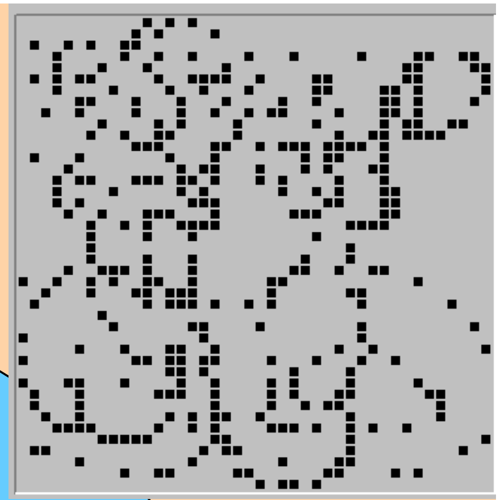




Sand grains
in a
migrating
ripple

Self-Organized Criticality

Cellular Automata



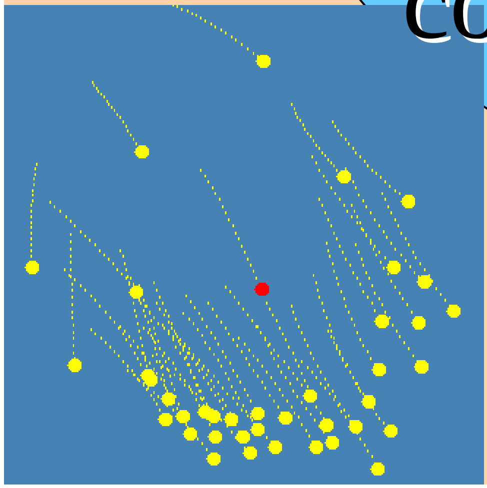
Complex Systems Theory

Chaos Theory

How does complex system theory say the agents behave?

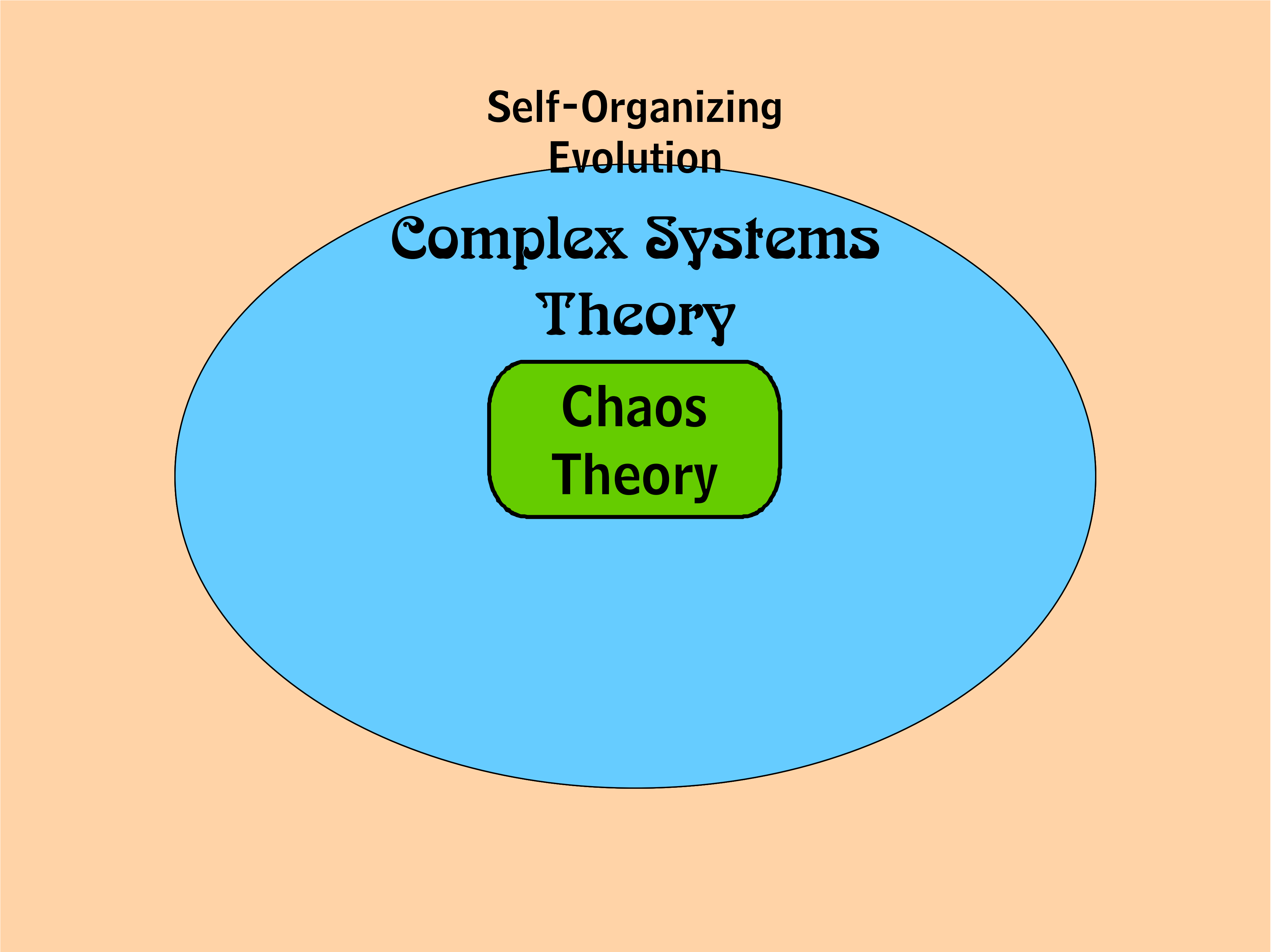
The central dogma is complex systems are Self-Organizing

Complex systems theory studies how systems with many "agents" that are already at high energy/information dissipation interact and behave.



Boids

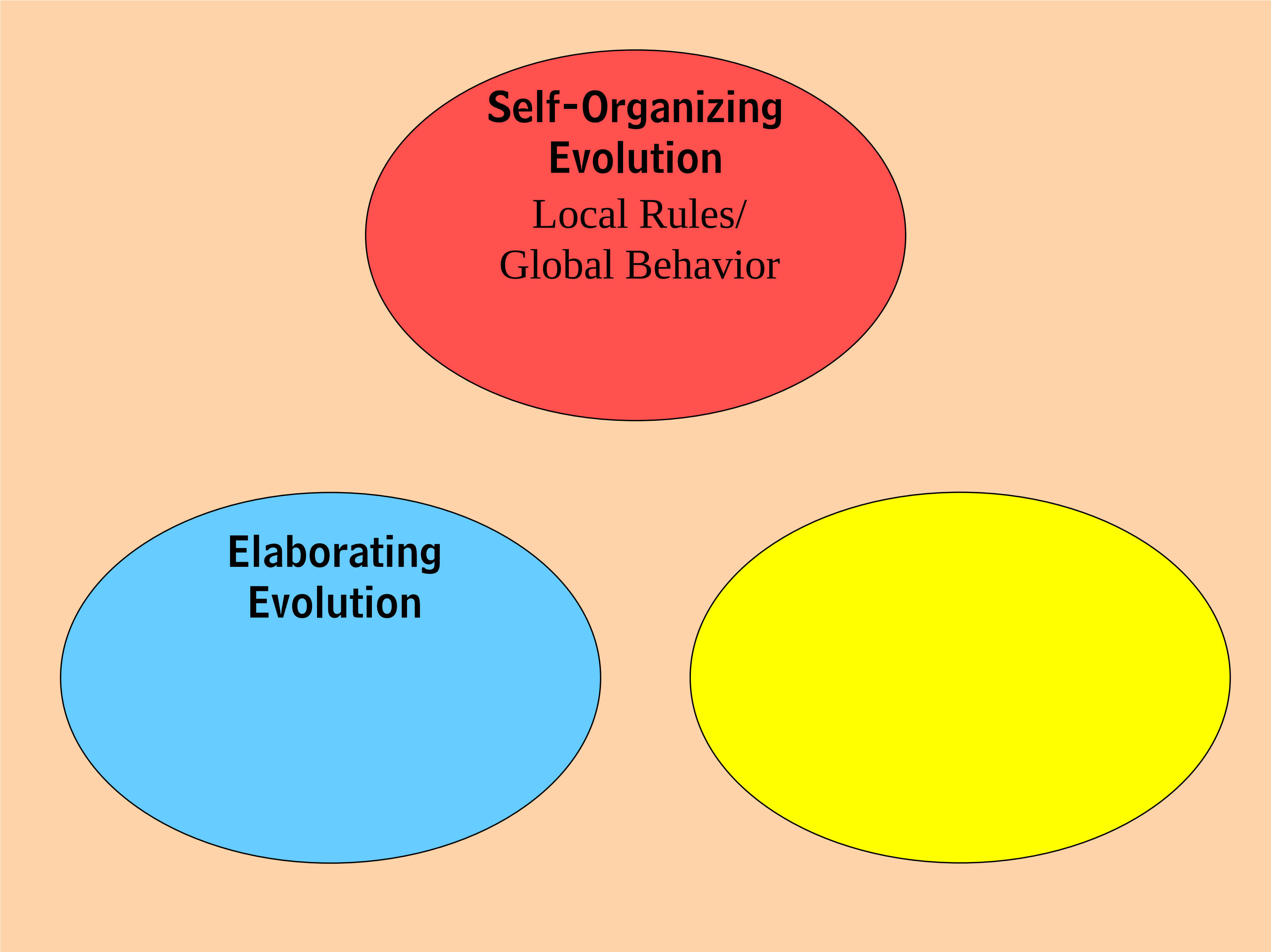
BZ Reactions


Self-Organizing
Evolution
Complex Systems
Theory
Chaos
Theory

Self-organizing evolution begins with an initial state of random agents that through the application of simple rules of interaction among the agents (e.g. an algorithm, or chemical/physical laws) evolves a system of ordered structures, patterns, and/or connections without control or guidance by an external agent or process; that is, pulls itself up by its own boot straps.

Local Rules leads to Global Behavior

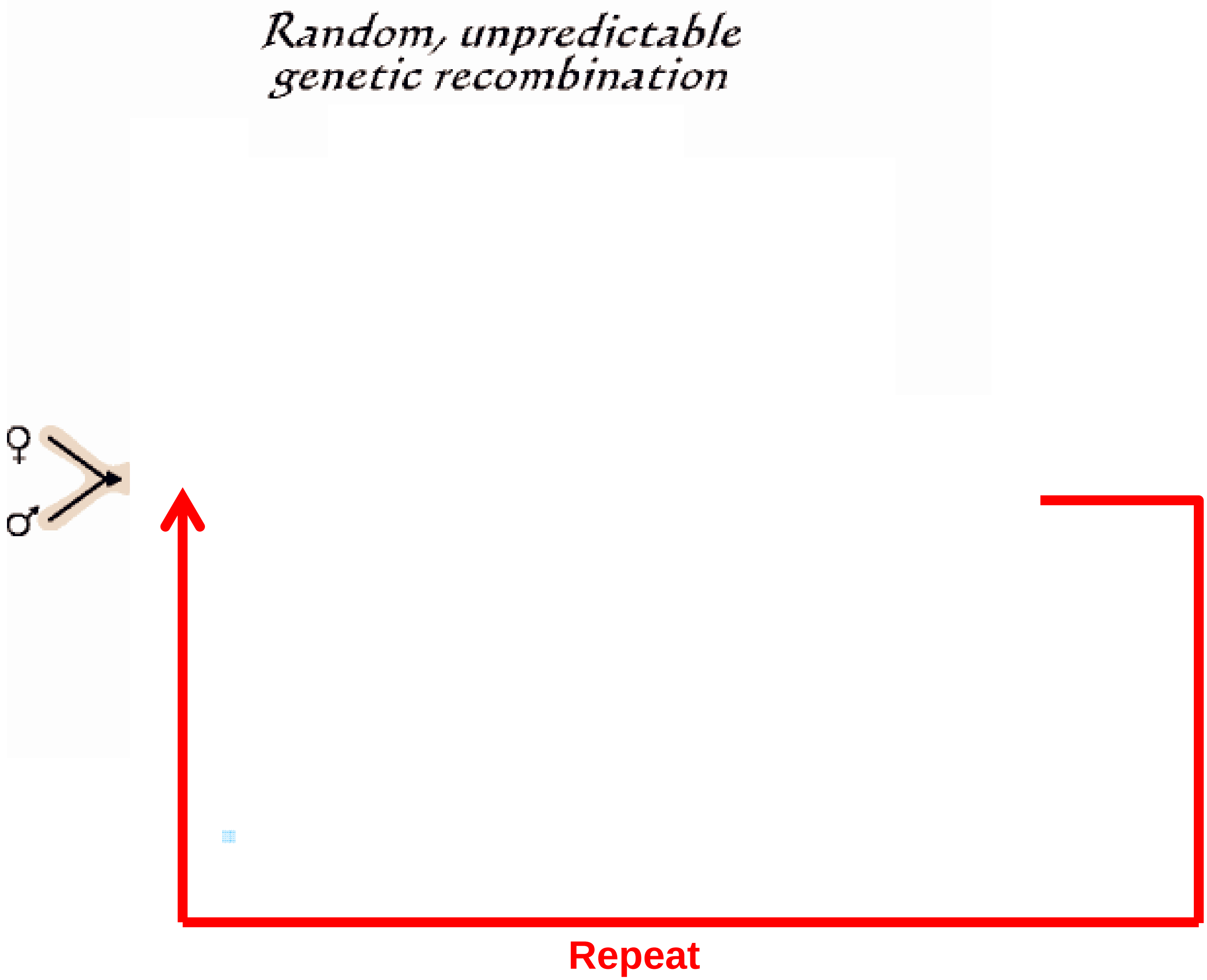
This is a different mechanism than attributed to biological evolution, meaning there are at least 2 evolutionary mechanisms

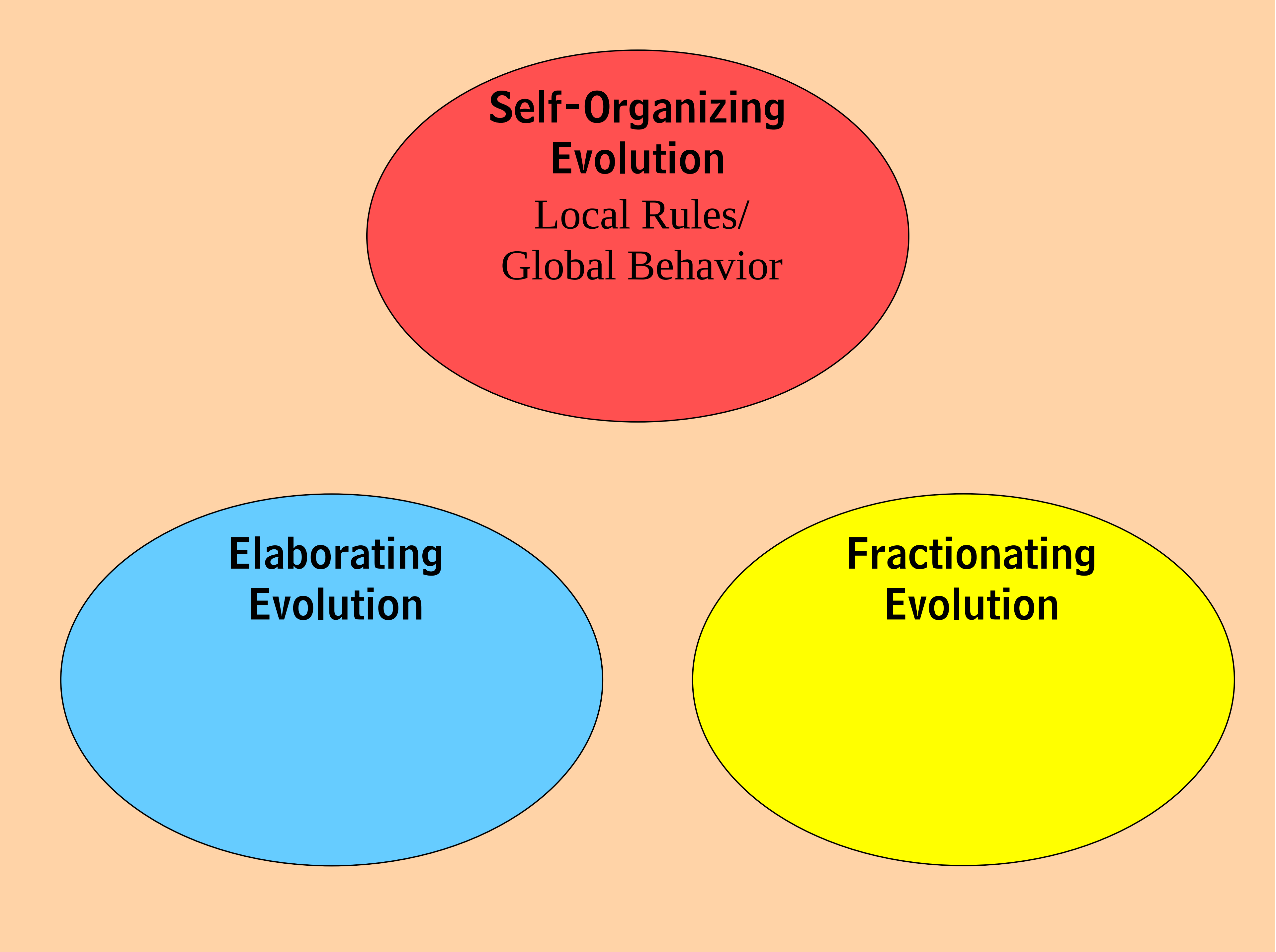

Self-Organizing
Evolution
Local Rules/
Global Behavior
Elaborating
Evolution

Elaborating evolution begins with a seed, an ancestor, or a randomly generated population of agents, and evolves by generating, and randomly mutating, a large diversity of descendants which are evaluated by an external fitness function; those that do not measure up selected out.

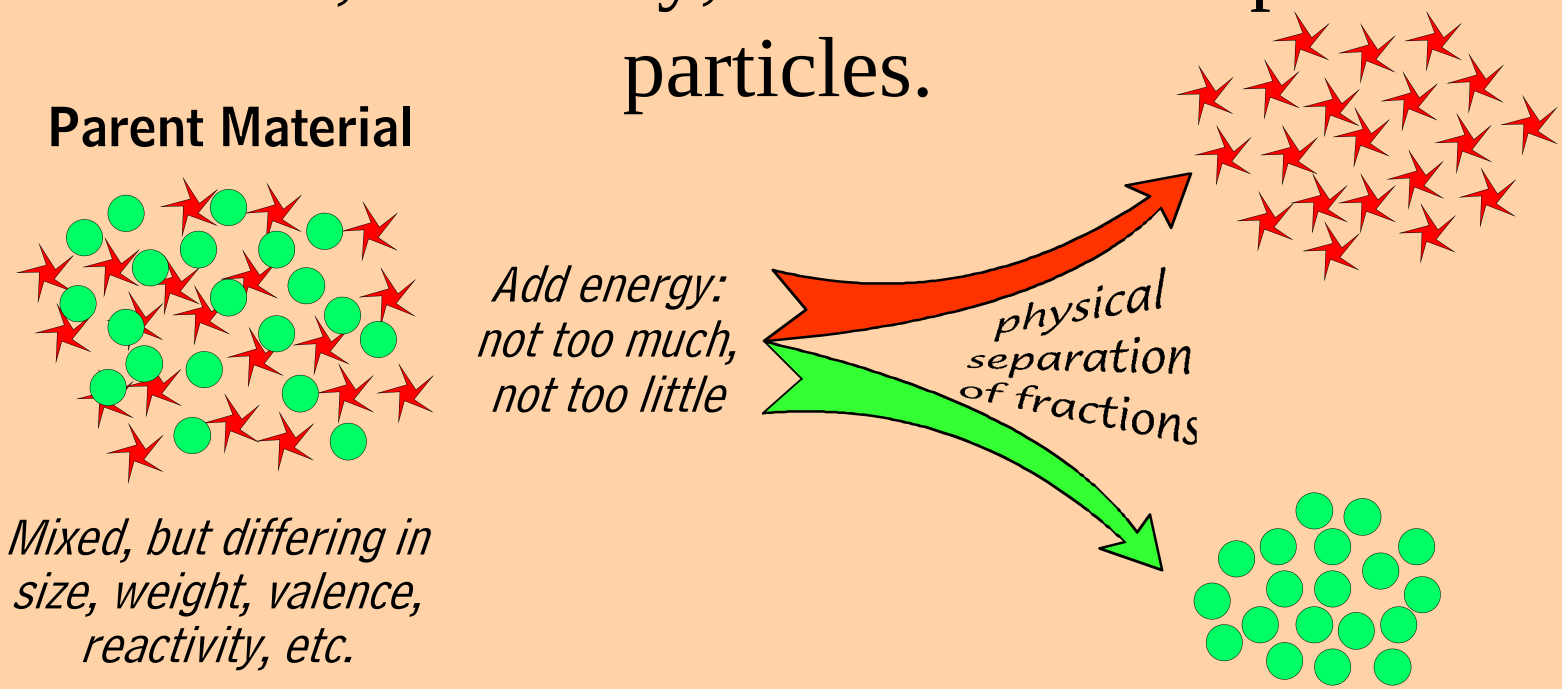
The fitness function may be a real environment, an abstract environment, or another "species" of agents.

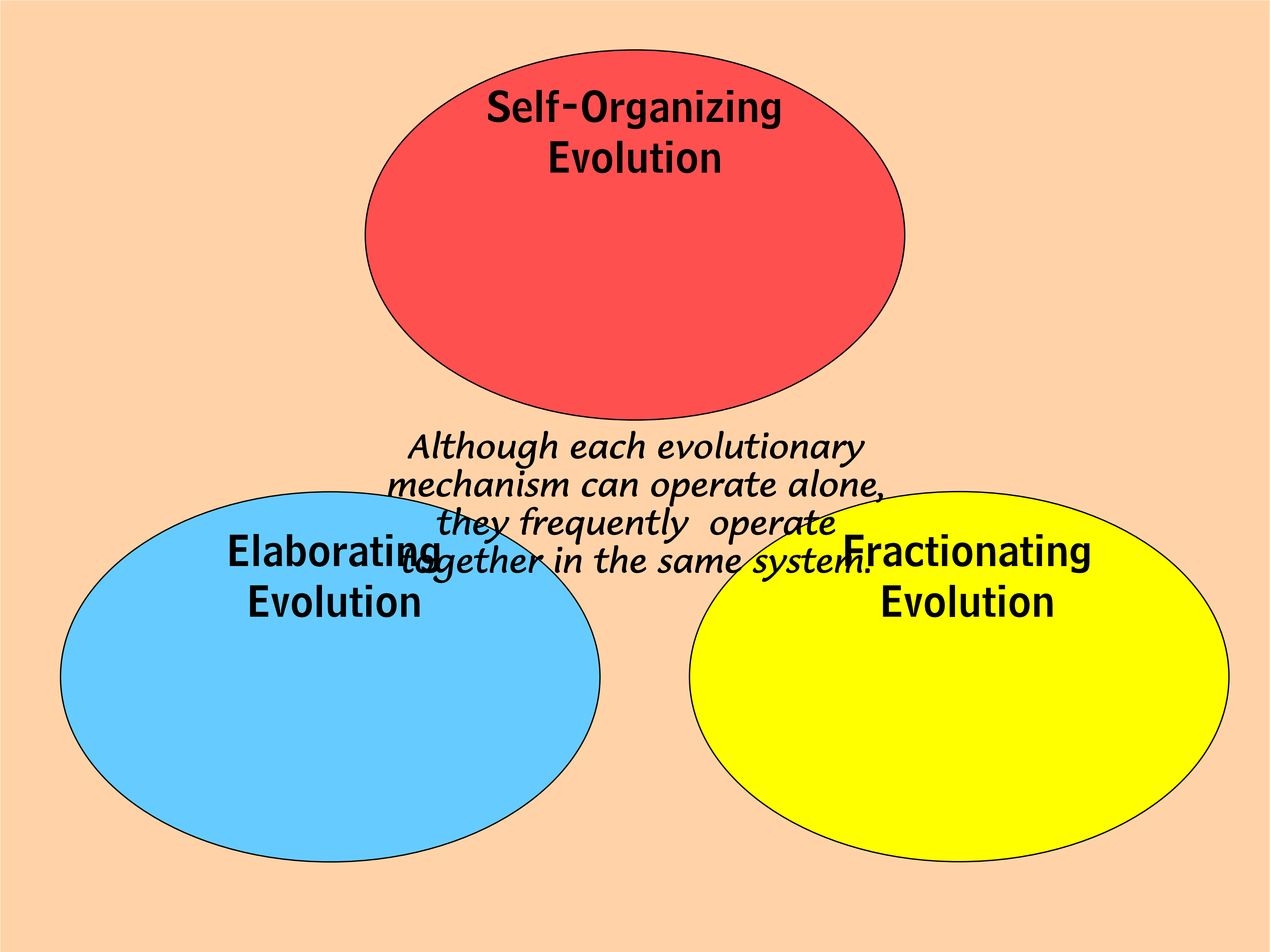
General Evolutionary Algorithm in Biology




Self-Organizing Evolution
Local Rules/
Global Behavior
Elaborating Evolution
Fractionating Evolution

Fractionating evolution begins with a complex parent which is physically, chemically, or biologically divided into fractions—through the addition of the right amount of energy—because of differences in the size, weight, valence, reactivity, etc. of the component particles.

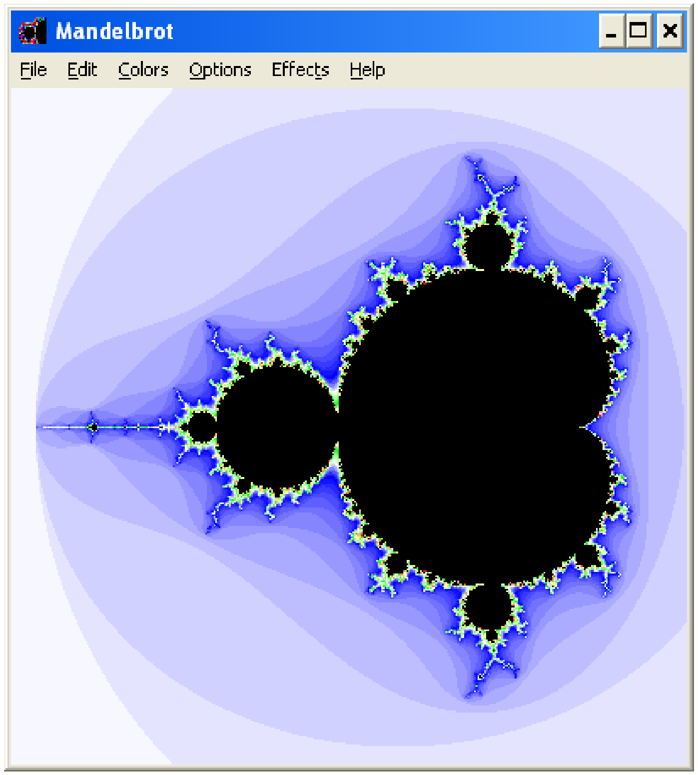



Self-Organizing Evolution
Although each evolutionary mechanism can operate alone, they frequently operate together in the same system.
Elaborating Evolution
Fractionating Evolution

Universality

So, what is common to all evolutionary systems that joins them into a common theory ?

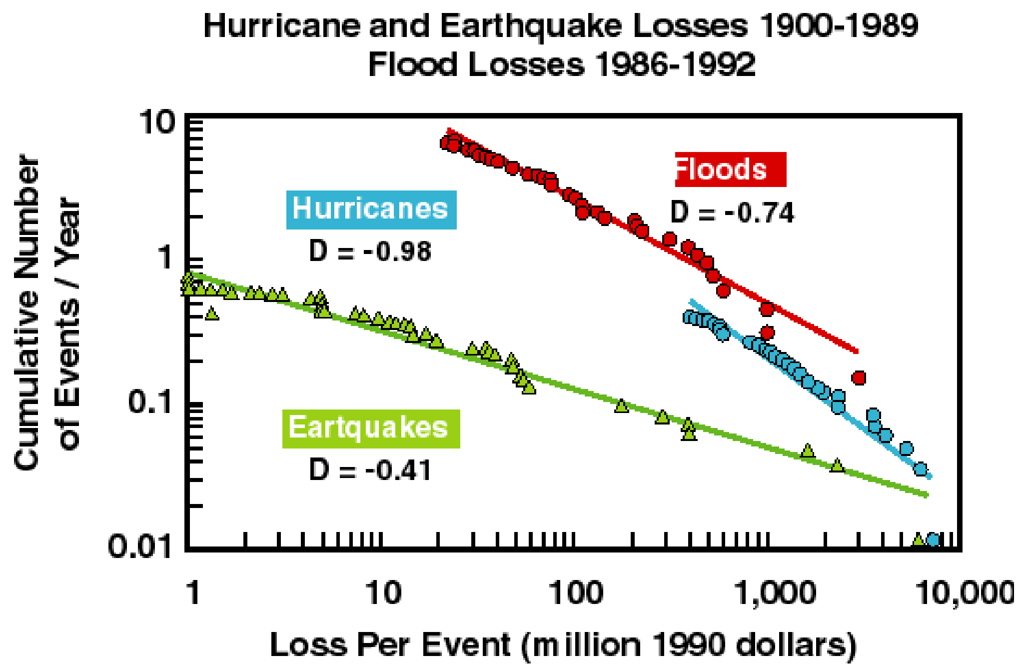
- Fractal organization.



Universality

So, what is common to all evolutionary systems that joins them into a common theory ?

- Fractal organization.
- Power law relationships

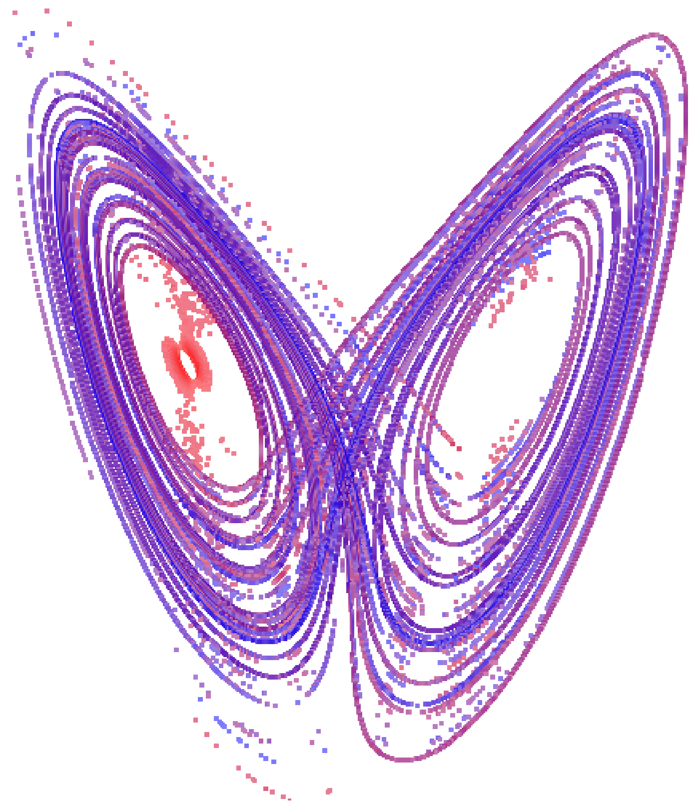


Christopher Barton USGS

Universality

So, what is common to all evolutionary systems that joins them into a common theory ?

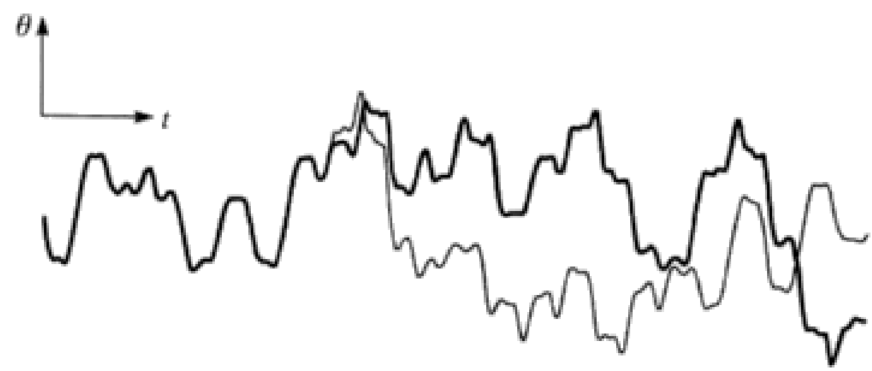
- Fractal organization.
- Power law relationships
- Behave as strange attractors



Universality

So, what is common to all evolutionary systems that joins them into a common theory ?

- Fractal organization.
- Power law relationships
- Behave as strange attractors
- Sensitive Dependence
- And others . . .



Impediments to Teaching Complex Systems

1. Confusion over the terms "complex" and "system."
2. The dominance of linear/equilibrium thinking and training in our schools.
3. The domination of biological evolutionary theory as the only systematic mechanism for evolutionary change.
4. The absence of rubrics for introducing chaos/ complex systems theories and modeling techniques in class rooms

Or,

Teaching chaos/complex evolutionary systems to

Introductory,

Non-science,

General Education students

Expanding Evolutionary Theory Beyond Darwinism with Elaborating, Self-Organizing, and Fractionating Complex Evolutionary Systems

Lynn S. Fichter[1,2], E.J. Pyle[1,3], S.J. Whitmeyer [1,4]

ABSTRACT

Earth systems increase in complexity, diversity, and interconnectedness with time, driven by tectonic/solar energy that keeps the systems far from equilibrium. The evolution of Earth systems is facilitated by three evolutionary mechanisms: *elaboration*, *fractionation*, and *self-organization*, that share universality features not found in more familiar equilibrium systems. These features include: 1. evolution to sensitive dependent critical states, 2. avalanches of changes following power law distributions with fractal organization, and 3. dynamic behaviour as strange attractors that often exhibit bi-stable behaviour. We propose a new approach to teaching Earth systems theory, where theoretical underpinnings of evolutionary mechanisms are introduced, followed by explorations of how the mechanisms interact to integrate the lithosphere, atmosphere, hydrosphere, and biosphere into a unitary evolutionary system. We incorporate conceptual and computer-based interactive models (included here as educational resources) within our lesson plans that illustrate a hierarchy of principles and experimental outcomes for evolutionary mechanisms. Application of this educational framework requires explicating complex systems mechanisms and their interactions, exploring their applicability to Earth systems, and imbedding them in high school as well as college introductory and upper level Earth Science classrooms to put all Earth systems on a comprehensive, integrated, universal evolutionary theoretical foundation.

INTRODUCTION

Ask the average person, "What is the theory of evolution?" and you are likely to get answers like "natural selection", or "survival of the fittest", or "Darwin's theory." Because these ideas are systematically taught in classrooms, they may represent the only evolutionary theory people know. But, ask, "What is the theory of Earth evolution?" you will likely get a blank stare, or at best a superficial discussion of the fossil record. The Earth as a multi-faceted evolutionary system that undergoes continuous change through time was incorporated in the National Science Education Standards, even if it is absent from many contemporary curricula and common perceptions (see Figure 1).

In this manuscript, we propose that an expanded definition of evolution be applied both in teaching and research to fully explicate the understanding of Earth systems. Such an expanded definition—explicating the

EXPLORATION

Biological evolution is commonly taught in terms of changes in the gene pool of a population from generation to generation by such processes as mutation, natural selection, and genetic drift as organisms adapt to changing environments. However, we do not teach the evolution of Earth systems (lithosphere, atmosphere, hydrosphere) through any similar sort of connective or transformative process. We may speak of the theory of plate tectonics, or describe the breakup of Pangaea, but these are usually taught as descriptive stories rather than as analytical theories following specific principles resulting in evolutionary outcomes that connect and integrate all Earth systems. As a result, many Earth science concepts are presented as discrete ideas, without connection to any central, universal, unifying theoretical framework for understanding such as evolutionary theory serves for biology.

Strategies and Rubrics for Teaching Chaos and Complex Systems Theories as Elaborating, Self-Organizing, and Fractionating Evolutionary Systems

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ABSTRACT

To say Earth systems are complex, is not the same as saying they are a complex system. A complex system, in the technical sense, is a group of "agents" (individual interacting units, like birds in a flock, sand grains in a ripple, or individual units of friction along a fault zone), existing far from equilibrium, interacting through positive and negative feedbacks, forming interdependent, dynamic, evolutionary networks, that possess universality properties common to all complex systems (bifurcations, sensitive dependence, fractal organization, and avalanche behaviour that follows power-law distributions.)

Chaos/complex systems theory behaviors are explicit, with their own assumptions, approaches, cognitive tools, and models that must be taught as deliberately and systematically as the equilibrium principles normally taught to students. We present a learning progression of concept building from chaos theory, through a variety of complex systems, and ending with how such systems result in increases in complexity, diversity, order, and/or interconnectedness with time—that is, evolve. Quantitative and qualitative course-end assessment data indicate that students who have gone through the rubrics are receptive to the ideas, and willing to continue to learn about, apply, and be influenced by them. The reliability/validity is strongly supported by open, written student comments.

INTRODUCTION

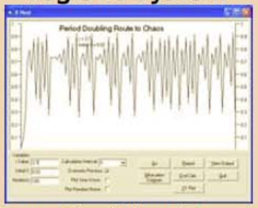
Two interrelated subjects are poised for rapid development in the Earth sciences. One is the application of chaos and complex systems theories, and the other is an expanded repertoire of theories about how Earth systems evolve—including theories compatible with but different from Darwinian evolutionary theory. These have the prospect of fundamentally changing the way we think about the evolutionary history of natural systems, but only if we develop systematic strategies for introducing and teaching these concepts.

Fichter, Pyle, and Whitmeyer (2010, in press JGE) posit that Earth systems, like many other natural systems, evolve by three evolutionary mechanisms: elaboration, fractionation, and self-organization, operating either individually or in concert within the same system. Each of these is best understood and explained as a complex system, in the technical sense of that phrase (explicated below). Elaborating evolution—subsuming biological evolution as a special case—begins with a seed, an ancestor, or a randomly generated population of agents, and evolves by generating, and randomly mutating, a large diversity of descendants which are evaluated by an external fitness function. The inclusive mechanism is the chemically, or biologically divided into fractions through the addition of sufficient energy because of differences in the size, weight, valence, reactivity, etc. of the component particles.

There are impediments to incorporating these ideas in the discipline and in the classroom. One impediment is the dominance of linear/equilibrium thinking and training in our schools (Fichter, Pyle, Whitmeyer, 2008). Teaching chaos/complex systems principles requires students be familiar with mathematical principles, techniques, and properties not yet systematically taught. A second impediment is the inconsistent and ambiguous use of the terms "complex" and "system." A third impediment is the domination of biological evolutionary theory as the only systematic mechanism for evolutionary change. Finally, a fourth impediment is the absence of rubrics for introducing chaos/complex systems theories and modelling techniques in class rooms. This paper addresses all these issues and develops a systematic, theoretically coherent, and practical set of definitions, concepts, models, and rubrics for teaching ideas of complex evolutionary systems at the introductory level. We also include assessment results of the level to which students' dispositions or habits of mind have been

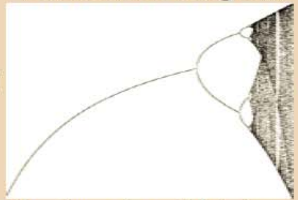
Chaos Theory

Logistic System



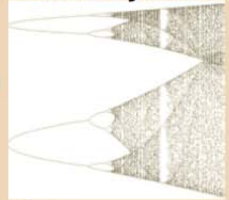
1. Computational Viewpoint
2. Positive/Negative Feedback
3. 'r' Values
4. Deterministic is not Predictable

Bifurcation Diagram



5. Bifurcation = change in behavior
6. Instability increases with 'r'.

Self-Similarity/Fractals



7. Self Similarity
8. No typical/average size of events/objects
9. Non-whole number dimensions

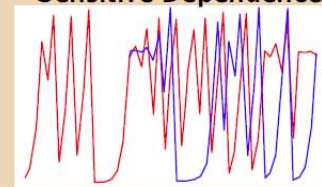
Feigenbaum Ratios

10. All complex systems accelerate rate of chage at the same rate.

Increasing Instability

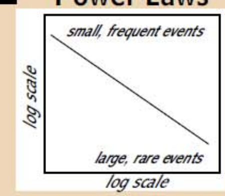
11. All changes (bifurcations) preceeded by increasing instability

Sensitive Dependence



12. Miniscule changes in 'r' can result in dramatic changes in behavior.

Power Laws



13. Small - low energy - events very common; large - high energy - events very rare.

Strange Attractors

14. Behaviors have recognizable large scale patterns but never repeat the same path.

Complex Systems Theory

A group of "agents" (individual interacting units, like birds in a flock, sand grains in a ripple, or individual units of friction along a fault zone), existing far from equilibrium, interacting through positive and negative feedbacks, forming interdependent, dynamic, evolutionary networks . . . . . . leading to increasing complexity, diversity, order, and/or interconnectedness

Fractionating Evolutionary Mechanisms

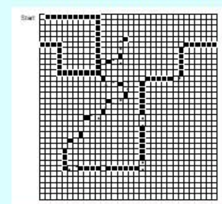
Self-Organizing Mechanisms

Elaborating Evolutionary Mechanisms

Word Evolv

15. The general evolutionary algorithm—1) differentiate, 2) select, 3) amplify, 4) repeat—is an extremely efficient and effective method of natural selection.

John Muir Trail



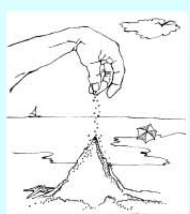
Tierra/Avida

Ancestral Program - consists of three 'genes'

Boids

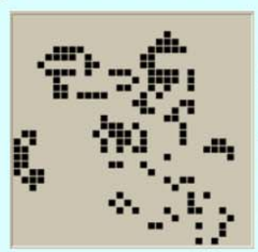
16. Local Rules lead to Global Behavior, self organization arises spontaneously without design, or purpose, or teleological mechanisms.

Self-Organized Criticality



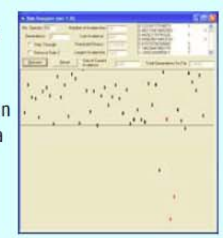
17. All open systems dissipating sufficient energy evolve—self-organize—to critical, sensitive dependent states which lead to avalanches of change that follow a power law distribution.

Cellular Automata



18. In a complex system everything is connected with everything else. Nothing exists in isolation from the rest, sitting in a protected niche, independent and self-sufficient.

Bak-Sneppen



19. In a complex system no one can be completely safe, with complete control over their fate.

Undeveloped as a chaos/complex system.

Fichter, Pyle, Whitmeyer, (in press), Strategies and Rubrics for Teaching Chaos and Complex Systems Theories

Teaching Chaos/Complex Systems to Beginners - Mozilla Firefox

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- About the Department
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- Expanding Evolution Beyond Darwinism
- Strategies/Rubrics Teaching Chaos/Complexity
- Power Point Lectures
- Learning Progression Flow Chart
- Logistic System
- Generating Bifurcation Diagrams
- Self Similarity

TEACHING CHAOS AND COMPLEX EVOLUTIONARY SYSTEMS THEORIES AT THE INTRODUCTORY LEVEL

Introduction

This web site contains the support materials for two papers on elaborating, self-organizing, and fractionating evolutionary mechanisms, and the teaching of of these mechanisms using chaos/complex systems theories, as published in the Journal of Geoscience Education. Strategies, rubrics, learning outcomes, computer models of various chaos/complex systems, and sample lab experiments are available by clicking the links below.

Expanding Evolutionary Theory Beyond Darwinism with Elaborating, Self-Organizing, and Fractionating Complex Evolutionary Systems
Fichter, Lynn S., Pyle, E.J., and Whitmeyer, S.J., 2010, Journal of Geoscience Education (in press)

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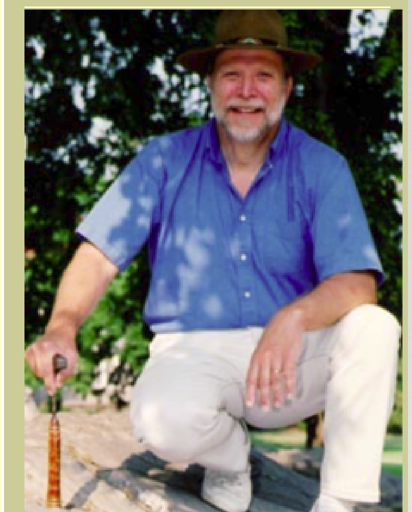

LYNN S. FICHTER

Done


Thank you
for you time
and attention