Complex Systems and Network Science:

Agent-Based Models

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Equation-based versus Agent-based models

- Equation-based (mathematical) models
  - Logistic map — population of species
  - Newton's laws of motion — orbit of the planets
  - Maxwell's equations — electromagnetism
- Agent-based models allow us to consider richer environments with greater fidelity than equation-based models and explore a larger set of questions
- Aspects of agent-based models
  - Individuals (agents) — objects of the model
  - Behaviors — simple or rational rules that guide agents (motives)
  - Outcomes — results of the behavior
- "Micro motives" versus "Macro outcomes"

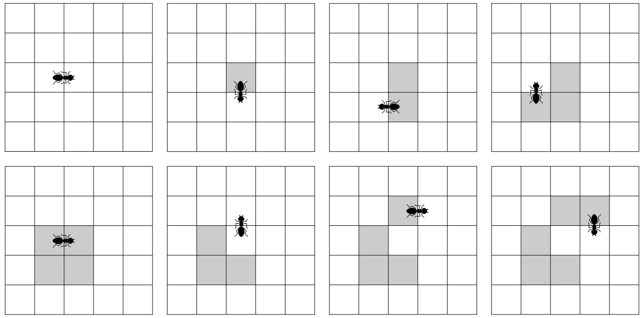
Agent-based models

- Behavior of individual agents may be
  - simple, "dumb", without goals or purpose
  - "optimal" based on rational choices (Game Theory)
- Furthermore, behavior may involve interacting with the environment and possibly changing it
- "Macro outcomes" observed as properties of the environment
  - Ants
  - Termites
- "Macro outcomes" observed as properties of the individuals —self-organization
  - Foraging of ants
  - Murmurations or flocking of birds, schooling of fish
  - Synchronization among fireflies

Langton's ants

- 2-Dimensional "grid"
- Each square can be "black" or "white"
- Ants have a direction and can turn right or left, move one square in the current direction, flip color of square they are on
- Rules:
  - If current square "white", turn 90° ***right***, flip the color of square, move forward one unit
  - If current square "black", turn 90° ***left***, flip the color of square, move forward one unit
- Think of "black" and "white" as the presence or absence of "pheromones" deposited by ants to their environment

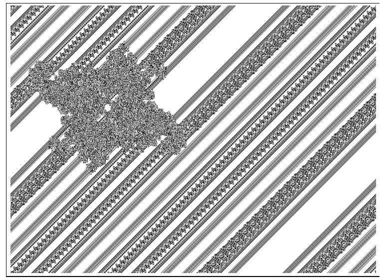
Langton's ants



- NetLogo Library/Computer Science/Vants

Multiple virtual ants

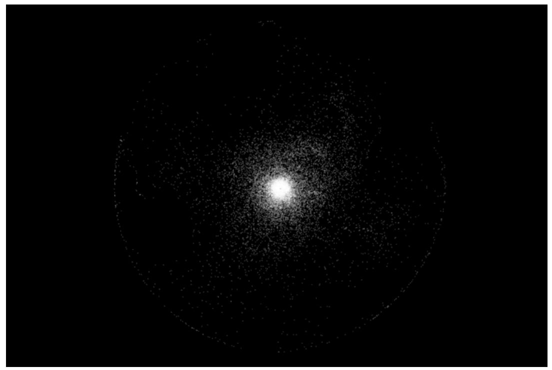
- What if we have multiple ants sharing the same space?
- If the system were linear, the collective behavior would be the "sum" of the individual behaviors
- But the system is not linear!



Foraging ants

- In nature, ants are known to "forage" — scout ants go looking for food far away from their nest while leaving pheromone trails for other ants to follow
- Unlike Langton's ants, real ant pheromone trails *diffuse* and *evaporate*
- The existence and strength of pheromone trails encode the ant colony's ***collective information*** about food in their environment
- NetLogo AntsNew

Foraging ants



Termites

- Wood "chips" distributed over a 2-Dimensional space
- Termites can move, pick up or drop wood chips
- Rules:
  - Wander randomly
  - If bump into a wood chip and "free", pick the chip up, and continue to wander randomly
  - If bump into a wood chip and "full", find a nearby empty space and put the wood chip down, continue to wander randomly
- NetLogo Library/Biology/Termites

Sorting and peer effects

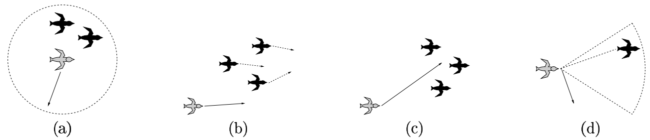
- Sorting (homophily) — individuals seek similar individuals
- Schelling's Segregation Model (coming up later in the course)
- Peer Effects — individuals adopt the behavior of their peers
- Examples of "Macro outcomes" observed as properties of the individuals — self-organization

Peer effects
Schooling and flocking

Peer effects
Schooling and flocking

Peer effects
Flocking

- Formation flying birds (Boids)



Collision avoidance — Copy near neighbors — "Drafting" — Clear view

- NetLogo Library/Biology/Flocking Vee Formation
- NetLogo FlockingWithEntropy

Other agent-based models

- Explicit interaction between agents (rather than indirectly through the environment)
  - Gossip-style interactions
  - Heartbeat synchronization
  - Formation creation

Gossip-style interactions

- Effective for structuring decentralized solutions to problems in large networks
- Interactions limited to small number of *peers* that know of each other
- System fully symmetric — all peers act identically
- Gossiping can be
  - Reactive, proactive
  - Push, pull, push-pull
- The set of peers that a node "knows" is called its *view* and defines an *overlay network*

Proactive gossip framework

```
// active thread
do forever
  wait(T time units)
  q = SelectPeer()
  send S to q
  receive S_q from q
  S = Update(S,S_q)

// passive thread
do forever
  (S_p,p) = receive * from *
  send S to p
  S = Update(S,S_p)
```

Push
Pull
Push-Pull

Proactive gossip framework

- To instantiate the framework, need to define
  - What constitutes the local state s
  - How peers are selected through method `SelectPeer()`
  - The style of interaction
    - push
    - pull
    - push-pull
  - How local state is updated through method `Update()`

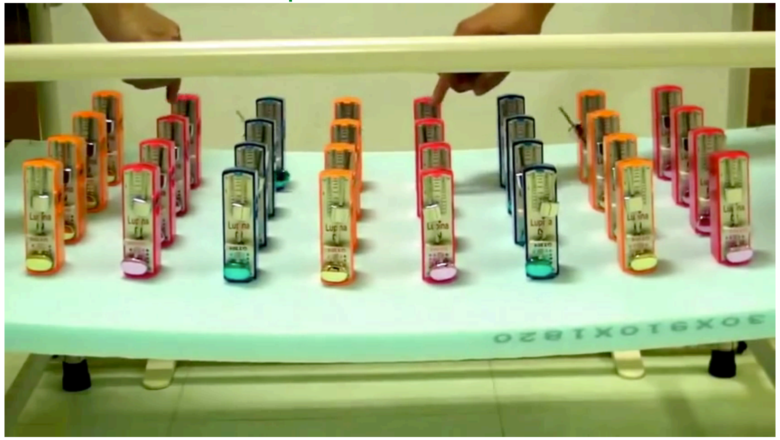
Heartbeat synchronization
Synchrony in nature

- Nature displays astonishing examples of synchrony among independent agents
  - Heart pacemaker cells
  - Chirping crickets
  - Menstrual cycle of women living together
  - Flashing of fireflies
  - Clapping of an audience at a concert
- Agents may belong to the same organism or they may be parts of different organisms
- All of these systems exhibit a form of "self-synchronization" without the presence of a central controller

Heartbeat synchronization
Coupled oscillators

- Self-synchronization can be explained through "coupled oscillators"
- Each agent is an independent "oscillator", like a pendulum
- Oscillators are "coupled" through their environment
  - Mechanical vibrations
  - Air pressure
  - Visual clues
  - Olfactory signals
- They influence each other, causing minor local adjustments that result in global synchrony to emerge in a decentralized manner
- https://youtu.be/t-_VPRCtiUg

Heartbeat synchronization
Coupled oscillators



Heartbeat synchronization
Fireflies

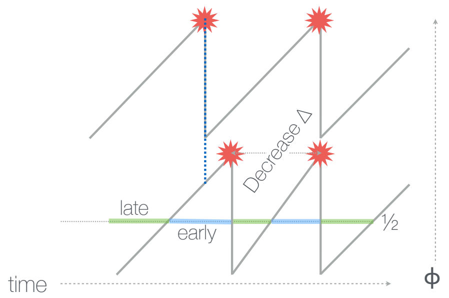
- Certain species of (male) fireflies (e.g., *luciola pupilla*) are known to synchronize their flashes despite:
  - Sparse connectivity network (each firefly has a small number of "neighbors")
  - Communication not instantaneous
  - Independent local "oscillators" with random initial periods

Heartbeat synchronization
Gossip framework instantiation

- Style of interaction: push
- Local state `S`: Current phase of local oscillator ϕ, period Δ
- Method `SelectPeer()`: (small) set of random neighbors
- Method `Update()`: Function to reset the local oscillator based on the phase of arriving flash

Heartbeat synchronization
The Ermentrout model

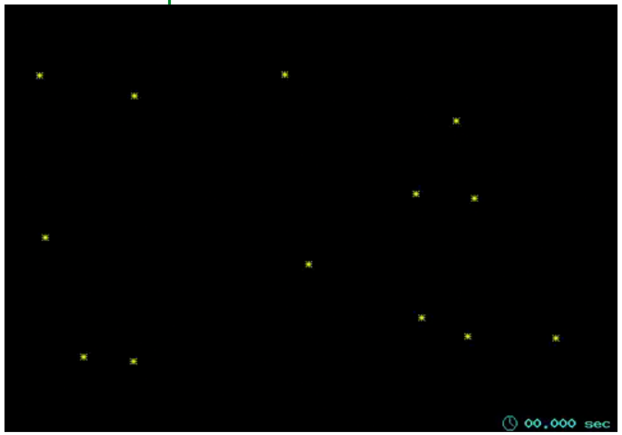
- Modify the local oscillator period based on when flash arrives:
  - if "too late" (ϕ<½), then "slow down" (increase period Δ)
  - if "too early" (ϕ>½), then "speed up" (decrease period Δ)



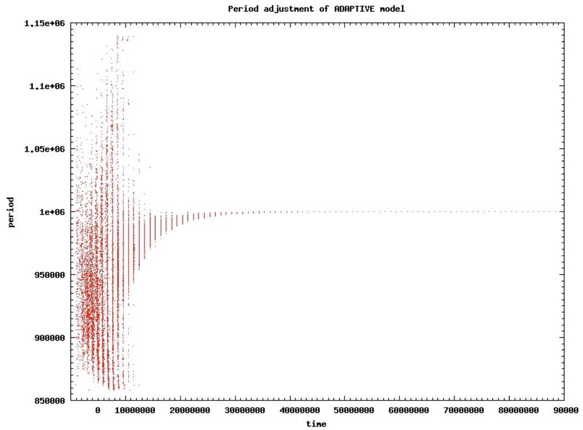
Heartbeat synchronization
Experimental results

- Network size: 210 nodes
- View size: 10
- Initial periods selected uniformly and randomly in the interval [0.85 — 1.15] seconds
- Message latency uniformly and randomly distributed in the interval [1 — 200] ms

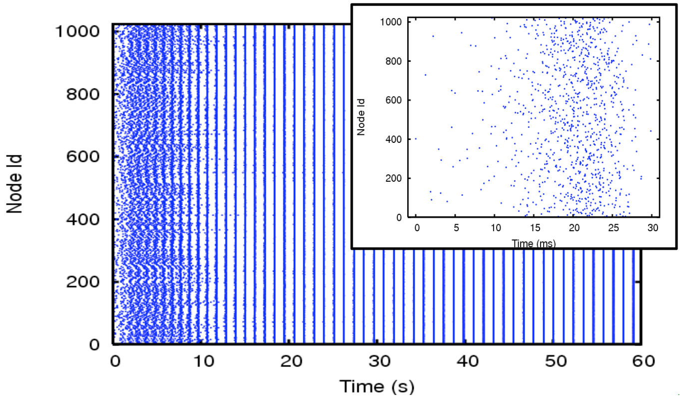
Heartbeat synchronization
Experimental results



Heartbeat synchronization
Convergence of periods



Heartbeat synchronization
Chaos to coherent emissions



Formation creation

- Dynamic collection of agents that can move in physical space in any direction
- Each agent has a unique ID and can determine the relative position of other agents
- Agents are interconnected through a sparse network that can be used to provide random samples from the entire population
- Devise a protocol such that mobile agents self organize into pre-specified global formations in a totally decentralized manner

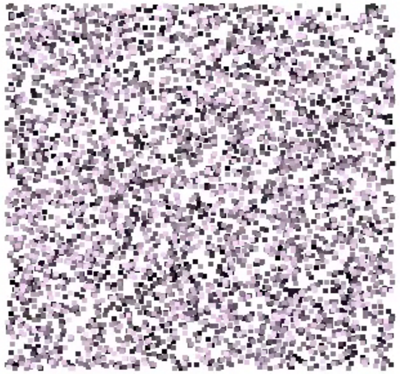
Formation creation

- Applications:
  - Ships engaged in search-and-rescue operation in open seas
  - Drones flying in formation
  - Satellites in orbit positions

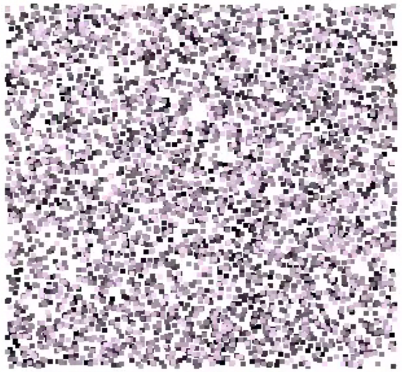
Formation creation
Gossip framework instantiation

- Style of interaction: pull
- Local state `S`: Current physical position and motion vector
- Method `SelectPeer()`: `k` random samples from population
- Method `Update()`: Compute motion vector based on positions of most and least preferred neighbor (defined in a manner similar to the ranking function of overlay topology creation inspired by differential cell adhesion)

Formation creation
Simulation: Ring formation

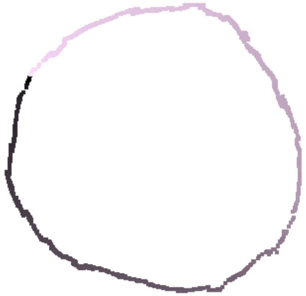


Formation creation
Simulation: Cross formation



Formation creation
Simulation: Self-healing ring

Starting formation: ring of 5000 nodes



Formation creation
Simulation: Self-healing ring

80% of the 5000 nodes are removed

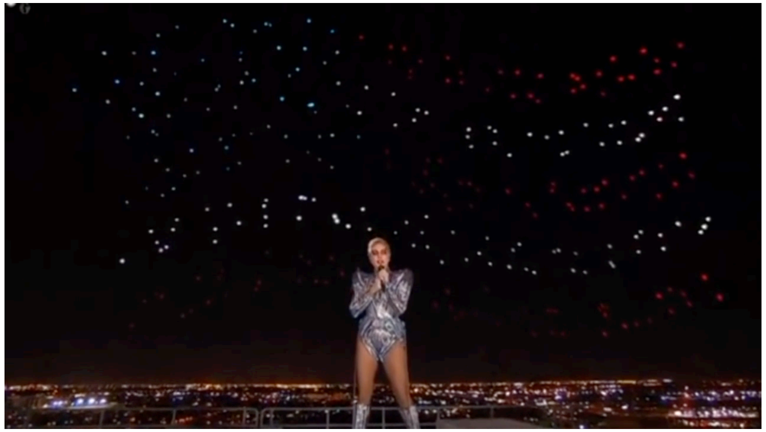
Formation creation
Simulation: Self-healing ring

Remaining 1000 nodes reform the ring

Formation creation
In real life

Formation creation

5 February 2017 (USA, Super Bowl)



Formation creation

12 February 2017 (South China)

Formation creation

9 February 2018 (Winter Olympics, PyeongChang)

Formation creation

New Years 2020 (Shanghai, China)

Formation creation

23 July 2021 (Tokyo Summer Olympics)