Design & Control of Swarm Dynamics

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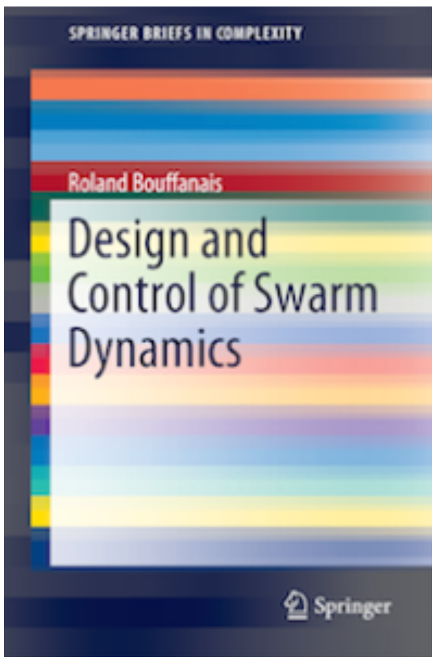
Design & Control of Swarm Dynamics

- **What this lecture is about:**

  - Introduce natural swarms and their powerful collective dynamics
  - Discuss what makes swarms so special
  - Present some design principles for artificial swarms
  - Study how to control swarming systems

Design & Control of Swarm Dynamics

- Most of this lecture is based on the detailed presentation in:



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Design & Control of Swarm Dynamics

- **How we are going to proceed:** design principles based on a multidisciplinary view of swarming

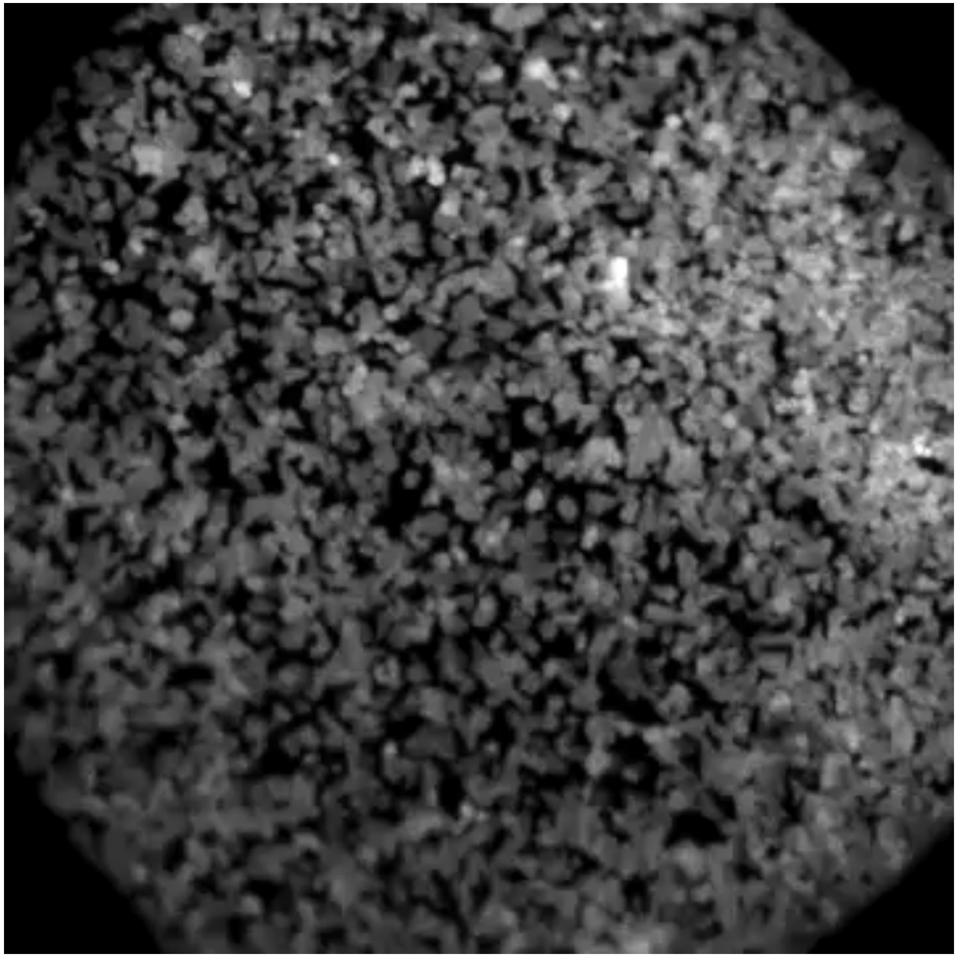
1. A biological introduction to swarming
2. A physical approach to swarming
3. A network-theoretic analysis of swarming
4. An information-theoretic view of swarming
5. Swarm-enabling technology for multi-robots
6. Outlook: can swarms be designed?

1. Biological Swarms

- Collective behaviors pervades nature:
  - Repeated interactions among individuals produce dynamic patterns on scales larger than individuals themselves
  - Apparent in a vast breadth of taxa
  - Across all animal sizes: from bacteria to elephants

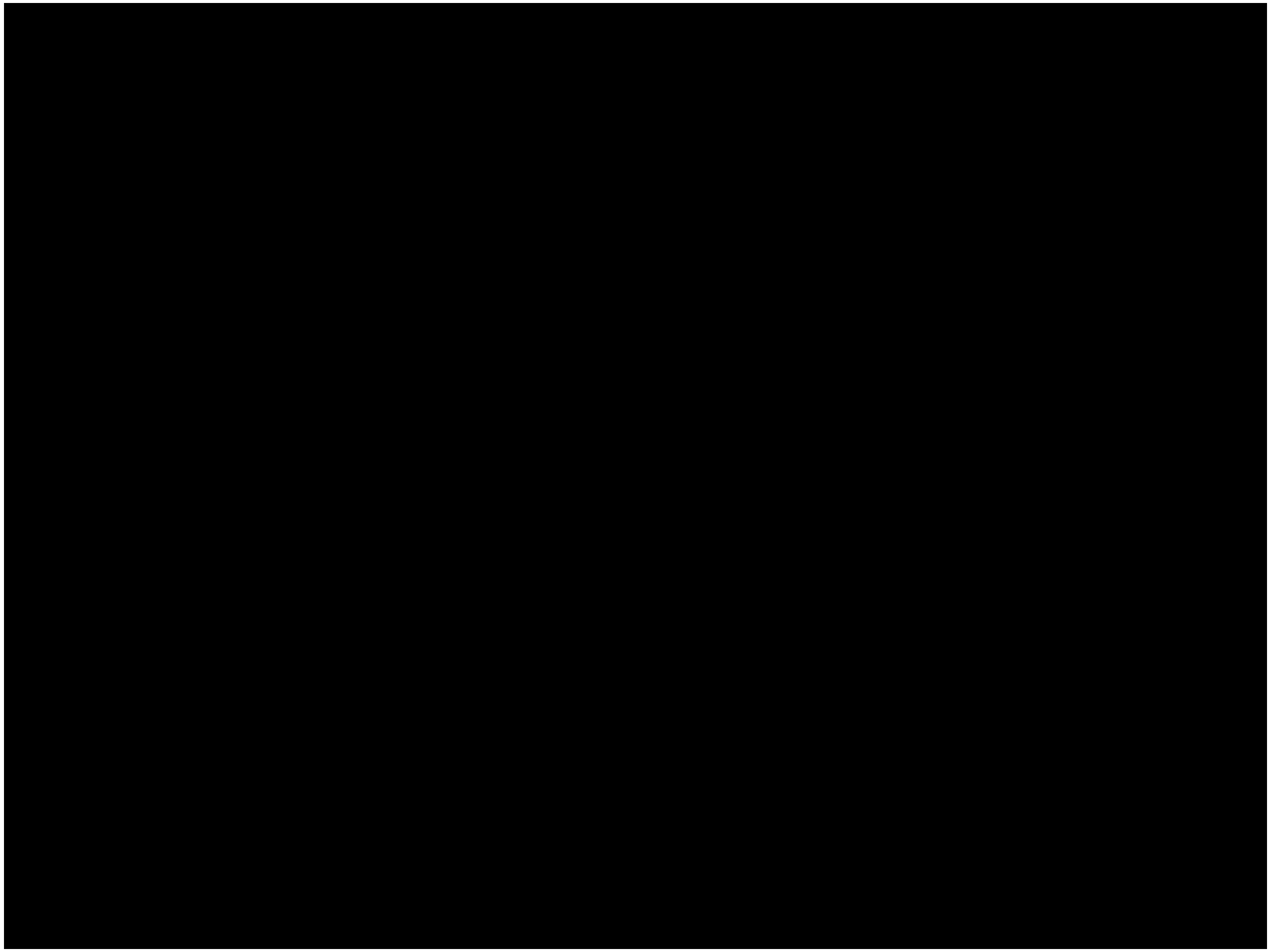
Generic term of "**SWARM**" is used to refer too all these collective behaviors

Amoebae Aggregating



Fish Schooling

Birds Flocking



Insects Swarming

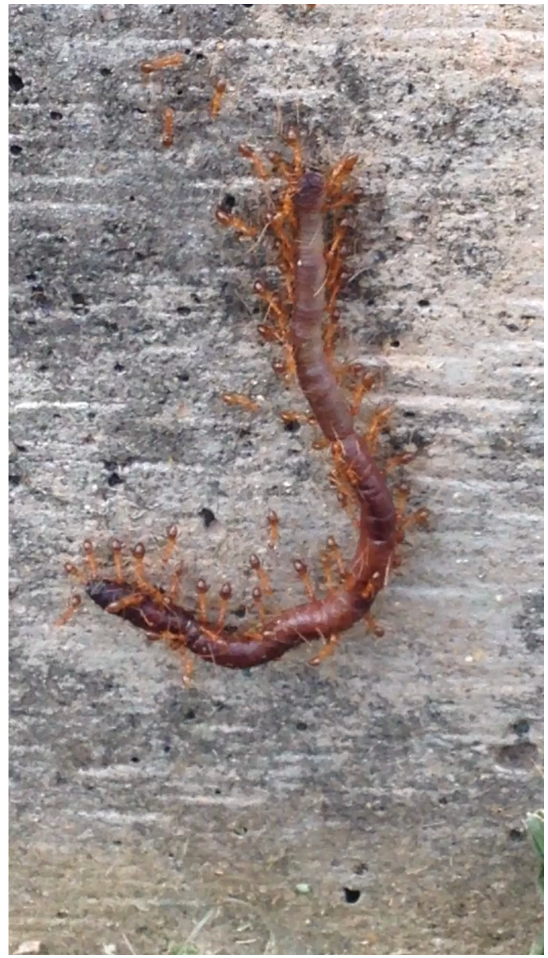
And many more examples

- Of Swarms:
  - Locusts marching
  - Fireflies synchronized flashing
  - Human crowds
  - Neurons firing
  - Clustering of differentiated cells (organogenesis)
  - Neutrophils as part of the immune response
  - Midges swarming
  - etc….

What characterizes swarming

- Complex Adaptive Operations
  - *Self organized*
  - *Decentralized*
    - Sensing
    - Information transfer/sharing
    - Decision making or information processing
  - *Swarm Intelligence*
    - Emergent collective response/action
- Benefits of Swarming
  - *Robustness*
    - with respect to the loss of many agents
  - *Flexibility*
    - in adapting to dynamic and changing circumstances
  - *Scalability*
    - continued effective operation with a wide range of swarm sizes

Swarm Intelligence In Action

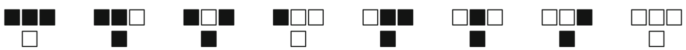


2. A Physical Approach to Swarming

- Seeking universal mechanisms at the root of collective dynamics
  - To explain the appearance of swarming across many length scales (and taxa)
  - Focusing on non-living or very “simple” agents
  - Using the frameworks of:
    - Statistical Physics (Phase transitions, Renormalization theory, etc.)
    - Theory of Dynamical Systems (Chaos, Bifurcations, etc.)

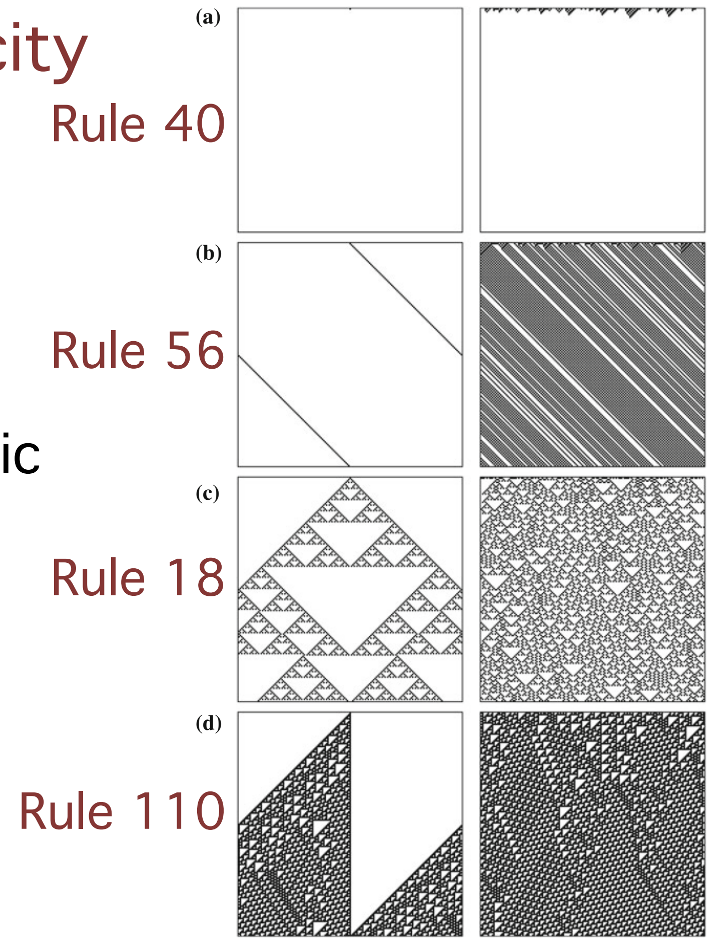
2. A Physical Approach to Swarming

- Complexity emerging from simplicity



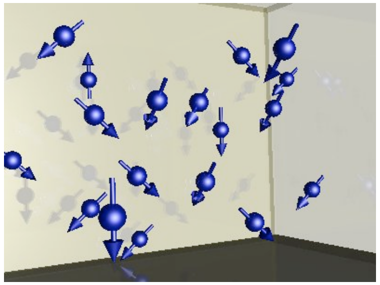
Rule 110

- – Paradigmatic example of Cellular Automata
    - Binary state variable
    - Nearest-neighbor interaction (basic interaction rules)
    - Exhibit a wide-range of collective behaviors
    - Generate large-scale patterns



2. A Physical Approach to Swarming

- Paradigmatic example: Collective motion
  - Self-Propelled Particles (SPP)
    - Simple model yet extremely rich in features
    - N agents placed in a box (periodic BCs)
    - Motion at constant speed
    - Velocity direction is determined as some sort of averaging of neighbors' direction of travel



$$\vec{v}_i(t+1) = v_0 \frac{\langle \vec{v}_j(t) \rangle_R}{\left| \langle \vec{v}_j(t) \rangle_R \right|} + perturbation$$

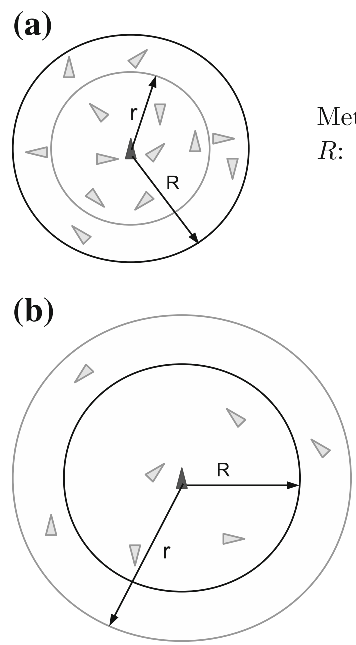
$$\vec{x}_i(t+1) = \vec{x}_i(t) + \vec{v}_i(t+1).$$

2. A Physical Approach to Swarming

- Paradigmatic example: Collective motion
  - Self-Propelled Particles (SPP)
    - Velocity direction is determined as some sort of averaging of neighbors' direction of travel
    - Average involves interacting neighbors
      - Metric interaction distance
      - Topological interaction distance

$$\theta_i(t+\Delta t) = \theta_i(t) + \frac{\Delta t}{k}\left[(\theta_j(t)-\theta_i(t)) + \cdots + (\theta_{j+k-1}(t)-\theta_i(t))\right] + \eta\xi_i(t), \quad (3.7)$$

where $\eta\xi_i(t)$ is a Gaussian white noise of magnitude η since $\xi_i(t) \in [-\pi, \pi]$.



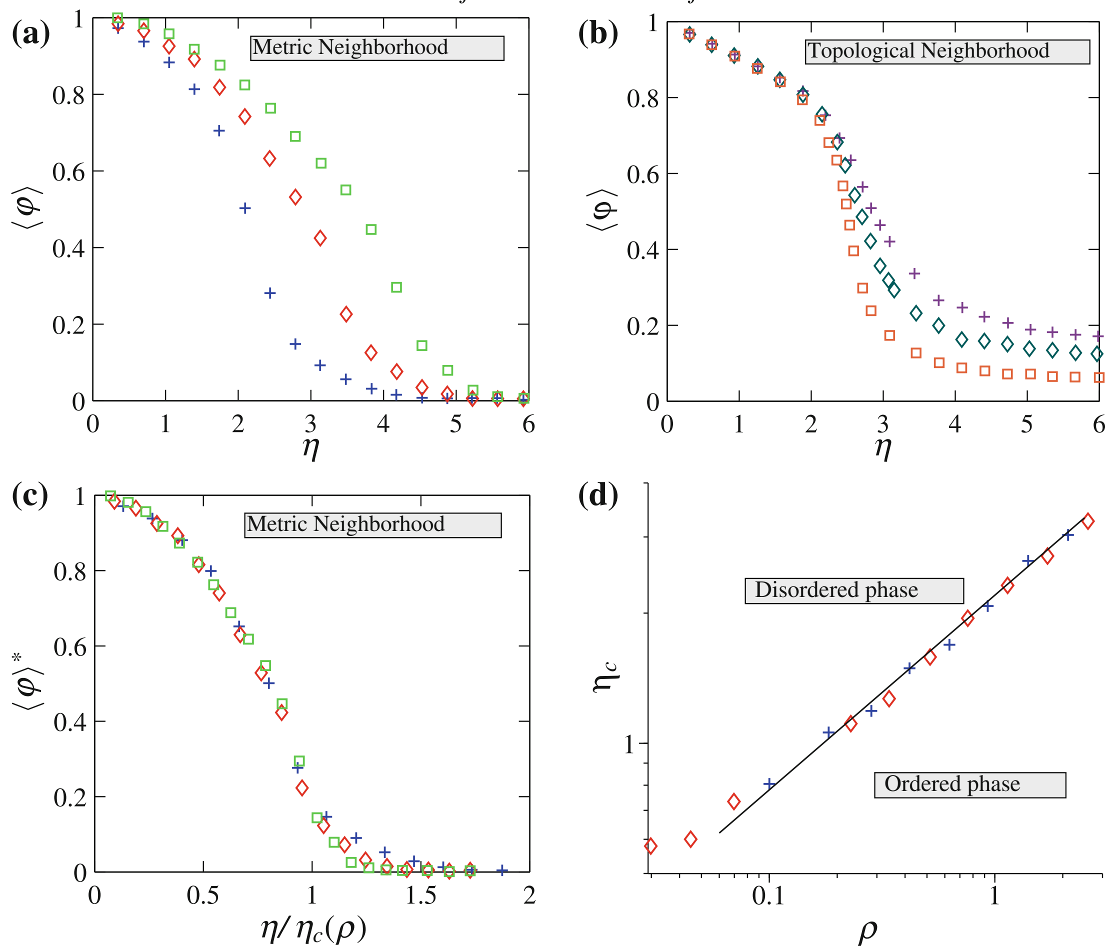
Metric interaction
R: radius of the metric neighborhood

Topological interaction
r: radius of the topological neighborhood

2. A Physical Approach to Swarming

- **Phase transitions**
  - Emergence of collective order
    - at high density
    - at low noise levels
  - Second-order phase transition
    - continuous
    - universal scaling involving critical parameters

$$\varphi = \frac{1}{N}\sum_{j=1}^{N}\frac{v_j(t)}{v_0} = \frac{1}{N}\sum_{j=1}^{N}\exp\left(i\theta_j(t)\right),$$



2. A Physical Approach to Swarming

- Theory of Dynamical Systems:
  - Bifurcation, collapse, and tipping points
    - Swarms operate near criticality: self-organized critical state
    - Swarms have a dynamics "at the edge of chaos"
      - exhibit non-apparent order
      - adaptive degree of ordering
      - capacity to very quickly adapt to changing in circumstances (crystal vs. gas)

2. A Physical Approach to Swarming

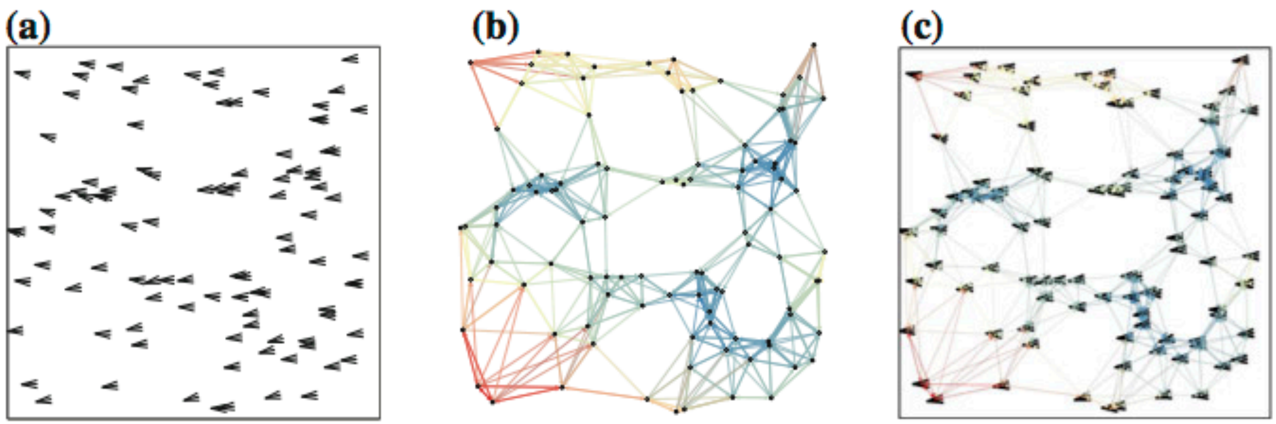
- Design principles:
  - Agents need not be complex (KISS principle)
    - Very simple nonliving agents are capable of developing complex adaptive behaviors
  - A large number of agents is not always necessary for swarm intelligence to kick in
  - The design of the interaction rule plays a key role in the development of adaptive behaviors
  - Swarms must be designed to promote adaptivity
    - To benefit from self-organized criticality

3. A Network-Theoretic Analysis of Swarming

- Network Science provides
  - Elegant and powerful framework
  - Allow to bridge the gap between
    - local dynamics at the agents level
    - global response at the swarm level
  - System-level analysis
    - to uncover "hidden" structures emerging through self-organization

3. A Network-Theoretic Analysis of Swarming

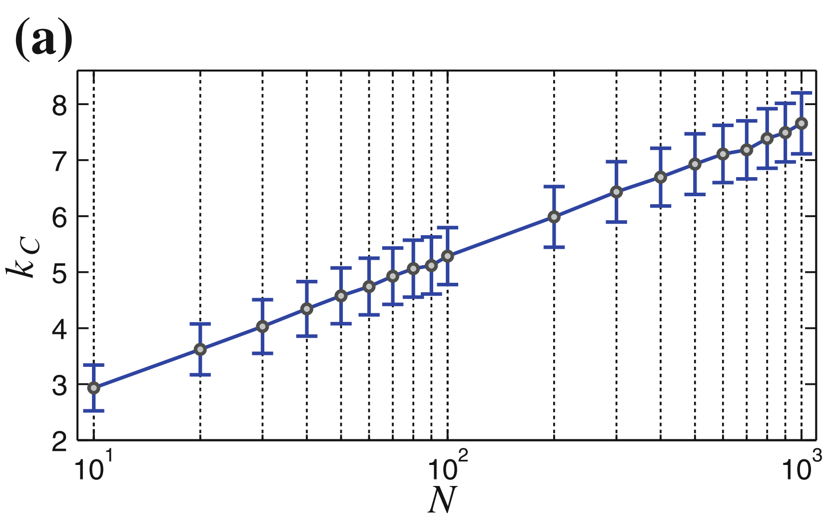
- Swarm Signaling Network (SSN)
  - Dynamic interaction network (switching/temporal)
  - Communication channel for social information transfer
  - Superorganism paradigm for the whole swarm

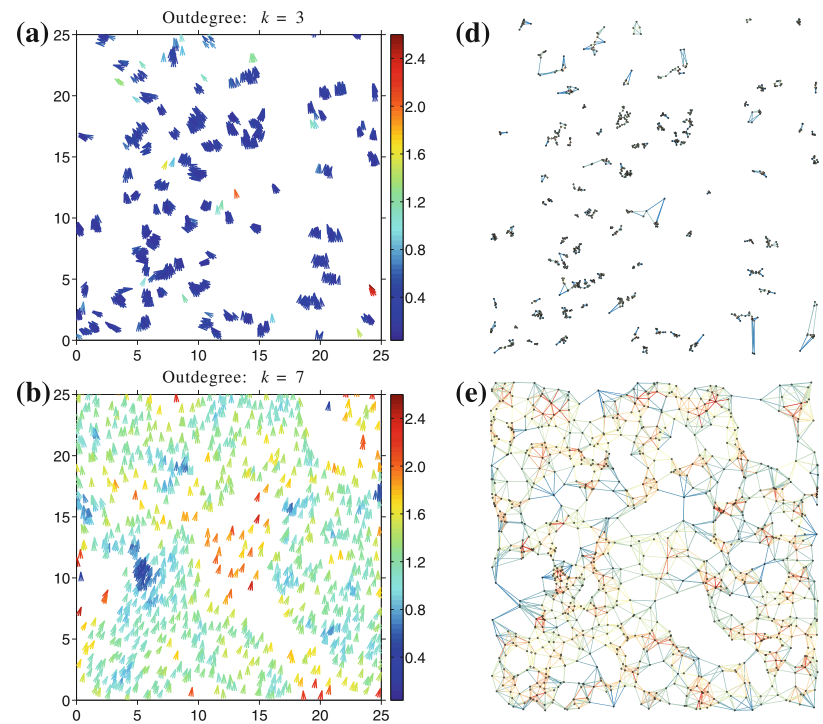


a Physical view: snapshot of a swarm of $N = 100$ topologically interacting individuals traveling at constant speed in a two-dimensional square domain (10×10) with periodic boundaries; each agent interacts topologically with $k = 7$ neighbors. **b** Network view: the associated swarm signaling network (SSN); the nodes and edges are colored according to the topological distance (increasing topological distance from *blue* to *red*). **c** Combined view: the swarm overlaid with the SSN

3. A Network-Theoretic Analysis of Swarming

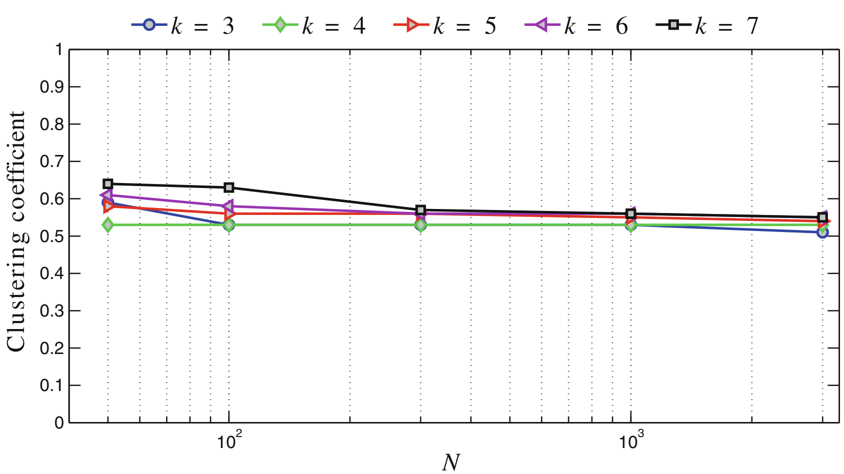
- Connectedness of the SSN
  – For information to be shared the SSN must be strongly connected

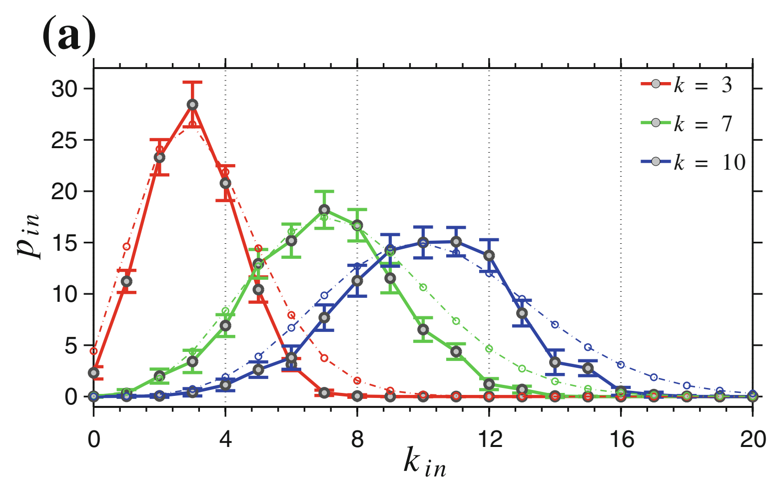




3. A Network-Theoretic Analysis of Swarming

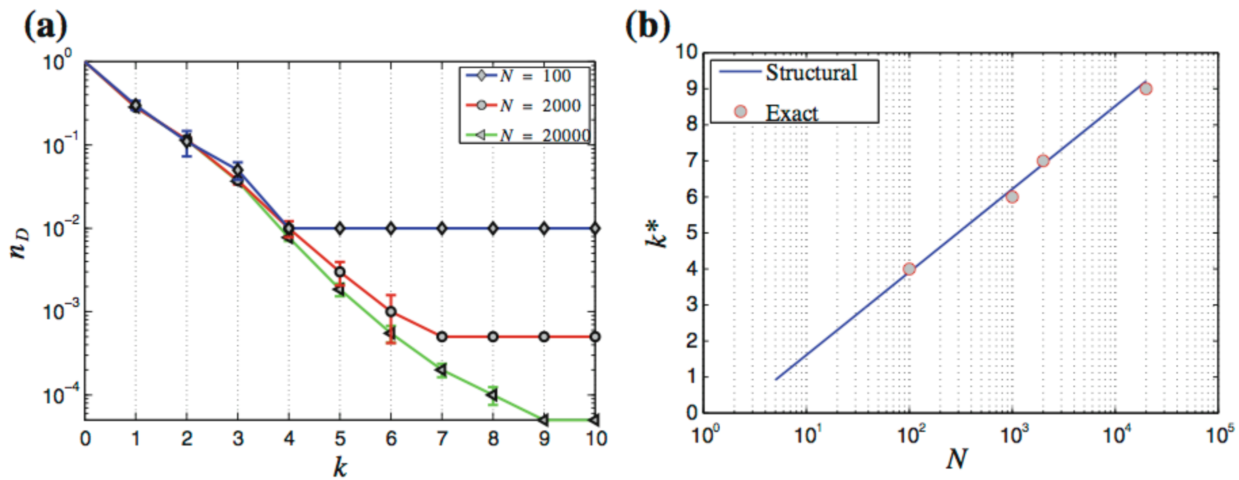
- Swarm Signaling Network (SSN)
  - Dynamic interaction network (switching/temporal)
  - Small-world network
  - Moderately clustered
  - Homogeneous degree distribution (no hub!)





3. A Network-Theoretic Analysis of Swarming

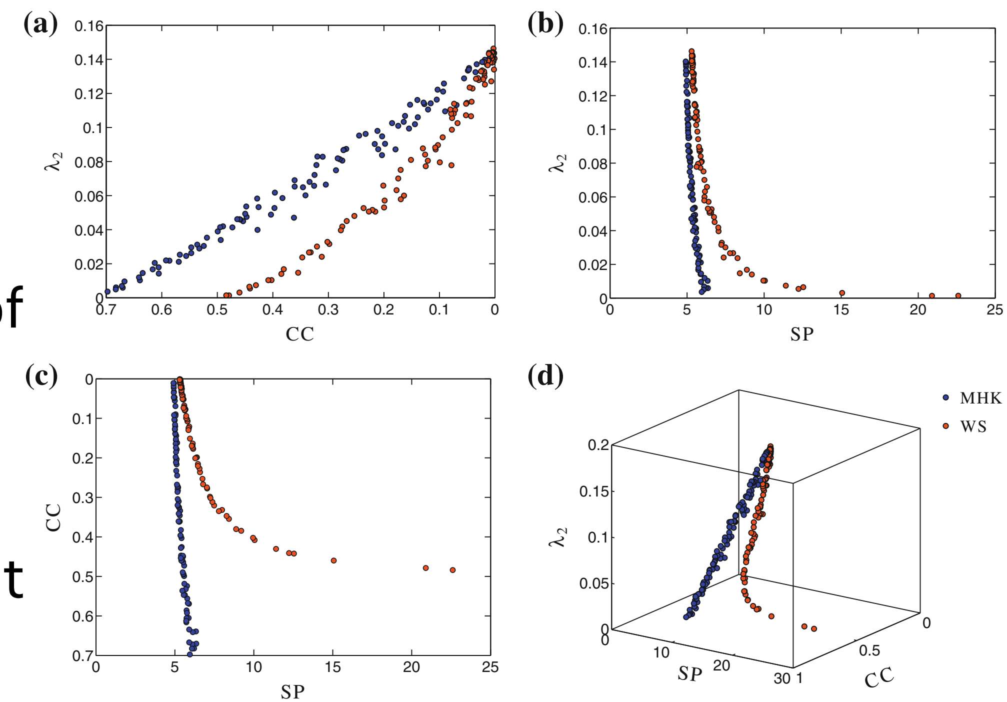
- Controllability of Swarming
  - Controllability of complex networks (Lect. by Prof. Justin Ruths)
  - Condition for one agent to gain control of the entire swarm



a Density of required driver agents for a swarm with topologically interacting members versus the number of neighbors (k) for three different swarm populations (N). Results applying the exact controllability tool were collected for 10 distinct SSNs at each data point. The average density of driver nodes is calculated and the related standard deviations are illustrated by means of *errorbars*. **b** Required number of topological neighbors (k^*) in a swarm to reach full controllability versus swarm size (N). The *blue line* corresponds to the approximate analytical result from the structural controllability analysis. The *red dots* refer to the result obtained with the exact controllability tool

3. A Network-Theoretic Analysis of Swarming

- Design a swarm through SSN Design
  - Social transmission of information is critical to swarming
  - Optimize for high speed of consensus reaching
  - Trade-off between small shortest path (SP) and small clustering coefficient (CC)



3. A Network-Theoretic Analysis of Swarming

- Swarm Design: Words of Caution
  - Swarms are dynamic and need information to properly operate
    - Focus just on the structure of the communication channel (i.e. network) is clearly not sufficient
    - Information-theoretic approach is required
  - Swarms are dynamic and need control
    - Changing the network also modifies the balance between positive and negative feedback loops
    - Networked-control systems perspective is required

4. An Information-Theoretic View of Swarming

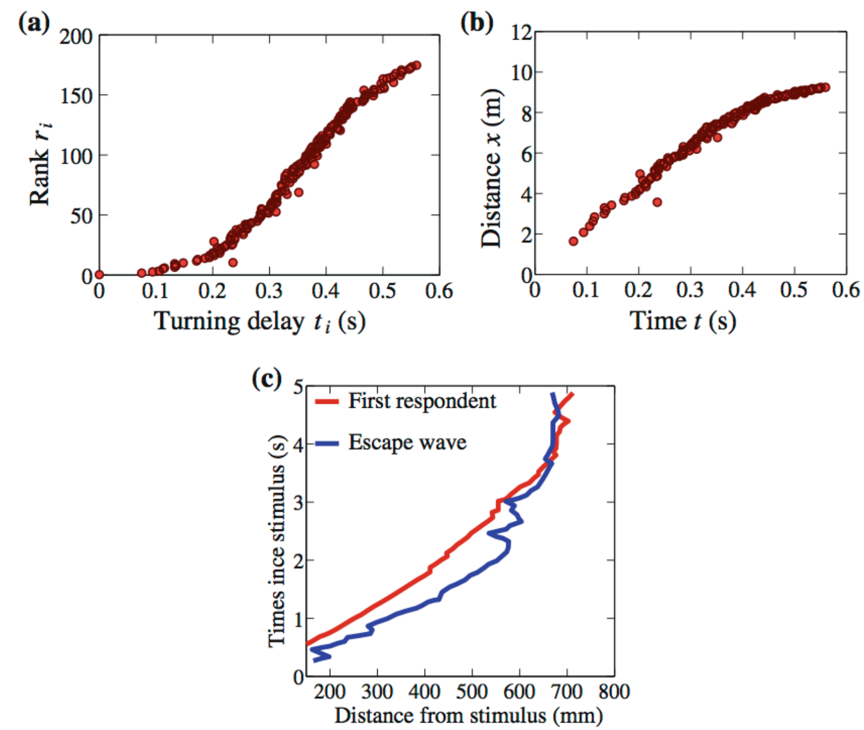
- "Information is Power!" Swarms need information to operate
  - Augmented sensory capabilities
    - through social exchange of information
  - Improved responsiveness to threat and dangers
    - collective surveillance against oncoming threats
    - "many eyes" theory
  - Information:
    - acquired locally through multimodal sensory modalities
    - globally shared between interconnected swarming agents
    - collectively processed to generate a beneficial response

4. An Information-Theoretic View of Swarming

- "Information is Power!" Swarms need information to operate

4. An Information-Theoretic View of Swarming

- Dynamics of information transfer
  - Tracing the flow of information
  - Information is flowing amazingly fast and in a nontrivial way throughout swarms
    - little damping and dispersion
    - swarm as fast as the "driving" agent



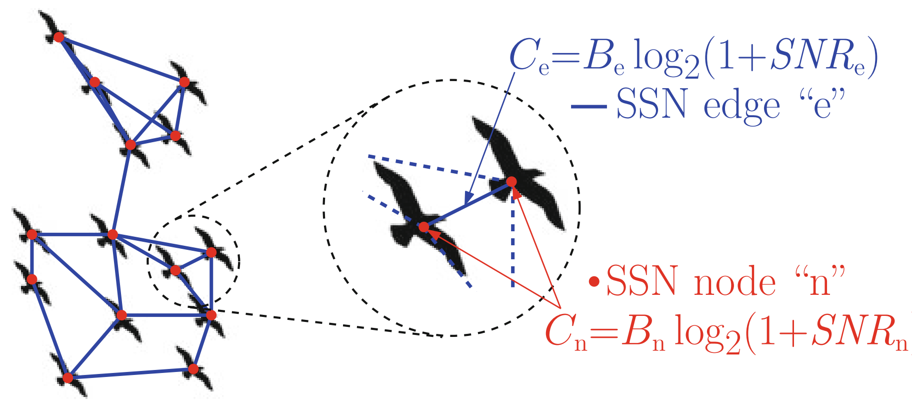
a Rank r_i of each bird in a given collective turn event ($N = 176$ birds for event 20110208_ACQ3), that is, its order in the turning sequence versus its absolute turning delay t_i with respect to the first bird to turn. Data and results from Ref. [2]. **b** Distance x traveled by the information as a function of time t ($N = 176$ birds for event 20110208_ACQ3). Data and results from Ref. [2]. **c** Dynamic of information transfer in a school of fish ($N = 51$ fish) startled with a simulated attack. Time since stimulus versus distance from stimulus, for the average position of the first responding individual (*red*) and for the average position of the escape wave (*blue*). Data and results from Ref. [10]

4. An Information-Theoretic View of Swarming

- Quantifying information flow
  - Capacity of the communication channel (SSN)

$$C = B\log_2(1 + SNR),$$

  - Shannon-Hartley Theorem
    - B: bandwidth (related to update frequency)
    - SNR: signal-to-noise ratio
  - Min-flow Max-cut Theorem
    - to identify informational bottlenecks
    - 4 possible types



4. An Information-Theoretic View of Swarming

- Condition for an emergent behavior under limited bandwidth
  - Analytical derivation for SPPs

$$\theta_i(t+T_\mathrm{n}) = \theta_i(t) + \frac{T_\mathrm{n}}{k_i} \sum_{j\sim i} \left\{\theta_j(t) - \theta_i(t)\right\} + \eta_\mathrm{n}\xi_i(t),$$

  - In the absence of noise: $\boldsymbol{\Theta}(t) = [\theta_1(t),\ \theta_2(t), \ldots,\ \theta_N(t)]^T,$

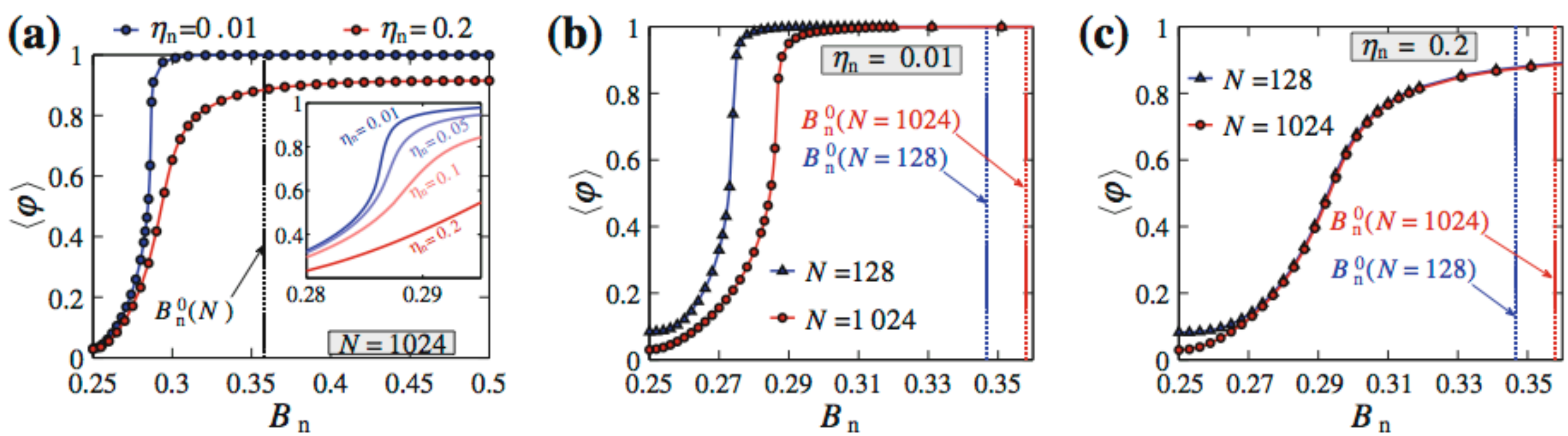
$$\boldsymbol{\Theta}(t+T_\mathrm{n}) = \mathbf{P}_\mathrm{n}(t)\boldsymbol{\Theta}(t) = (\mathbf{I} - T_\mathrm{n}\tilde{\mathbf{L}}(t))\boldsymbol{\Theta}(t),$$

  - Sufficient condition on the bandwidth for the emergence of order

$$B_\mathrm{n} > B_\mathrm{n}^0 = \frac{1}{4} \max_{1\le i\le N} |\lambda_i(\tilde{\mathbf{L}}(t))| \qquad \text{for all } t,$$

4. An Information-Theoretic View of Swarming

- Collapse of swarming
  - In the presence of noise and limited bandwidth

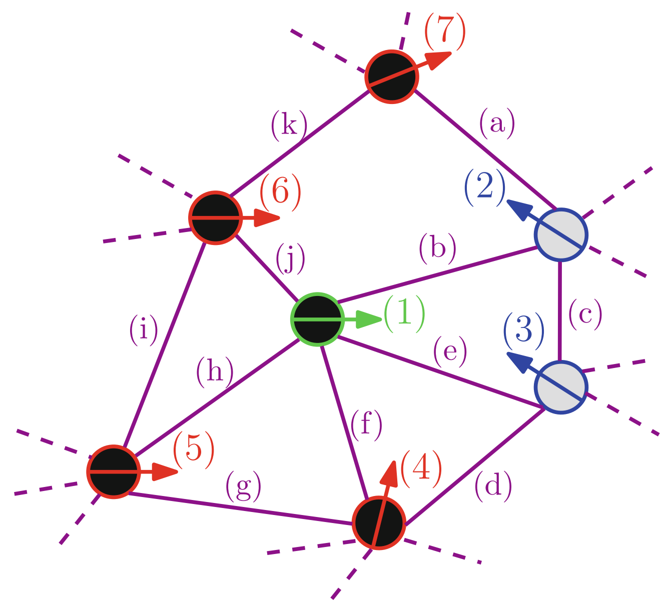


Collapse of swarming with decreasing B_n: **a** $N = 1{,}024$; **b** $\eta_n = 1\,\%$; **c** $\eta_n = 20\,\%$. Values for $B_n^0(N)$ are obtained from (5.11) in the $\eta_n = 0$ limit upon averaging over a sample of 10^4 SSNs ($v_0 = 0.3$, $k = 7$, $\rho = N/L^2 = 100$, and equivalent statistics for all data points. See Sect. 3.2)

4. An Information-Theoretic View of Swarming

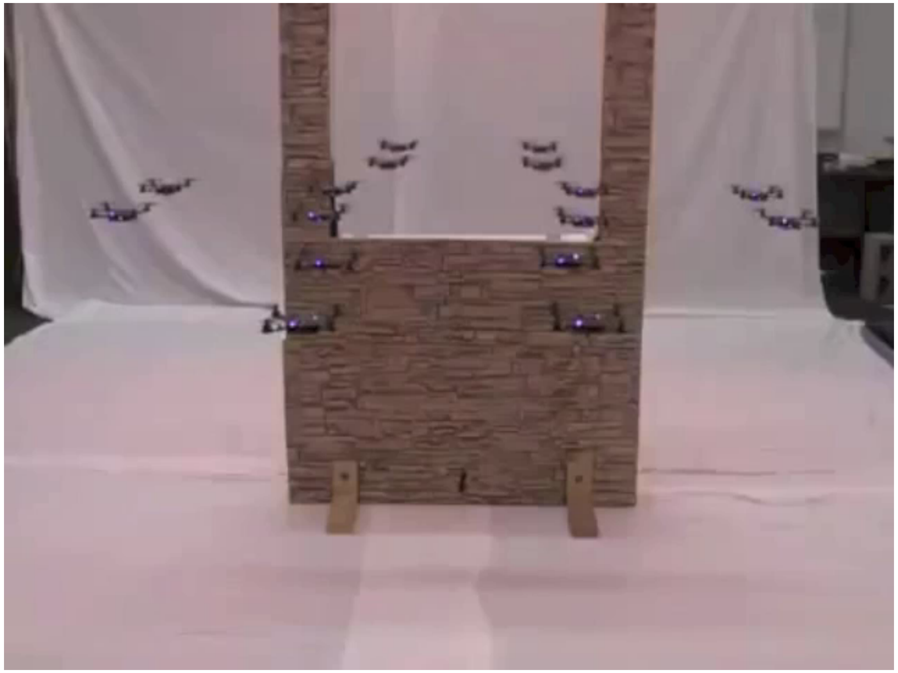
- Swarm Design: the intricate relationship between channel structure and channel flow
  - Maintaining the information flow: SSN connectedness
  - Allowing the effective transfer of salient behavioral features: high capacity C
  - Maintaining the right balance between positive and negative feedback loops

Schematic of a subset of collectively moving agents within a swarm. *Arrows* show the direction of travel and *straight lines* represent the existence of an interaction link between any two agents (considered bidirectional for simplicity)



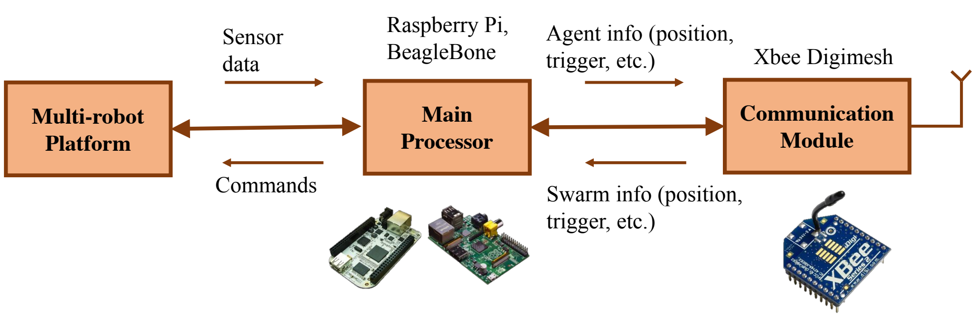
5. Swarm-enabling Technology

- A multi-robot system does not make a swarm
  - A swarm requires decentralized sensing, communication, computation and response



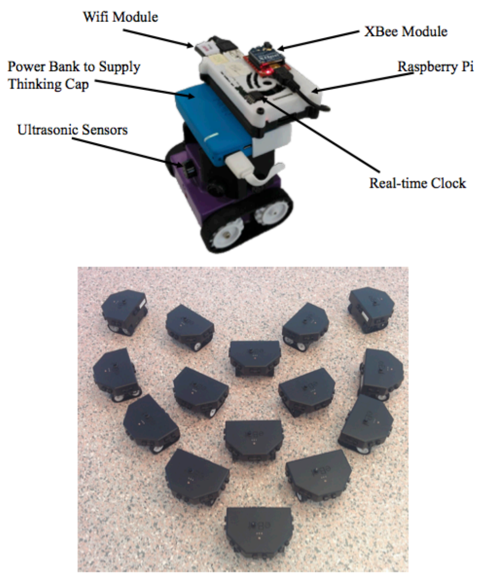
5. Swarm-enabling Technology

- A multi-robot system does not make a swarm
  - A swarm requires decentralized sensing, communication, computation and response
- A perfect time to make your own swarm!
  - Explosive advances in the fields of
    - sensors (miniature and multisensory)
    - communication devices (ad hoc mesh networks)
    - microcomputer (Raspberry Pi zero & 3)
  - Platform-agnostic swarming technology



5. Swarm-enabling Technology

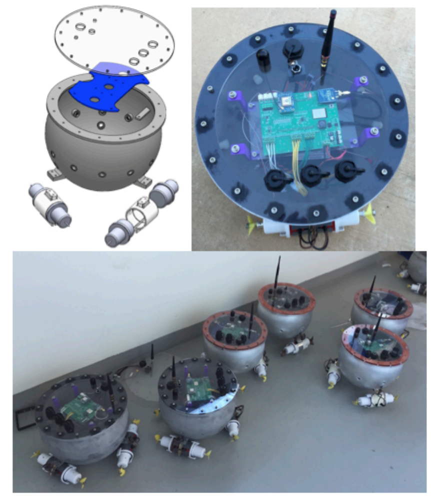
Swarm of eBots



the eBot with ultrasound sensors crowned with the Thinking Cap. A 3D printed structure is hosting the Raspberry Pi, XBee module and real-time clock, along with a power bank serving as the power source. The WiFi module is used exclusively for monitoring and updating purposes, and is not required for the autonomous operation of the robot. Bottom: Swarm of 15 eBots with IR sensors.

https://www.youtube.com/watch?v=JzbWV1sfZ-A

Swarm of buoys



A cast aluminum hull mitigates magnetic interference with sensitive MEMS sensory elements used to reference buoy orientation. Many standard expansion ports along the perimeter allow for the addition of environmental measuring devices seamlessly in the field. A large access cover at the top provides easy access for maintenance as needed, while all data transfer can be conducted via WiFi or USB through USB-A ports in the access cover. All Thinking Cap components are housed securely within the watertight hull and can be seen on the top view (top right corner).

https://www.youtube.com/watch?v=_FbnaQbKUKw

6. Outlook: Can swarms be designed?

- Swarm Intelligence
  - Offers a unique alternative way of designing “intelligent” systems through a combination
    - autonomy
    - emergence (through self organization)
    - distributed problem solving
      - →Replacing embedded central control
- Swarming systems leverage the power of
  - Robustness
  - Flexibility
  - Scalability

6. Outlook: Can swarms be designed?

- But…
  – Self-organization is not an element that can be naturally integrated into a traditional and methodical design process (Propenko, Springer 2013)
  – The vast breadth of swarming behaviors existing in nature might not be the one you need

- Self-design through self-organization remains a vision of the future!!

Thank you!

- Postdocs
  - Dr. David Mateo
  - Dr. Mohammad Komareji
  - Dr. Yilun Shang
  - Dr. Alex Zhukov
  - Dr. Mohammadreza Chamanbaz
  - Dr. Xiaoying Zhu
  - Dr. Wen Xin
- Research Assistants
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- PhD Candidates
  - Yoke Kong Kuan
  - Sreetej Lakkam
  - Komal Agarwal
- Visiting Master Students:
  - Andre Sekunda
  - Nikolaj Sorensen
  - Ajay Kumar