When You Can't Beat 'em, Join 'em: Leveraging Complexity Science for Innovative Solutions

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Current Problem Domain

- Commander’s intent: Networked Navy & the intent of CYBERSAFE
  - Weak links on autonomous vehicles
  - Challenges with large scale ad-hoc battlespace networks

- Needs:
  - Dynamically adaptable cyber resilience
  - Threats may use autonomous (e.g. machine learning) adaptation.
  - Collective behaviors, e.g., swarms.
  - Novel approach may need novel mathematics as foundation.
  - Fundamentally, a complex adaptive system.
Historical Problem Domain: Net-Centricity and its Problems

• Books by Moffat, Alberts, published 2000-2003 describe aspects of the Net-Centric Battlespace needed for NCW (Net-Centric Warfare):
  • Has attributes of self-similarity (fractal nature)
  • Involves thousands of entities (network nodes)
  • Answers may lie somewhere within complexity science / chaos theory

• A solution would need:
  • Adaptive dynamic behaviors for resiliency
  • Scale upwards at least several orders of magnitude
  • Be computationally tractable
  • Converge to solution in short timeframe (milliseconds to a few seconds)
Fields of study and their overlap

Complexity Science: deterministic / non-deterministic chaos

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<th>Autonomy</th>
<th>Architecture &amp; Topology</th>
<th>Cyber</th>
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<td>• A.I./M.L.</td>
<td>• Hierarchical</td>
<td>• Resilience</td>
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<td>• Emergent attributes</td>
<td>• Self-similar (Fractal)</td>
<td>• Adaptability</td>
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What shaped my perspective on tackling the problem

- Physics undergrad, software engineering jobs in comms, video games, robotics
- Started NAWCAD (NADC) as a computer scientist / engineer researching Neural Networks (NNs) and mathematical modeling of physical & biological phenomena
- A.I. Branch – broadened my focus on machine learning, also had opportunities to apply NNs to real-world Navy problems
  - Noticed need for distributed architectures & emergent phenomena
  - Leveraged fractals and chaotic systems for advanced NN prototypes
  - Deep dive on chaos & complexity science.
- Modeling & Simulation (DFS Centrifuge) developed expertise in distributed networks and graphical software
- Private start-up “big data” focus, was director of research focused on semantics, fractal topologies and genetic algorithms
- M&S –ACETEF, software, specific focus on algorithms
- 2010-now: cyber engineering, autonomy & Machine Learning, advanced architectures
What is complexity science?

- Complexity science is informally known as order creation science. Novel coherent properties can result from self-organizing System of Systems (SoS). Collective actions of many entities in a system produces emergence.

- There are various methods to create complex SoS and emergence, for example:
  - New approaches in computational (experimental) mathematics for multi-agent systems.
  - Deterministic chaos (fractals).
  - Pecora & Carroll’s research on information embedded below chaotic noise threshold, similar chaotic circuit can “decrypt” signal from noise.

- Application Focus: Cognitive robotics incorporates the behaviors of intelligent agents within the shared world model.
  - Multi-agent systems create challenges for desired behaviors within a planned environment due in part to the problem of translating and using symbolic reasoning for world abstractions.
  - Even the lowest level distributed C2 (Command & Control) comms can produce complexity.
Emergent behaviors result **not** from stochastic (e.g. thermodynamics) models, but instead from multi-agent interactions (e.g. RoboCup).

Emergence can produce ‘creative’ system behaviors.

Artificial Life - uses emergence generating algorithms:
- genetic algorithms, neural nets, cellular automata.

Emergent SoS **cannot** be designed by functional decomposition.

Nonlinear systems: Can they have predictable behavior?
- Predictability ‘collapses’ as sequence progresses (complexity increases).
- Chaos can result from even small changes.
- Known initial and intermediate conditions can have unpredictable results = Emergent behavior.
Why should we use complexity science & how?

• Why?
  • Systems engineering is limited by its current System of Systems (SoS) approach to consistently predict novel / emergent behaviors that would give the U.S. an edge on our adversaries.
  • Large-scale multi-agent SoS, which are complex systems, typically show emergent behaviors.
  • Collective actions of many entities in a system produces emergence.
  • Complexity can provide a solution to translating the world into actions, by bounding the behaviors of distributed agents to produce new (emergent) and desired collective behaviors.

• How?
  • System elements need to be more adaptable, loosely coupled, and create a dynamically interoperable environment.
  • Complexity science is better modeled by using a localized, connectionist ontology of heterogeneous agents than by using equilibrium models from thermodynamics.
  • Novel coherent properties can result from these self-organizing systems.
What is a Complex System?

• Consists of many components associated by structure or just abstract relationship.
• May be scalable and self-similar at more than one level.
• Not described by simple rule or from the fundamental level. Predictable parts can form unpredictable system behavior.
  • E.g. Mandelbrot (fractal’s inventor): “transmission line noise” appeared random, was predictable “Cantor Dust”.
  • Bifurcation - “Feigenbaum diagram” at phase transitions (solid/liquid/gas), etc. represents nonlinear dropoff.
  • Devil’s staircase – at phase transition = chaos.
Diagrams: Feigenbaum and Devil’s Staircase
Most body functions exhibit complex behavior - fractal pattern of heartbeat, ionic channels, etc.

- when ECG pattern becomes *less* complex, then indicates potential heart problem !!

- Chaotic (complex) chemical reactions:
  - Belousov-Zhabotinskii reaction (color change)

- Can even build an electronic circuit with complex behavior - can be driven to chaotic

- *Can we control chaos?*
Chaos rules!
Generalized conjecture on chaos:

• Simple deterministic or even random stochastic models may not be the answer in our quest for human-like behaviors, or even the self-organizing patterns that occur in nature

• Perhaps we should look to controlling chaotic phenomena, as nature does, for the discovery of emergent patterns. This may lead to solutions for self-organizing large scale networks, or even human-like behavior in robots
Self-Organizing Complex Systems: Chaos Under Control

• Artificial biological systems:
  • Neural networks, Genetic algorithms, Boolean nets (Kauffman), Cellular Automata (Wolfram).

• Real biological systems:
  • Civilizations, economies, evolution (Kauffman), biological organisms, cognitive thought process.

• Experimental mathematics:
  • A “new” type of mathematics, previously unexplored due to computational limitations of the past.
  • Not Formal Methods, and no available proofs.
  • May depend upon deterministic chaos.
Control of chaos – an example

Problem: Spatially distributed large dynamic networks:
• Lose edge node communications.
• Congressional Research Report (2007):
  • Scaling limitations for large numbers of battlespace networked nodes.
  • Combinatorial explosion from massive numbers of route calculations.
• To increase availability and resiliency in network-centric clouds and swarms, ad-hoc nodes must rapidly self-organize using shared topology data.
• Topology can affect network failures and success of cyber offense and defense.

Perhaps we can leverage complexity science for a solution:
• Moffat's 2003 paper titled "Complexity Theory and Network Centric Warfare" referenced complex systems and their relationship to fractals and decentralized NCW.
• High volume network traffic packets self-organize to fractal (Leyland et al., 1994), therefore fractal may increase availability for large networks.
• Use a fractal that can adapt to needed topology.
Adaptive fractal experimental math discovery: an outgrowth of the linear chaos game

Like the simple point-slope equation for line:

- Deterministic chaos equation is \( X(n) = M \times X(n-1) + Z \).

  \[ X(n-1) = \text{current point}, \quad X(n) = \text{next point}. \]

Z: “vertices” = a set of initial points that constrain all node points, can represent network hubs. Z is randomly selected out of this set.

M: scale parameter = controls where the next point is generated from the current point. 0<|M|<1.

Both variables \( M \) and \( Z \) share interdependencies that affect the overall network topologies, including thresholds for clustering and the mappings to certain cluster elements.
Naming the algorithm and using the results

Algorithm Name: Non-predetermined Parametric Random (NPPR) Iterated Function System (IFS)

Running it:
• Node and hub considerations:
  • Points plotted show distribution of network nodes; vertices = hubs.
  • Hubs may be virtual, i.e. location for calculation purposes only, and can add, move, delete.
  • Nodes know relative layout of clusters, coalesce around hubs for communications clusters.

Results:
• Combinatorial explosion and cyber impact avoided by use of NPPR.
  • Usually is an issue in large ad-hoc networks (Adams & Heard, 2014).
• NPPR topology is information-dense: a little info can reconfigure network.
  • Hub changes broadcasted as lat/lon position.
  • Scale parameter changes from chaos to order.
• Produces repeatable macroscopic results, even with unique node positions
  • Can apply to large-scale swarm control, adaptive cyber warfare.
  • Shared stigmergic knowledge by all nodes – i.e. each knows position of “neighborhoods”
Attributes of this solution

• Solution is:
  • Self-similar – each node can “know” the topology relative to other nodes
  • Facilitates situational awareness for tens of thousands of distributed nodes
  • Uses Deterministic Chaos

• Solution has:
  • **Adaptive fractal topology** with dynamic behaviors for resiliency
  • Fractal **self-similarity** can scale upwards many orders of magnitude
  • **Linear equation** = like point-slope equation of line is computationally tractable
  • Converges to solution in short timeframe in 10-100 millisecond timeframe
  • Exhibits stigmergic behaviors

• **This is but one possible solution out of many, that can be discovered by using computational (experimental) mathematics**

DISTRIBUTION STATEMENT A
Personal Consequences of this Research

• Used as my successfully defended dissertation topic
• Discovered interesting emergent behaviors in a simple equation
• Received 2015 Outstanding Workforce Development Award as a direct result of this academic research project
• Wrote a chapter for engineering book on Engineering Emergence
Screen layout of NPPR “tool”:

A = Slider controls size (# pixels) in node-points plotting window, at bottom.
B = Hubs topology map, used to drag-and-drop a hub relative to others, or create hubs.
C = Resets diagram to a default 3-vertex, 0.5 scale for equilateral Sierpinski gasket.
D = Checkbox that toggles display of horizontal and vertical axes.
E = Slider for number of pixels selected to represent each node plotted.
F = Scale slider for the NPPR parameter (floating point multiplier).
G = Slider for the total number of points (nodes) to plot.
H = Lines indicate Voronoi partitions, for cluster observation guidance.
I = Nodes plotted using formula at top of window. Center points correspond to hubs.
From Random to Order
More Patterns

Point[n] = 0.172134 Point[n-1] + RandomVertex

Point[n] = 0.161066 Point[n-1] + RandomVertex
Changing the sign (+/-)
Some differing 4-vertex patterns
Some of the references

• Stigmergy:

• Network Topology:
  • Kleinberg, et al. (2004) showed topology affects network failures as well as attack successes.

• Fractal Traffic Self-organizing:
  • Paxson and Floyd (1995).