Self–Organizing Systems
Chaos, Complexity and Self–Organization
Self-organizing systems are system structures that are ordered, or otherwise show some form of stability, without involvement from outside the system.

A lot of systems in nature exhibit self-organization.
Critically interacting components self-organize to form potentially evolving structures exhibiting a hierarchy of emergent system properties.
Examples of self-organizing systems

The spiral galaxy NGC 4414 as imaged by the Hubble Space Telescope (1995)
Examples of self-organizing systems

The inner planets, from left to right, Mercury, Venus, Earth and Mars
Examples of self-organizing systems

A Bengal tiger in Bannerghatta National park in Bangalore
Examples of self-organizing systems

Two flocks of Common Crane migrating in the V-formation, spotted over Marburg, Germany
Examples of self-organizing systems

Safari ants foraging food for the colony in Mount Kenya
Examples of self-organizing systems

Diagram of an idealized Lithium atom
Self-organization is the ability of a class of systems to change their internal structure and/or their function in response to external circumstances.

- Elements of self-organizing systems are able to manipulate or organize other elements of the same system in a way that stabilizes either structure or function of the whole against external fluctuations.
Definition of self-organization

- The organization evolves either in space or time, and can exhibit stable forms or show transient phenomena.

- This process is understood not to be instructed from outside the system and is therefore called self-organized.
A system is a group of interacting agents functioning together. Those are distinguishable from their surroundings by recognized borders.

Systems are diverse, on one end of the spectrum, interactions between agents might be fixed (engine), and on another unconstrained interactions (gas).

System functions usually depend on the nature and arrangement of agents.
When system agents are connected, the resultant system no longer just shows the additive properties of the agents, instead new properties appear that are attributed to the system.

Those properties are defined as emergent system properties.
System emergence is the appearance of new qualitative features on the level of an entire system that could not be observed at the level of its components.

The emergent properties are usually higher-level properties (i.e.: the movement of a car is an emergent property of the connected parts)
Emergent behavior occurs when:

- the system shows qualitatively new behavior on a higher level of description which could not have been easily predicted from the interactions of components at the lower level (obeys a non-linear relationship).
- is the result of a self-organization process.
Emergence

- Supervenience
  - The emergent properties will no longer exist if the lower level is removed

- Properties are not aggregates
  - The resultant properties are no longer the sum of the agent properties

- Causality
  - The properties are not secondary properties of the component agents
Organization

Organization is a somewhat complex concept, built up from several more primitive concepts.

It is the arrangement of the internal agents in order to perform a specific function.

Organization restricts the behavior of the system and the agents in a confined manner.
“Communication” between self-organizing agents is necessary.

This implies a constraint.

If what happens to some node $A$ has some no correlation with what happens to a node $B$, then there is no communication between $A$ and $B$. 
If, however, there is some correlation between what happens with node $A$ and $B$, then there is said to be communication.

Out of all the possible events that can take place with node $B$ in response to an event in node $A$, $B$ is restricted to the subset that would correlate to the event in $A$. 
"Good" Organization

- The term organization makes no reference to any usefulness of such organization.
- In some cases the difference between good organization and bad organization is obvious.
- A “good organization” is a relative term, an organization that is good in one context might be bad in another.
  - Ex: half a dozen lenses which could be assembled to make a microscope or a telescope, “goodness” depends on purpose
Self-organization is:

- an evolution of a system into an organized one in the absence of external forces.

- a move of a system from occupying a large space to a smaller space as a result of the system itself.

- the introduction of patterns over time or space from previously independent variables.
Self-organization features

- Absence of external control (autonomy)
- Dynamic operation (time evolution)
- Fluctuations (searching through options)
- Symmetry breaking (loss of freedom)
- Global order (emergent from local interactions)
- Dissipation (energy usage)
- Instability (self-reinforcing choices)
- Multiple equilibria (many possible attractors)
Self–organization features

- Criticality (threshold effects)
- Redundancy (insensitivity to damage)
- Self–maintenance (repair)
- Adaptation (tracking of external variables)
- Complexity (multiple concurrent values)
- Hierarchies (nested, self–organized levels)
Classification of self-organization

- Systems that form organization without it being outside forces imposing (i.e.: by forces, walls or machines) are said to be self-organized.
- However, self-organization is more used to refer to systems that self-organize not as a direct result of physical law.
- Examples: cellular autocatalysis, organism structures, immunity system, fish flocking, bird flocking, etc..
Self-organization phenomena occur according to natural/physical laws.

Self-organization systems can be described as finding an organization from a seemingly chaotic and complex force relationships of inanimate nature.

Self-organization agents are not decision nodes and do not steer toward algorithmic optimization.

Examples: crystallization, magnetism
Attractors are preferred position for systems, in a way that if distorted, systems would tend to evolve till they reach their attractor.

- Attractors can be a:
  - point
  - regular path
  - complex series of states
  - or, an infinite sequence
Attractors and self-organization

- Systems that move to a stable structures are said to be drawn to attractors.

- Complex systems might have a number of attractors which might change with changes to the system.

- Approaching self-organization can be thought of as studying the attractors of self-organizing systems.
How does self-organization come to be?

- Random changes that might occur because of various reasons can result in self-organization.

- Systems that start out as unstable, this instability puts a pressure on the system resulting in its movement towards more stable forms.
Difference between self-organization and selection

- Selection is the process in which a choice is made between two or more competing options due to external factors (the choice between two stable systems in state space).

- In contrast, self-organization is the process in which a system restricts the area of state space it occupies.
Swarm Intelligence
Self-organization in nature
Swarm intelligence

“The emergent collective intelligence of groups of simple agents.”

- Examples of swarm intelligence:
  - group foraging
  - cooperative transportation
  - labor distribution
  - nest building (insects)
  - collective sorting and clustering
Of all insects, researchers are most interested by ants.
Ants solve complex tasks by simple local means.
The overall ant colony productivity is much greater than the sum of the individual contributions.
Ants are masters in exploration and exploitation.
Ants feeding on honey
The capabilities of a single ant are very limited, but ants collectively establish the shortest route between a source of food and their nest.

As the ants move, they lay down a trail of pheromones that other ants can follow.

Ants move randomly, when they encounter a pheromone trail, they decide whether or not to follow it. If they do so, they lay down their own pheromone on the trail, reinforcing the pathway.
Ant colony behavior

- The probability that an ant chooses one path over another increases with the amount of pheromone present.

- The more ants use a given trail, the more attractive that trail becomes to other ants.

- If a colony of ants is presented with a short path and a long path to a source of food, they will first use both paths in equal numbers, laying down pheromones as they move.
Ant foraging

1

2
Ant foraging
Ant colony optimization

- But the ants taking the shorter path will return to the nest first.

- Thus the shorter pathway will then be likely to contain more pheromone, and will be more attractive to those ants that return to the food source.

- Not all ants follow the pheromone trial, this allows more for exploration of alternate paths.
Common Crane migrating north over Spain
Bird flocking behavior

- Flocking is a behavior exhibited when a group of birds fly or forage in groups.
- Flocking follow simple rules:
  - Separation: avoiding crowding
  - Alignment: following the direction of the group
  - Cohesion: sticking to a position within the group
- Individual birds position and align themselves relative to the position and alignment of their immediate neighbors (i.e.: five or six birds at most).
Formation flight and migration

- Many bird populations migrate long distances between winter and summer habitats.

- Flocks flying in formation result in reduced drag force.

- A flock flying in V–Shaped formation, conserves the energy, reduces the drag, and increases the speed of individual birds, which allows birds to increase their flying range by 70%.
Formation flight and migration

Migration routes of some birds:
- *Oenanthe oenanthe*: Northern Wheatear
- *Sterna paradisaea*: Arctic Tern
- *Falco amurensis*: Amur Falcon
- *Puffinus tenuirostris*: Short-tailed Shearwater
- *Philomachus pugnax*: Ruff
- *Buteo swainsoni*: Swainson's Hawk
Formation flight and migration

- Birds flying in formation save energy by flying in the updraft of the wingtip vortex generated by the previous animal in the formation.
- The birds flying at the tips and at the front are rotated in a timely cyclical fashion to spread flight fatigue equally among the flock members.
- V formation birds place themselves roughly at the optimum distance predicted by simple aerodynamic theory.
Swarm Intelligence
Self-organization in computation & robotics
Following the introduction of user friendly computers and web in the 1980s, software development has been growing rapidly attempting to keep with constant and new innovations.

The most underestimated problem is the complexity of the task environment.

Ex: information systems depend on many modules, data sources, network connections, input and output devices that predicting and controlling their behavior is becoming an increasingly complex task.
The complexity bottleneck

- This results in applications with numerous bugs, corrupt data, security holes and other risks.

- On top of that, there is constant change in hardware, software, protocols, data and user exceptions.

- The complexity bottleneck result in confusion and limits further progress.
Different research approaches are being investigated in order to achieve organization i.e.: IBM, *autonomic computing*, is an attempt to achieve adapting, correcting and repairing functionality without human intervention.

Another emerging approach is to toggle into a completely self-organizing system, which on top of the mentioned functionality creates its own organization.
The complexity bottleneck

- Organization in this context is defined as *structure with function*.

- Structure is the ability of the system to arrange its components into an order, connecting components from parts to a whole, while separating some components from others to avoid interference.

- Function is the ability of the structure to fulfill a purpose.
Swarm robots

Swarm-bot
Passing over a Gap

www.swarm-bots.org
Swarm robots

S-bots in swarm-bot configuration climbing a step
Swarm robots

S-bots in swarm-bot configuration passing over a gap
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