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Leveraging Complexity Science and Emergence for a Self-organizing Battlespace [video]

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Leveraging Complexity Science and Emergence for a Self-organizing Battlespace

Dr. Josef Schaff, NAVAIR 4.5

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.

Why should we use it & how?

- Why?
  - Current systems engineering is limited in its approach to SoS in any consistent way to predict novel / **emergent** behaviors that would give the U.S. an edge on our adversaries.
  - Large-scale multi-agent SoS 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

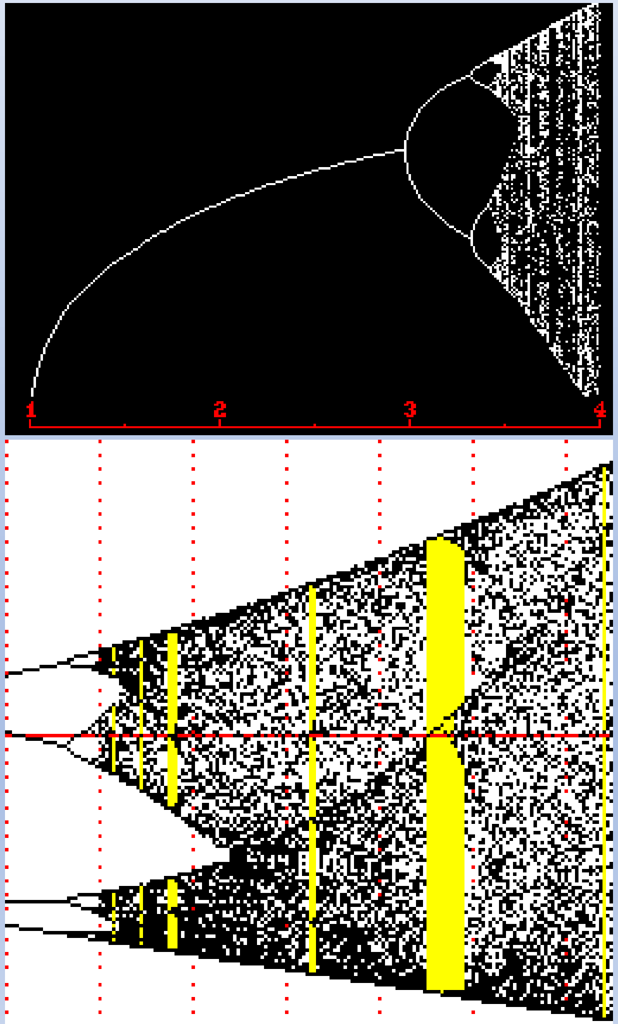
Emergent Behavior: what is it?

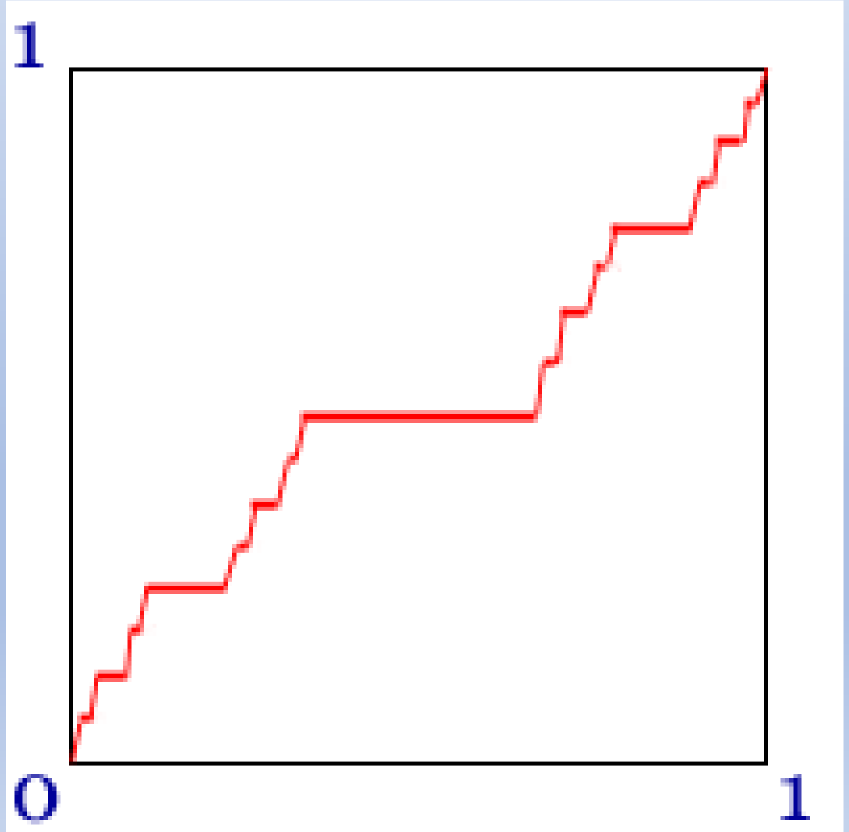
- Emergence can produce ‘creative’ system behaviors.
- Artificial Life - uses emergence generating algorithms:
  - genetic algorithms, neural nets, cellular automata.
    - E.g. “The Sims” uses genetic algorithms for automata.
- Emergent behaviors result ***not*** from stochastic (e.g. thermodynamics) models, but instead from multi-agent interactions (e.g. RoboCup).
- 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.

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





Complexity in Other Realms

- 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?***

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:
  - ***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):*
  - Showed scaling limitations for large numbers of networked nodes needed for battlespace.
  - 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*X(n-1) + Z.**

X(n-1) = *current point,* **X(n)** = *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.

Running NPPR algorithm and using the results

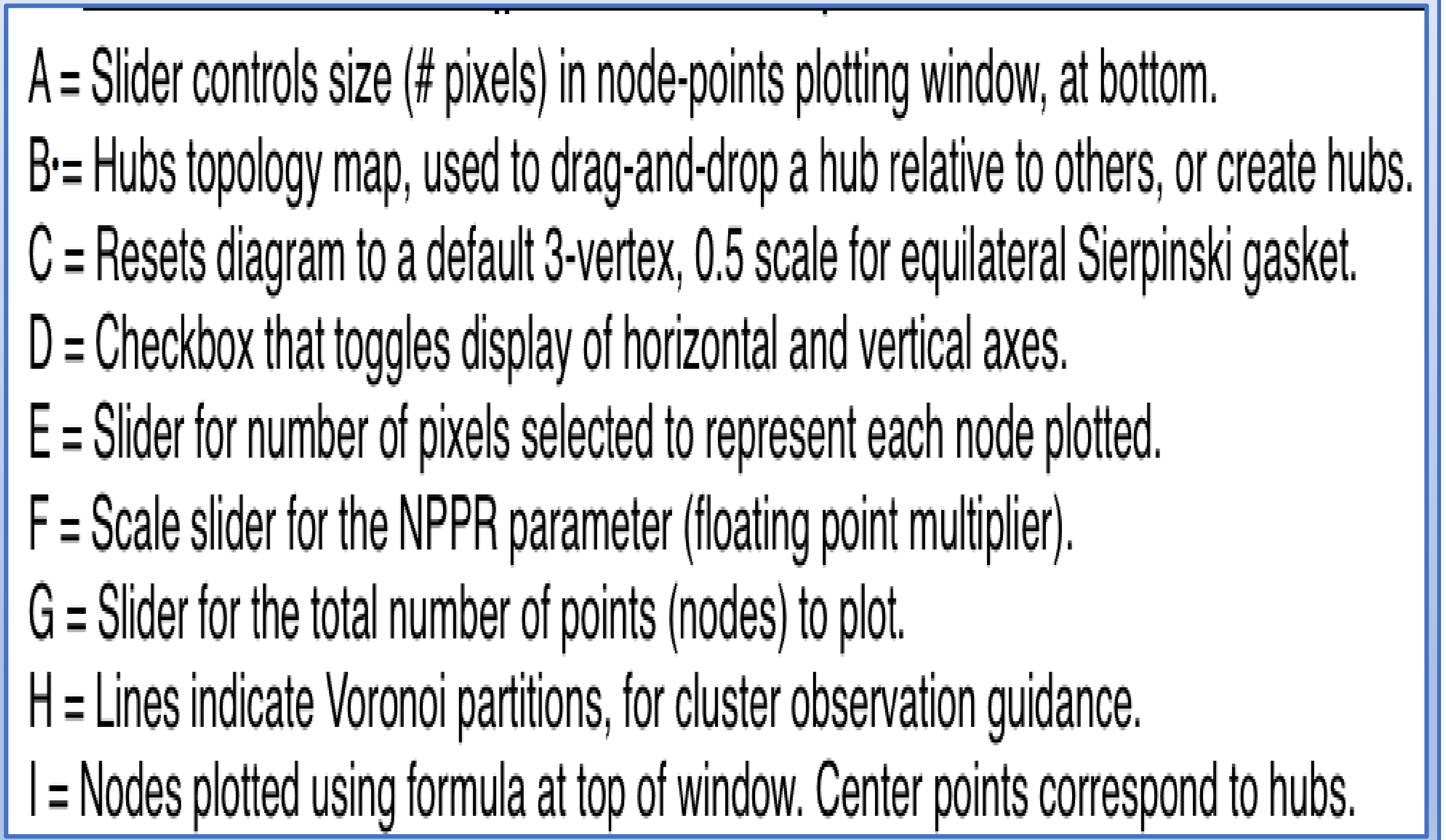
Running it:

- 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”

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.

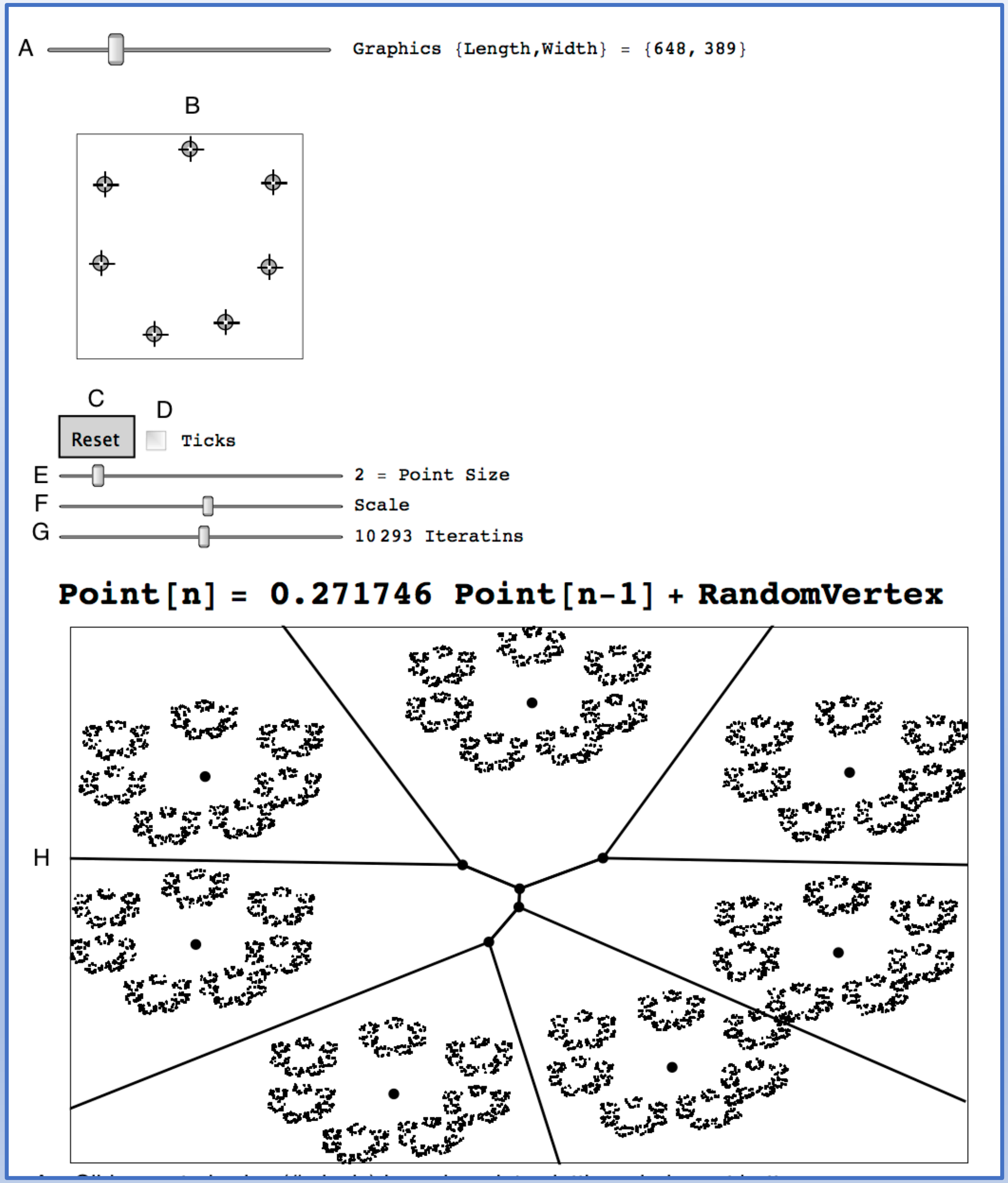
E = Slider for number of pixels selected to represent each node plotted.

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.



Graphics {Length,Width} = {648, 389}

☐ Ticks

2 = Point Size

Scale

10 293 Iteratins

Point[n] = 0.271746 Point[n-1] + RandomVertex

Some of the references

- Stigmergy:
  - Lemmens and Tuyls (2010) suggested stigmergy for routing protocols issues. Masoumi and Meybodi (2011) showed relationship of shared information to 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).