Complex Adaptive Systems

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- Complex Systems
- Omplexity
- Emergence
- Emergent Intelligence

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Complex Adaptive Systems

- a.k.a. Complex Systems
- Highly interdisciplinary study of systems that
 - Consist of many interacting components/agents, and
 - Exhibit many of the following properties:
- Distributed Control Nothing oversees or manages the collection of agents.
- Synergy The sophistication of the global whole greatly exceeds that of the sum of the (simple) parts (nonlinear).
- Emergence/Self-Organization Global structure **arises** purely from local agent-agent interactions (positive feedback).
- Autopoiesis Global structure **maintained** by self-regulation (negative feedback).
- Dissipation Far from equilibrium, yet stable.
- Adaptive Learning and/or evolving: modify structure and/or behavior to enhance survival/functionality.

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Complexity

- Stems not from the **number** of agents, nor their individual capabilities, but from the **difficulty of predicting** the emergent whole from the interacting parts.
- Many different (often informal) meanings in different fields.
- Many attempts to mathematically formalize are helpful.
- But there are no universal, quantitative measures that allow complexity comparisons of ant colonies to rat brains to I-80 traffic patterns to Mozart symphonies to a friend's personality.
- All have elements of emergence and surprise that defy standard, formal techniques for predicting their behavior.

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Examples of Complex Systems

- Cells
- Metabolic pathways
- Immune systems
- Brains
- Social insect colonies
- Ecosystems
- Transportation networks
- Economies and Markets (Adam Smith's Invisible Hand)
- The internet
- Epidemics and pandemics
- Social networks
- Societies

These are often modelled as **networks** of interacting components.

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Economics: Emergent Prices



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Stigmergy: Emergent Structure from Indirect Signals.



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Swarms







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Evolving Annular Sorting Behavior



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The Intelligence of Swarms

- Swarm Applications: animation, telecommunications, internet routing, passenger and freight scheduling, assembly-line task selection, and many more
- Mistaken Genius: In emergent systems, intelligence is often in the eye of the observer (who sees the global pattern), but not in the brain of the agent, which only understands local interactions.
- Simple Minds in complex bodies (Pfeifer + Scheier, 2001) and environments (Herb Simon, 1969) ⇒ Complex behavior.
- General Implications: Intelligent behavior need not involve intelligent planning and coordination. It may **emerge** from complex interactions between brains, bodies and the world.

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Some Important Principles of Complex Systems

Mitchell, 2006

- Global information encoded as patterns over the individual components.
- Prevalent randomness (often magnified by positive feedback).
- Parallel and continuous exploration and exploitation at the lower levels.
- Continual interaction between bottom-up and top-down mechanisms.

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Formal Definitions of Complexity (Mitchell, 2009)

- Information theoretic: High Shannon entropy = high complexity
- Algorithmic: Length of shortest generator. Random patterns must be listed in their entirety - i.e. cannot be expressed by compressed programs - and are therefore very complex.
- Effective Complexity: Algorithmic complexity of the regularities in a system. Now, most complex patterns are intermediate between the random and highly structured, both of which are low complexity.
- Thermodynamic depth: length of sequence of events that produce the system.
- Fractal dimension measure of structural intricacy
- Statistical: minimum historical info needed to predict system's future states - same properties as effective complexity.
- Degree of hierarchy: complex = hierarchical + semi-decomposable. Similar to specialized + integrated used by many to assess brain complexity.

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The Logistic Equation

- *p_i* = population size of a species at time i
- k = carrying capacity of the environment
- r = combined rate of reproduction minus starvation for the species

Dynamics

$$\frac{dp}{dt} = rp(1 - \frac{p}{k})$$

Dividing both sides by k, then letting $x = \frac{p}{k}$:

$$\frac{d}{dt}(\frac{p}{k}) = r\frac{p}{k}(1-\frac{p}{k}) \Leftrightarrow \frac{dx}{dt} = rx(1-x)$$

Widespread applications: ecology, economics, neural networks, chemistry, medicine...

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In a discrete model (e.g. where population levels are monitored at the end of each year):

$$x_{t+1} = x_t + rx_t(1-x_t)$$

Now assume full population turnover each year: the only individuals in year t+1 are the offspring of individuals in year t.

The Logistic Map

$$x_{t+1} = rx_t(1-x_t)$$

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The logistic map has a wide variety of dynamics, depending upon the parameter r:

- Small r: x converges to a point attractor. Stability.
- Medium r: x oscillates between m attractors, where m increases (very quickly) as r approaches 3.57. Often called the edge of chaos, criticality or the complex regime.
- Large r: x never settles into a stable pattern of oscillation. Chaos!!.

Signature of Chaos

Sensitive Dependence on Initial Conditions(SDIC): small changes in the inputs (or initial state) produce large changes in the state trajectory and/or outputs.

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From Point Attractor to Cyclic Attractors



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From Cyclic Attractor to Chaos



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Sensitive Dependence upon Initial Conditions

r = 3.9 for both runs, but initial conditions vary slightly.



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The Edge of Chaos (r \approx 3.57)



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Self-Organized Criticality (SOC) (Per Bak et. al., 1987)

Per Bak's Sandpile

- Perturbation: Add sand grains, one at a time, to a sandpile.
- Observation: Avalanche sizes (i.e. number of displaced sand grains) after each perturbation.
- Analysis: Plot of the frequency of each avalanche size.

Key Result: Most perturbations lead to small avalanches, but some lead to large ones, with a declining (but non-zero) frequency for larger and larger avalanches. Avalanches exhibit a power law distribution.

Critical State \approx Edge of Chaos

- States where most small perturbations have small consequences (stability) but a few can produce widescale change (chaos).
- Many dynamic systems naturally transition to this edge: it doesn't take a lot of special intervention and parameter tuning.

Power Laws

Events whose frequencies vary as a power (k) of some feature (x) of the event, such as the avalanche size in Per Bak's sandpile.

 $f(x) = cx^k$



Cellular Automata



- Popular medium for studying ALife and emergence.
- When neighborhood size = 8, there are 2⁸ = 256 rows in the update table .. and thus 2²⁵⁶ possible tables (i.e. update rules)!!
- Edge of Chaos behavior when $\lambda \approx .273$ (Langton, 1990), where λ = fraction update-table rows that turn a cell on.

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The transition of a multi-component system into a state containing high-level properties and relationships:

- whose causal origins involve a non-linear (and often unpredictable) combination of other component' properties and relationships, and
- that often add further constraint to the low-level interactions.

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Emergence



Examples of Emergence

- Pond ice formation: Colder water ceases to sink at temps just above freezing, thus halting convection currents. Ice formation then constrains further cooling.
- Orderly crowd movement: Local interactions lead to larger and larger groups using particular *lanes* of motion. Large, crowded lanes severely discourage (constrain) wrong-way traffic.
- Stigmery in social insects: Small perturbations amplified and combined into huge structures.
- Properties of liquids such as temperature and viscosity arise from the myriad interactions of molecules at lower levels.
- Stock market booms and busts: local buy/sell interactions affect stock prices, which affect buying and selling.
- The "V" formation of flying birds.

Sperry's Wheel (1987)



On Emergent properties of the brain

A molecule within the rolling wheel, for example, though retaining its usual inter-molecular relations within the wheel, is at the same time, from the standpoint of an outsider observer, being carried through particular patterns in space and time determined by the over-all properties of the wheel as a whole.

Better example: Tumbleweed

Emerging Hexagons (Spears et. al., 2004)



- Goal: Maintain a hexagonal formation while moving (e.g. across a battlefield).
- Each agent repels agents within radius (R) and attracts those beyond R.
- Yields a triangle formation where resultant force on each agent = 0.
- In a large group, the triangles produce a hexagonal pattern.
- Similar (local) rules produce a square-grid pattern.

Emergence and Search: V Pattern of Flying Birds



- Birds want to see horizon while flying, and conserve energy.
- Each flapping bird wing creates a pocket of uplifting air.
- Star = pocket with clear view; circle = pocket with obstructed view.
- (Left) New birds have many options → symmetry. (Right) Search is constrained to a few options → asymmetry.

Emergence and Search: Schooling Fish



- Fish want to move, conserve energy, and avoid collisions.
- (Left) unorganized state: many movement options.
- (Right) organized school: constrained movement

ALife Pioneers and their Videos

Karl Sims

- Fascinating evolved creatures
- Uses detailed physical simulations.
- Evolves bodies and brains
- URL = https://www.karlsims.com

Craig Reynolds

- Simple hard-wired individual behavior rules.
- Emergent flocking, following, pursuit, evasion, etc.
- Won an Academy Award (1998) for animation (The Lion King, Batman Returns, and many others)
- URL = https://www.red3d.com/cwr/boids/

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Deacon's (2003,2011) Emergence Definition

2 Temporal Perspectives

- Synchronic Emergence Constantly present and usually involving a transition in **spatial scale**, such that relationships at higher levels are not clearly predicted by those at lower levels. E.g. temperature is a synchronically emergent property of molecular interactions.
- Diachronic Emergence Happening across time (i.e. history dependent) such that interactions of low-level components eventually lead to high-level patterns. E.g. Water molecule movement and surface cooling gradually produce ice layer.

Related to Deacon's 3 orders of emergence.

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1st Order Emergence (Deacon)

- High-level patterns (often described by properties) created by the aggregate of lower-level interactions.
- Synchronic no history needed to explain current state.
- Does not involve feedback of high-level patterns as constraints on lower levels.
- Statistical arguments can usually explain the high level in terms of the low level, since the aggregate tends to be easily predicted by the low level.
- Perturbations at the low level tend to average out.
- E.g. temperature, viscosity, color, phase of a substance.
- A somewhat boring type of emergence, with little surprise.
- Still, the high-level properties are not easily explained in terms of a simple series of low-level interactions. Only by aggregation (and statistical mechanics) do things make sense.

2nd Order Emergence (Deacon)

- Amplified asymmetry: High-level patterns created by amplification of a perturbation (asymmetry).
- Recurrent causal architecture: high-level patterns feed back as constraints on the low level.
- Self-organizing and self-maintaining (autopoietic) via bottom-up and top-down interactions.
- Diachronic history needed to explain current state.
- E.g. snow flakes history of atmospheric passage and flake morphology determines future form.
- Material and energy flow through these systems, while form is recirculated and amplified.
- The majority of *classic* emergence examples of this type.
- Notions of self first enter here, since system actively maintains a structure, a self.

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3rd Order Emergence (Deacon)

- Involving information or memory.
- Constraints derived from past, high-order structures are stored and then **re-presented** to the lower levels to re-create the past pattern.
- Representation (of self) = a seed for repeated 2nd-order emergence.
- Synergy between representation and self-organization: rep implicitly holds a history of the past which can jump-start future self-org, creating more reps, etc.
- This information can also be selectively amplified or dissipated → evolution.
- Any aspects of a (living) system that are adaptations to an environment = information about that envir encoded in the system (and possibly in its memory/rep).

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Memory and Re-Presentation



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Deacon's (2011) Autogen



- Membrane depends upon AC loop for production + maintenance.
- AC loop depends upon membrane for protection (against diffusive loss of reactants A-D)
- But AC loop needs X and Y, which cannot permeate the membrane.

Autogen Replenishment and Reproduction



- Minor membrane deterioration enables influx of reactants X and Y.
- Major deterioration splits membrane into pieces M1 and M2.
- M1 and M2 may each become protection for 2 auto-catalytic loops.

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Autogen Memory





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3rd Order Emergence in Autogens

- As AC loops get larger, involving more reactants, it gets harder to insure the proper reactions. E.g. B may start to react with D and Y.
- Spatial constraint can help to bias proximities so that A is normally close to X and B, which is close to W, etc.
- Autogens that HAVE these constraints will persist longer and reproduce more often. I.e., they will be selected.
- If AC loops arise that produce products A*,B*,X*,W*, etc. (similar to nucleic acids), and if these products both: a) selectively bind to A, B, X W, etc., and b) bind to each other in the proper sequence (X*,A*,B*,W*), then
- they form a memory, representation (or template) for re-creating the AC loop (anywhere in the environment).
- This chain = information about the auto-catalytic process, and
- serves as a structural embodiment of the dynamic process.

Intelligence Emerging (2015, MIT Press)



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Spatiotemporal Levels of Emergent Intelligence

- Intelligence emerges via search at multiple timescales.
- One emergent search forms landscape for search at next (faster) level.



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Intelligence Emerging

- Investigating the fundamental role of search and representation in emergent intelligence.
- Understanding mental function in terms of 2nd- and 3rd-order emergence.
- This encompasses the brain, body and environment, not just the brain.
- How do complex neural networks emerge via evolution of the brain and body?
- How do mature neural networks arise from development and learning?
- How does sophisticated control emerge via the dynamics of a neural network?
- Can this EvoDevo route to intelligence build better AI?

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Approaches to Commonsense in Al



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Emergent Commonsense in ChatGPT

Keith: Imagine yourself on a steeply slanted roof, 6 stories above the ground. A storm is brewing and the roof is covered in butter. Explain how this feels.

ChatGPT(3.5): Standing on a steeply slanted roof six stories above the ground during a brewing storm with a butter-covered surface would be an incredibly dangerous and precarious situation. Let me describe how it would feel:

- Height and Fear: The height of six stories above the ground is still significant and would induce a sense of vertigo and fear. The steep slope of the roof would amplify this feeling, as you'd constantly feel like you're on the edge.
- Instability: The butter-covered surface on a slanted roof would make footing extremely unstable. Butter is slippery, and the incline of the roof would make it challenging to maintain balance. Each step or movement would require extreme caution to avoid slipping and tumbling down.
- Precariousness: The combination of the height, steep slope, and the impending storm would make you feel extremely vulnerable. You'd worry about losing your footing, being blown off the roof by the storm's wind, or sliding uncontrollably due to the butter and the incline.
- …etc…

All this emerges from doing a simple predictive task !!

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Google Robot with Commonsense?



RT-2: Vision-Language-Action (VLA) Models Transfer Web Knowledge to Robotic Control (50+ co-authors, Google Deepmind, July 2023)