Theory of Complex Systems

Marco Aurelio Alzate Monroy

Introduction

Doctoral Program in Engineering
<table>
<thead>
<tr>
<th>Sistemas Dinámicos</th>
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<tbody>
<tr>
<td>¿Sabes qué es un sistema dinámico no-lineal?</td>
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<td>¿Sabes qué es un punto de equilibrio?</td>
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<td>¿Sabes qué es estabilidad?</td>
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<td>¿Sabes qué es un espacio de fase?</td>
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<td>¿Sabes qué es caos?</td>
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<th>Procesos Estocásticos</th>
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<td>¿Sabes qué es una distribución conjunta?</td>
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<td>¿Sabes qué es auto-correlación?</td>
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<td>¿Sabes qué es un proceso estacionario?</td>
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<td>¿Sabes qué es convergencia en probabilidad?</td>
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<td>¿Sabes qué dice el teorema del límite central?</td>
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<tr>
<th>Machine Learning</th>
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<tr>
<td>¿Sabes qué es una red de Hopfield?</td>
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<td>¿Sabes cómo funciona un algoritmo genético básico?</td>
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<td>¿Sabes cómo funciona el algoritmo de “back propagation”?</td>
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<td>¿Sabes qué es un conjunto difuso?</td>
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<td>¿Sabes qué es un sistema Takagi-Sugeno?</td>
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<th>Teoría de la Información</th>
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<td>¿Sabes qué es entropía?</td>
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<td>¿Sabes qué es información mutua?</td>
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<td>¿Sabes qué es un código Huffman?</td>
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<td>¿Sabes cómo se define la capacidad de un canal?</td>
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<td>¿Sabes qué es la región de capacidad de una red?</td>
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<th>Teoría de Grafos</th>
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<tr>
<td>¿Sabes qué es el grado de un nodo?</td>
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<td>¿Sabes qué es el diámetro de un grafo?</td>
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<td>¿Sabes qué es una matriz de adyacencia?</td>
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<td>¿Sabes qué es un grafo conectado?</td>
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<tr>
<td>¿Conoces un algoritmo para encontrar la ruta más corta entre dos nodos de un grafo?</td>
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<th>Teoría de Computación</th>
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<tr>
<td>¿Sabes qué es una máquina de Turing?</td>
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<td>¿Sabes cuál es la tesis de Turing-Church?</td>
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<td>¿Sabes qué es un problema P y qué es un problema NP?</td>
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<td>¿Sabes qué es computación biológica?</td>
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<tr>
<td>¿Entiendes algo de los teoremas de Gödel?</td>
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District University
Francisco José de Caldas

School of Engineering

Doctoral Program in Engineering
District University
Francisco José de Caldas

School of Engineering

Doctoral Program in Engineering

where we are?

who we are?
District University
Francisco José de Caldas

School of Engineering

Doctoral Program in Engineering

where we are?

who we are?

What we will become?
• **University**
  o Search for truth and knowledge in a free academic environment

• **Engineering**
  o Application of scientific principles for developing technology

• **Doctoral program**
  o Independent and original research for uncovering new knowledge through judicious application of the scientific method
Technology development

IT'S THE MESOLITHIC AGE? - BUT I JUST GOT USED TO THE PALEOLITHIC!

“He has gone high-tech”
Lascaux and Sáchica... Consciousness!
El Infiernito
Models

\[ F = G \frac{M \cdot m}{r^2} \]
Egypt, Babilon,...
Aristotle (384 – 322 BC)

Bacon (1214 – 1294)

Bacon (1561 – 1626)

Galileo (1564 – 1642)

Descartes (1596 – 1650)

Kepler (1571 – 1630)

Newton (1643 – 1727)

Einstein (1879 – 1955)
“Scientific Method...”

Theory

Induction

Empiric generalization

Analysis

Observation of the world

Prediction

Hypotesis
"Scientific Principles..."

"I think you should be more explicit here in step two."

"...and that is my philosophy."

"It's an excellent proof, but it lacks warmth and feeling."

"You want proof? I'll give you proof."
“Scientific Principles...”

"YOU REALIZE, OF COURSE, THAT MUCH OF IT DOESN'T CONFORM TO THE RELIGIOUS BELIEFS OF SOME GROUPS."

"TONIGHT'S TOPIC: IS THE POPULAR BELIEF CORRECT THAT THE SQUARE ROOT OF 5486.6911 IS 74.07220, AND IF NOT, WHY NOT?"

"VERY CREATIVE. VERY IMAGINATIVE. LOGIC... THAT'S WHAT'S MISSING."
"Scientific Principles..."

"What's most depressing is the realization that everything we believe will be disproved in a few years."
“Scientific Principles...?”

• Determinism
• Mechanicism
• Reductionism
“Scientific Principles...?”
Determinism

“We can observe the current state of the Universe as the effect of its past and the cause of its future. An intelligence which at a given instant knew all the forces acting in nature and the position of every object in the universe — if endowed with a brain sufficiently vast to make all necessary calculations — could describe with a single formula the motions of the largest astronomical bodies and those of the smallest atoms. To such an intelligence, nothing would be uncertain; the future, like the past, would be an open book.”

Pierre Simon Laplace (1749-1827)
Mechanicism

“This will not be extrange for those acquainted with the variety of movements performed by the machines made by human industry, based on a few components, as compared with the many bones, muscles, arteries and other parts found in animal bodies. It is just natural to see their bodies as machines made by the hand of God, much better suited for amazing movements than any other machine of human invention. I claim that if a machine of human invention replicates the organs and external forms of an irrational animal, we could not distinguish it from the animal itself.”

Descartes (1596 – 1650)
Reductionism

• “I think we can infer every other phenomenon of nature using the same type of reasoning, from mechanical principles, because there are many reasons that induce me to suspect that all of them depend on certain forces”

Divide each difficulty into as many parts as is feasible and necessary to resolve it.

Rene Descartes
... Predictability!

- **Napoleon**: “How is it that you say so much about the Universe but you say nothing about its Creator?”
- **Laplace**: “Sire, I had no need of that hypothesis.”
  
  (Newton used God will to justify why the universal law of gravity does not explain the anomalies in the movements of Jupiter and Saturn).

- **Lagrange**: “Ah, but God is such a good hypothesis. It explains so many things.”
- **Laplace**: “Although it explains everything, it predicts nothing”.
  
  (Laplace solved the Jupiter and Saturn problem by iterating partial solutions).
Mechanistic Reductionism

And, since then, all the great (and not so great) scientists (and engineers, and managers, and ...)
of the last 4 centuries. Until ...


And, since then, each day more and more scientists (and engineers, and managers, and...)
Conceptual and historical overview of complexity science
Studies of complexity

• George Cowan founded the Santa Fe Institute in 1984 ([http://www.santafe.edu/](http://www.santafe.edu/))
  – Founded for multidisciplinary collaborations in the physical, biological, computational, and social sciences, attempting to uncover the mechanisms that underlie the deep simplicity present in our complex world. Understanding of complex adaptive systems is critical to addressing key environmental, technological, biological, economic, and political challenges.

• Stephen Wolfram began the Center for Complex Systems Research at the University of Illinois, in 1986 ([http://www.ccsr.uiuc.edu/](http://www.ccsr.uiuc.edu/))
  – Studies systems that display adaptive, self-organizing behavior and systems that are usually characterized by a large throughput, such as turbulent flow, lightning, and the flow of information through the internet. To describe these complex systems, we develop models and techniques drawn from nonlinear dynamics and chaos, neural nets, cellular automata, artificial life, and genetic algorithms.

  – Studies how parts of a system give rise to its collective behaviors, as well as how the system interacts with its environment. By using mathematics to focus on pattern formation, and the question of parts, wholes and relationships, the field of complex systems cuts across all the disciplines of science, as well as engineering, management, and medicine.
Studies of complexity

• Northwestern Institute of Complex Systems (http://www.northwestern.edu/nico/)

• Institute for Complex Systems Simulation, University of Southampton (http://www.icss.soton.ac.uk/)

• Plexus Institute (http://www.plexusinstitute.com/)

• Instituto de Sistemas Complejos de Valparaiso (http://www.iscv.cl/index.html)

• Centro de Estudios Interdisciplinarios Básicos y Aplicados CEIBA (http://www.ceiba.org.co/)

• Etc.
Complex Systems are systems that comprise many interacting parts with the ability to generate a new quality of macroscopic collective behavior the manifestations of which are the spontaneous formation of distinctive temporal, spatial or functional structures. Models of such systems can be successfully mapped onto quite diverse "real-life" situations like the climate, the coherent emission of light from lasers, chemical reaction-diffusion systems, biological cellular networks, the dynamics of stock markets and of the internet, earthquake statistics and prediction, freeway traffic, the human brain, or the formation of opinions in social systems, to name just some of the popular applications. Although their scope and methodologies overlap somewhat, one can distinguish the following main concepts and tools: self-organization, nonlinear dynamics, synergetics, turbulence, dynamical systems, catastrophes, instabilities, stochastic processes, chaos, graphs and networks, cellular automata, adaptive systems, genetic algorithms and computational intelligence.
Complex Systems

Emergence over scale

Nonlinear Dynamics
- Attractors
- Stability analysis
- Population dynamics
- Chaos
- Multistability
- Bifurcation
- Coupled map lattices

Game Theory
- Prisoner’s dilemma (PD)
- Rational decision making
- Iterative PD
- Bounded rationality
- Cooperation versus competition
- Spatial/network game theory
- Evolutionary game theory

Collective Behavior
- Social dynamics
- Collective intelligence
- Herd mentality
- Self-organized criticality
- Agent-based modeling
- Phase transition
- Irrational behavior
- Synchronization
- Ant colony optimization
- Particle swarm optimization
- Swarm behavior

Networks
- Scale-free networks
- Social network analysis
- Small-world networks
- Community identification
- Centrality
- Motifs
- Scaling
- Graph theory
- Systems biology
- Dynamical networks
- Adaptive networks

Self-Organization over time

Systems Theory
- Homeostasis
- Feedbacks
- Self-reference
- Goal-oriented/guided behavior
- Sensomotor interference
- System dynamics
- Entropy
- Autopoiesis
- Information theory
- Complexity measurement

Evolution & Adaptation
- Artificial neural networks
- Evolutionary computation
- Genetic algorithms/programming
- Artificial life
- Machine learning
- Evo-Devo
- Artificial intelligence
- Evolutionary robotics
- Evolvability

Pattern Formation
- Spatial fractals
- Reaction-diffusion systems
- Partial differential equations
- Percolation
- Cellular automata
- Spatial ecology
- Self-replication
- Spatial evolutionary biology
- Geomorphology
Complex Systems

Involve:

Many Components

Dynamically Interacting
and giving rise to

A Number of Levels or Scales

which exhibit

Common Behaviors

Tomado de http://www.art-sciencefactory.com/complexity-map_feb09.html
Characteristics of Complex Systems

A 'complex' system

Emergent behavior that cannot be simply inferred from the behavior of the components

Complex Systems

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A Number of Levels or Scales

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Common Behaviors

A 'simple' system

Emergence

Hierarchies

Self-Organization

Control Structures

Composites

- Substructure
- Decomposability

Tomado de http://www.art-sciencefactory.com/complexity-map_feb09.html

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Characteristics of Complex Systems

A 'complex' system

Emergent behavior that cannot be simply inferred from the behavior of the components

A 'simple' system

Trandisciplinary Concepts

Across Types of Systems, Across Scales, and thus Across Disciplines

Complex Systems

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- A 'complex' system
  - Emergent behavior that cannot be simply inferred from the behavior of the components

- Complex Systems
  - Involve:
    - Many Components
    - Dynamically Interacting and giving rise to
    - A Number of Levels or Scales which exhibit
    - Common Behaviors
  - Size Scale
    - Emergence
    - Hierarchies
    - Self-Organization
    - Control Structures
    - Composites
      - Substructure
      - Decomposability
  - Time Scale
    - Evolution

- Transdisciplinary Concepts
  - Across Types of Systems, Across Scales, and Thus Across Disciplines
Characteristics of Complex Systems

A 'complex' system

Emergent behavior that cannot be simply inferred from the behavior of the components

Complex Systems

Involve:

Many Components

Dynamically Interacting and giving rise to A Number of Levels or Scales which exhibit Common Behaviors

A 'simple' system

Chaos

Fine Scales Influence Large Scale Behavior

Evolution

Emergence

Hierarchies

Self-Organization

Control Structures

Composites

- Substructure
- Decomposability

Transdisciplinary Concepts

Across Types of Systems, Across Scales, and thus Across Disciplines

Tomado de http://www.art-sciencefactory.com/complexity-map_feb09.html
A Complex System
A Complex System

An isolated ant is very “simple”:
- Deposits pheromones
- Follows pheromone tracks
- Superposes random walk

An ant colony easily solves highly complex problems (NP-complete):
- Shortest path
- Sorting
An isolated neuron is very “simple”:
- Processes input stimuli
- Generates output stimuli

An human brain is capable of highly complex behaviors:
- Learning
- Generalizing
- Consciousness
- Intuition
A Complex System

Family
Friends
Working mates

Colombian Civilians commemorating on 26 June,
International Day against Drug Abuse and Illicit Trafficking
A Complex System

- Fractal traffic
- Scale free topologies
- Potentially chaotic dynamics
- Self-organization at edge of congestion
- ...

Theory of Complex Systems
Marco Aurelio Alzate Monroy
A Complex System

- Self-organization at a critical state of phase transition
Multiple disciplines
\[ \frac{d}{dt} x(t) = f(x(t), u(t), t) \]

\[ y(t) = g(x(t)) \]
Linear systems

- When the postulates of mechanistic reductionism are valid

\[ \alpha F_1 + \beta F_2 = \alpha v_1 + \beta v_2 \]
Modeling

Reality

Model
Models: Laws of nature

\[ v_i(t) = v_0(t) + v_R(t) \]
\[ v_i(t) = v_0(t) + R \cdot i(t) \]
\[ v_i(t) = v_0(t) + RC \frac{d}{dt} v_o(t) \]

\[ F(t) - \rho \cdot v(t) = M \frac{d}{dt} v(t) \]
\[ \frac{1}{\rho} F(t) = v(t) + \frac{M}{\rho} \frac{d}{dt} v(t) \]

\[ \frac{1}{\alpha} (x(t) - y(t)) = \frac{d}{dt} y(t) \]
\[ x(t) = y(t) + \alpha \frac{d}{dt} y(t) \]
Matemathical model for mechanistic reductionism: Linearity

\[ V(t) = R \cdot I(t) \]

\[ I(t) = C \cdot \frac{d}{dt} V(t) \]

\[ V(t) = L \cdot \frac{d}{dt} I(t) \]
The logic of linearity

"If 40 Amish farmers can build a barn in 8 hours...

Then 1280 of them can do it in 15 minutes"
Non-linear dynamical systems

\[ x_{n+1} = x_n^2 + c \]

- \( c = 0 \)
- \( c = 0.15 \)
- \( c = 0.25 \)
- \( c = 0.26 \)
- \( c = 0.3 \)
- \( c = 0.5 \)
- \( c = 1 \)
- \( c = -0.5 \)
- \( c = -0.75 \)
- \( c = -1 \)
- \( c = 0.5i \)
- \( c = -0.125 + 0.65i \)
- \( c = -1.25 \)
- \( c = -1.4012 \)
Some complexity signatures

- Power laws
- Free scale networks
- Fractals
- Chaos
- Criticality
- Phase Transition
- Self-organization
- Emergence
- Learning
- Evolution
- Adaptability
- ...
Fractals
Fractals

Introduction to Complex Systems
Fractals

Introduction to Complex Systems

From iterative algorithms
Fractals

From random processes

From iterative algorithms

Introduction to Complex Systems
Fractals
From iterative algorithms
From non-linear systems
From random processes
Introduction to Complex Systems
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Fractals

From self-organized systems

From random processes

From non-linear systems

From iterative algorithms
Introduction to Complex Systems

Fractals

- From self-organized systems
- From random processes
- From non-linear systems
- From iterative algorithms

Complex systems engineering
From reductionsm, mechanicism, determinism, and predictability to self-organization, emergence, evolution and adaptation.
Introduction to Complex Systems

From self-organized systems

From non-linear systems

From random processes

From iterative algorithms

Fractals in nature, Affine transformations and Iterated function systems, symmetry and growth, Lindenmayer’s systems, formal grammars, computability, decidability, Gödel’s incompleteness theorems, recursion, Euclidean measures of fractal objects, self-similar dimension, Hausdorff measure, Hausdorff dimension, box-counting dimension

From reductionsm, mechanism, determinism, and predictability to self-organization, emergence, evolution and adaptation.
Fractals
From iterative algorithms
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Random process, Brownian motion, fractional Brownian motion, Hurst parameter, midpoint displacement, variance-time plot, stochastic self-similarity, second-order strict self-similarity, second-order asymptotic self-similarity, long-range dependence, 1/f noise, heavy tailed distributions, FARIMA, M/G/∞, wavelet analysis of fractal signals, MWM.

From reductionsm, mechanism, determinism, and predictability to self-organization, emergence, evolution and adaptation.
Introduction to Complex Systems

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From self-organized systems

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From non-linear systems

Linear and non-linear systems, equilibrium and stability, bifurcation, bounded/unbounded regions, Julia sets and Mandelbrot set, chaotic systems, strange attractors, butterfly effect, unpredictability of deterministic systems

From iterative algorithms

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Introduction to Complex Systems

From reductionsm, mechanism, determinism, and predictability to self-organization, emergence, evolution and adaptation.

Fractals

From self-organized systems

Cellular automata, game of life, swarm intelligence, spatial and temporal patterns, game theory, SOC/EOC (Self-Organized Criticality/Edge Of Chaos), HOT (Highly optimized Tolerance), optimization and power laws, Free-Scale networks.

From random processes

Random process, Brownian motion, fractional Brownian motion, Hurst parameter, midpoint displacement, variance-time plot, stochastic self-similarity, second-order strict self-similarity, second-order asymptotic self-similarity, long-range dependence, 1/f noise, heavy tailed distributions, FARIMA, M/G/∞, wavelet analysis of fractal signals, MWM.

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Inspiration on neuroscience (perception, memory, attention, intelligence, language), Perception and Bayesian filtering, Action and Dynamic programming for optimal control, reinforcement learning, Examples from our own research: Emergent synchronization, Emergent Cooperation, Emergent Bandwidth estimation.

From iterative algorithms
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From reductionsm, mechanism, determinism, and predictability to self-organization, emergence, evolution and adaptation.
Homework # 2

After studying the class material, the presentation slides and any other reading you consider, turn off your computer, close all your books and take only a clean piece of paper and a pencil. Now explain briefly and concisely on your own words the following concepts:

• Mathematical modeling
• Reductionism/Mechanicism
• Adaptation
• Self-organization
• Collective intelligence
• Emergence
• Nonlinearity
• Complex system

We have recognized that the classical scientific principles of determinism, mechanism and reductionism have been overcome on the theory of complex systems. How does this affect the use of the scientific method in your dissertation research project? Explain in a single paragraph.

Read the first two assigned readings and be prepared for discussion next class.