HuBIRT

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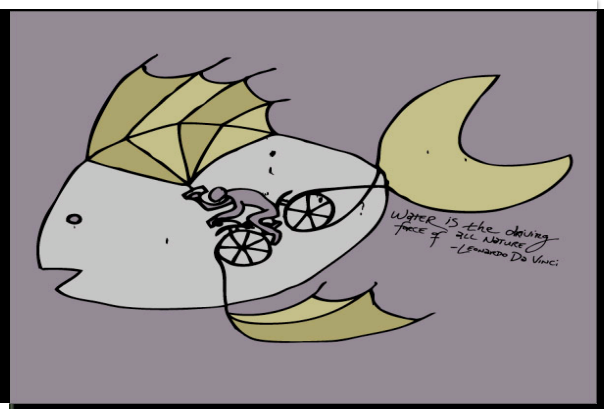
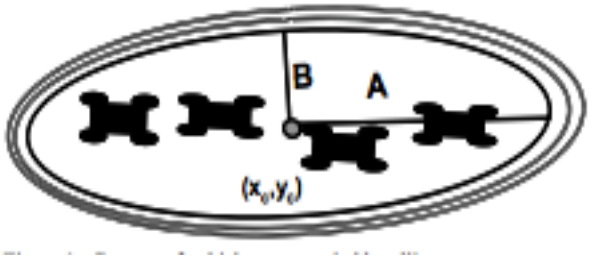
Toward Human-Interaction with Bio-Inspired Robot Teams

ONR via CMU
RCTA via USF

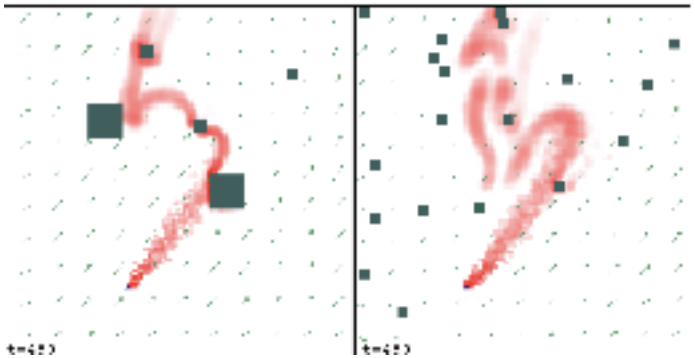


What types of problems

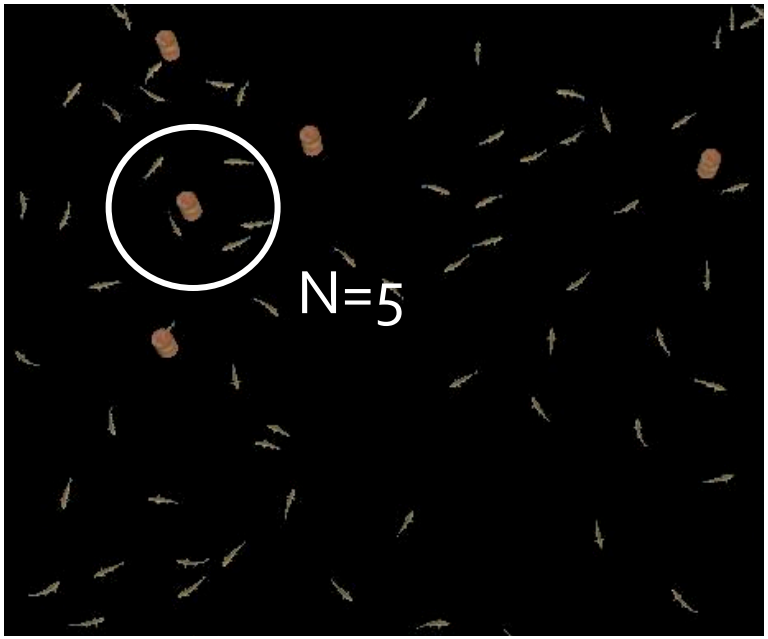
- Barnes & Fields:
  - Convoy protection



- Spears
  - Plume tracking



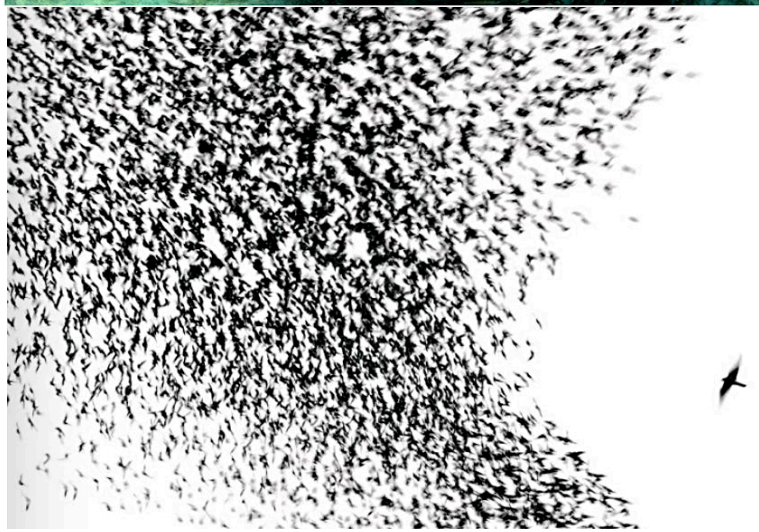
- Abstraction: Information Foraging
  - Resource depletion rate



$$S_j(t+1) = S_j(t) - N$$

Which Types of Bio-Inspired Teams?

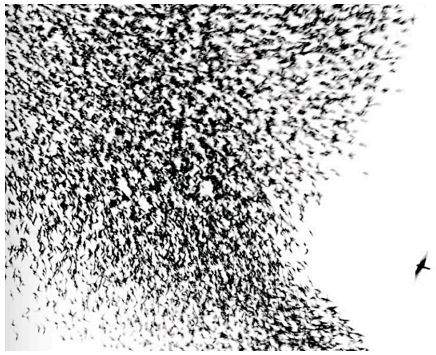
- Simple agent behaviors
- Collective group intelligence
- Goal-driven group behavior

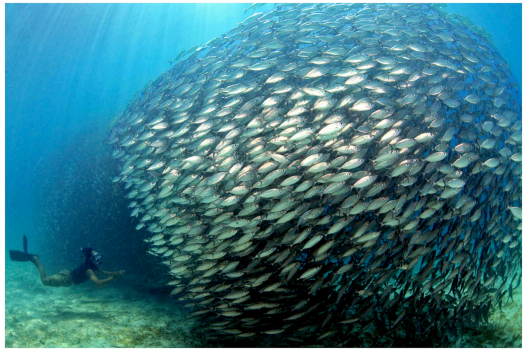


Model Class:
Inter-Agent Influence + External Influence

- Sumpter
  - Positive feedback: "imitation or recruitment behaviour [yielding] collective patterns."
  - Negative feedback: inhibition that yields stable collective behavior
  - Individual: each agent has its own state
- Reynolds
  - Mutual attraction
  - Mutual repulsion
  - Mutual alignment
- Restrict to additive model (for now)

$$\mathbf{x}_{t+1} = f(\mathbf{x}_t) + g(\mathbf{x}_t, u_t)$$





HuBIRT Model: Connectivity and Sparseness

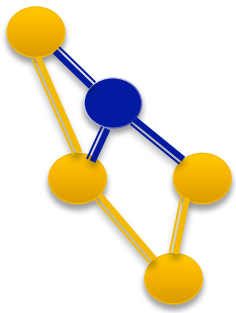
- Egerstedt:
  - Stable decentralized control relies on ***connectedness***
- Ballerini:
  - Natural models use ***structured sparseness***

$$
\begin{aligned}
x_{t+1}^i &= f^i(\mathbf{x}_t) + g^i(\mathbf{x}_t, u_t) \\
&= f^i(x_t^i, \mathbf{x}_t^{\neg i}) + g^i(x_t^i, u_t)
\end{aligned}
$$

Autonomy Assumption:
what else influences me?

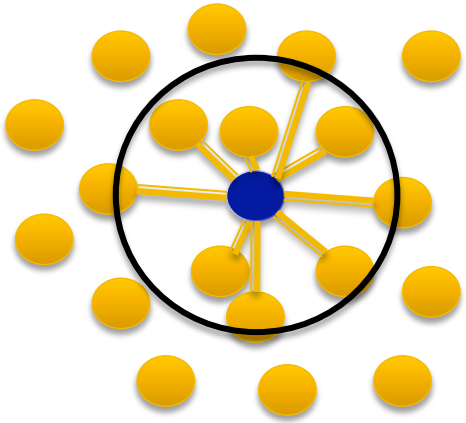
Cohesiveness Adjacency Matrix:
who influences me?

$$
A_t = \begin{bmatrix}
0 & 1 & 0 & 0 & 1 \\
1 & 0 & 1 & 0 & 1 \\
0 & 1 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 1 \\
1 & 1 & 0 & 1 & 0
\end{bmatrix}
$$

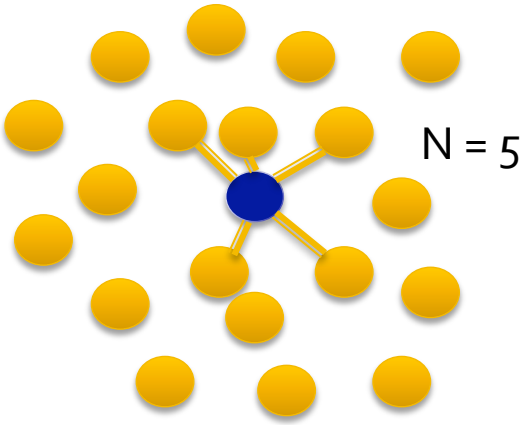


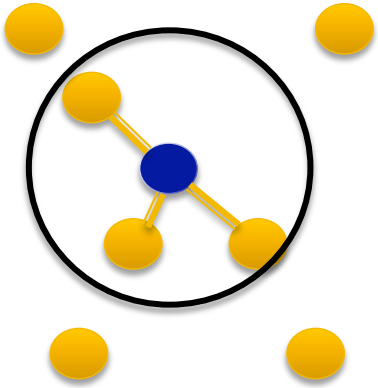
Inter-agent Connectivity: Structured Topologies A_t

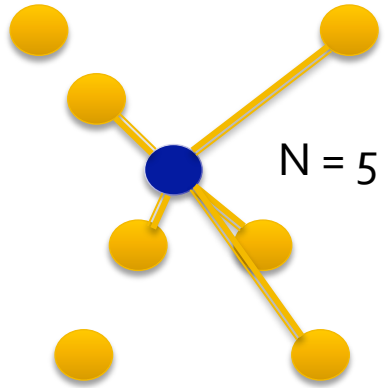
- Power-limited Comms
  - Metric-based topologies



- Bandwidth-limited Comms
  - Nearest-neighbor topologies







Model: Human Influence

- Autonomy: an agent's response to an external signal
  - Depends only on the signal
  - And the agent's own state
- Two external influences
  - Operator input
  - Environment signals

Notional

$$g^i(x_t^i, u_t) = d^i(x_t^i, u_t^{\text{op}}) + e^i(x_t^i, u_t^{\text{env}})$$

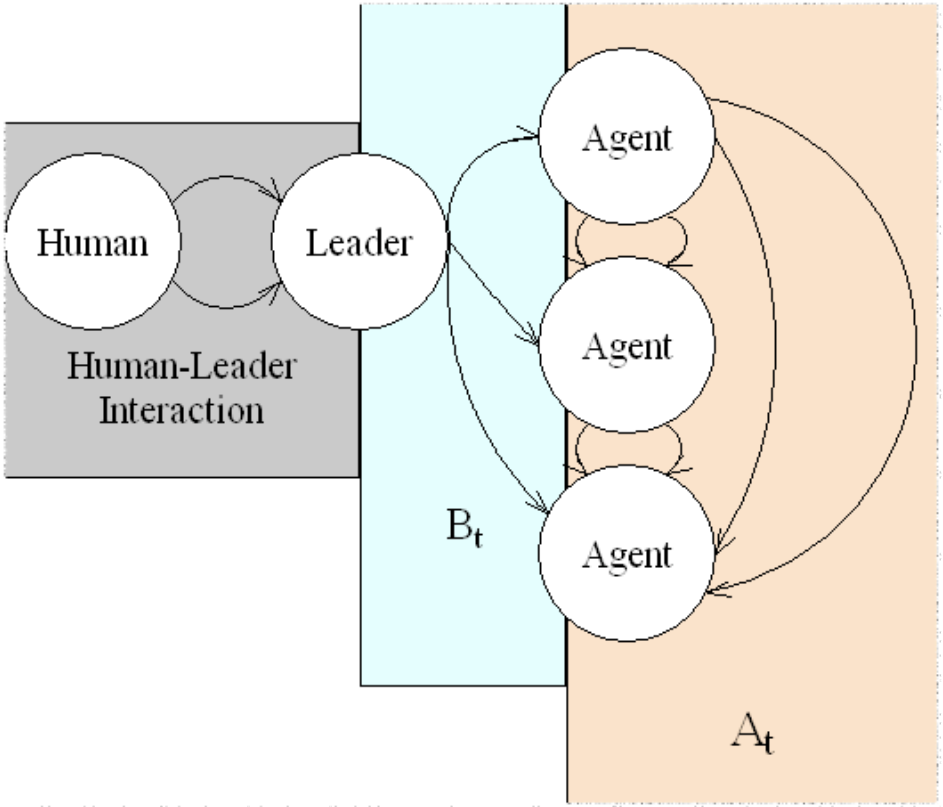
Management Adjacency Matrix:

$$B_t = [0\ 0\ 1 \ldots 0\ 1]$$

Which agents are affected by human?

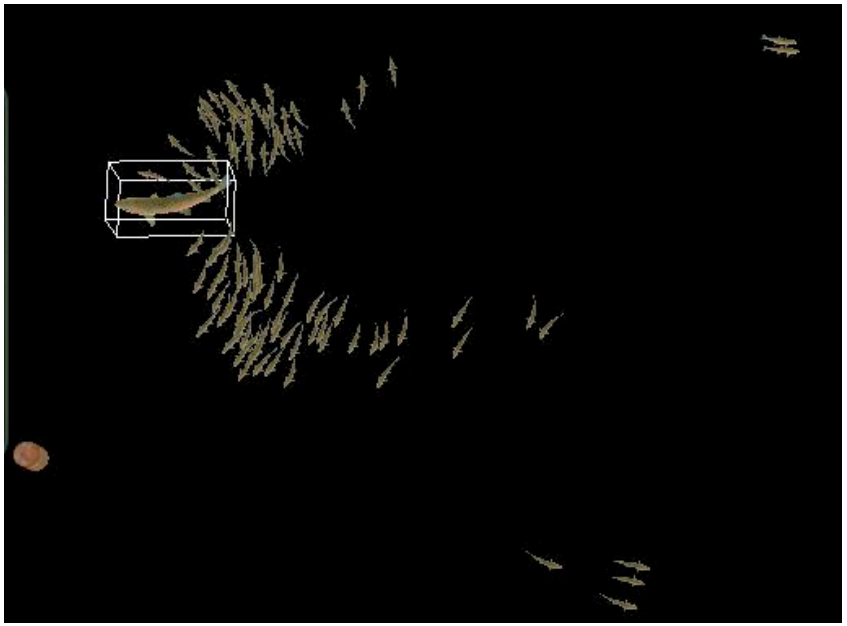
Experiment Design: Human Influence

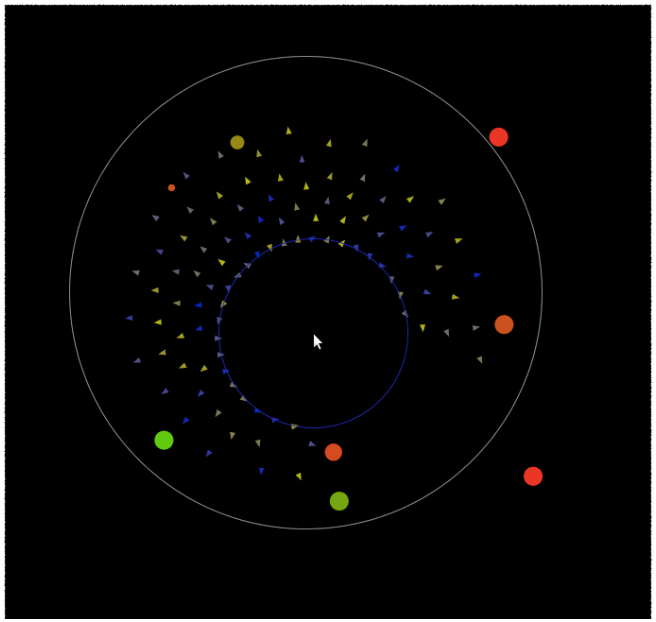
- State-of-the-Art
  - Centralized leader with decentralized formation
  - Centralized selection of model parameters
  - Decentralized w/o human
  - Ad hoc
- ***Leaders and Predators***
  - Sumpter: what is a leader?
  - Decentralized leader influence



Experiment Design:
One natural & one artificial structure

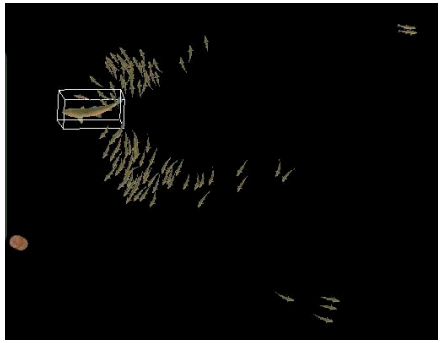
- Bio-mimetic
  - Imitate a biological system
  - Zoomorphic agents
  - Couzin et al., 2002
- Physico-mimetic
  - Imitate an artificial system
  - Point-mass agents
  - Spears et al., 2005





Building Intuition w/ Experiments:
How relevant to real robots?

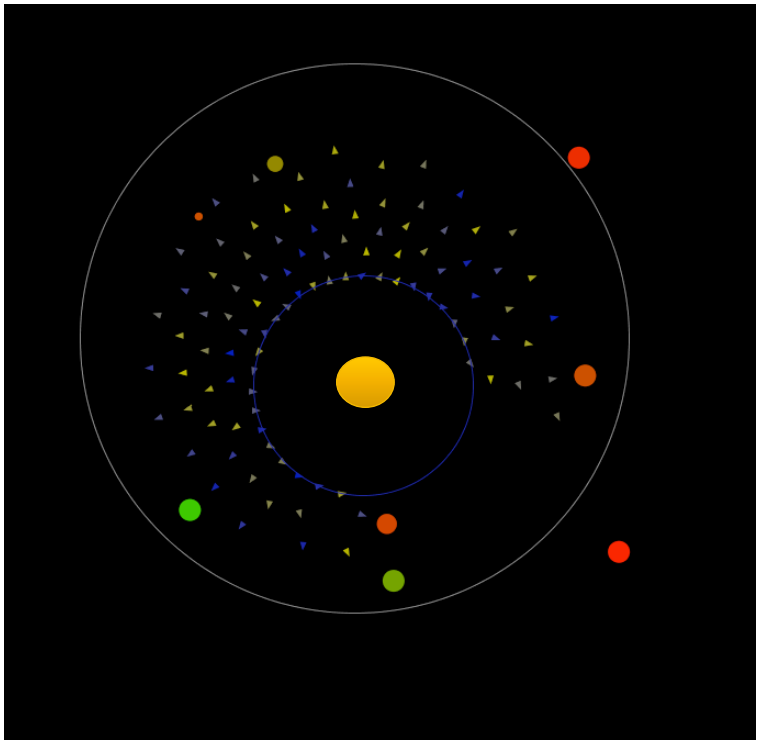
- Ecologically Valid
  - Topological connectivity
  - Limited inter-agent communication
  - Human influence over a small subset of agents
  - Additive inter-agent influence
  - Human operators
- Not Valid
  - Human can observe state of all agents
  - Holonomic, noise-free dynamics
  - Noise-free communication
  - Few operators

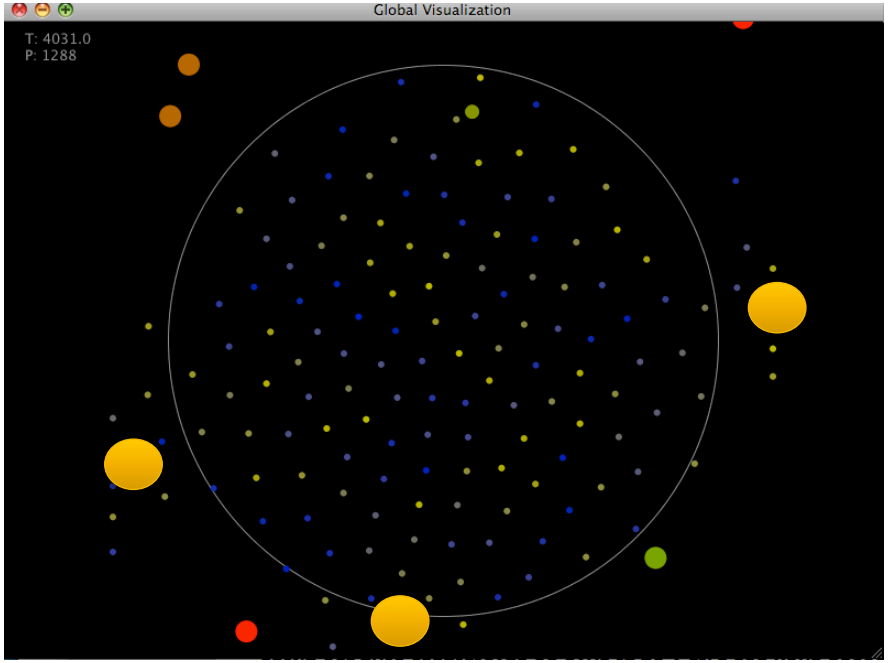


L. Parker

Sample Models: Physico-mimetic

- Physico-mimetic
  - Agents as point masses
  - Attract and repel



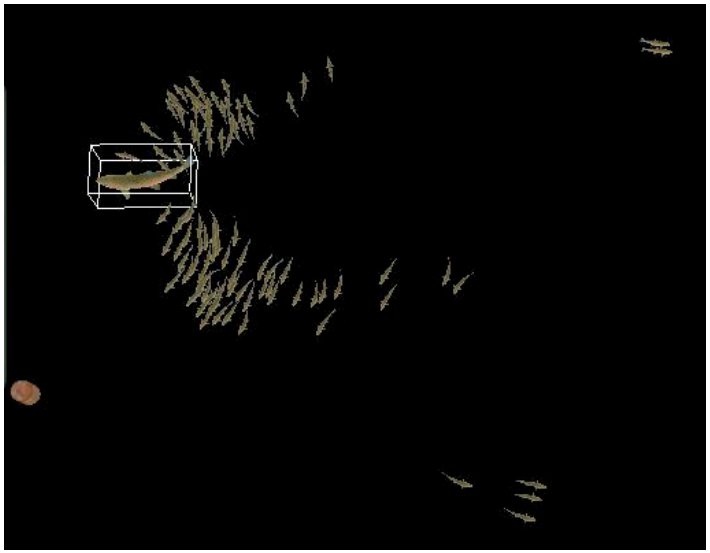


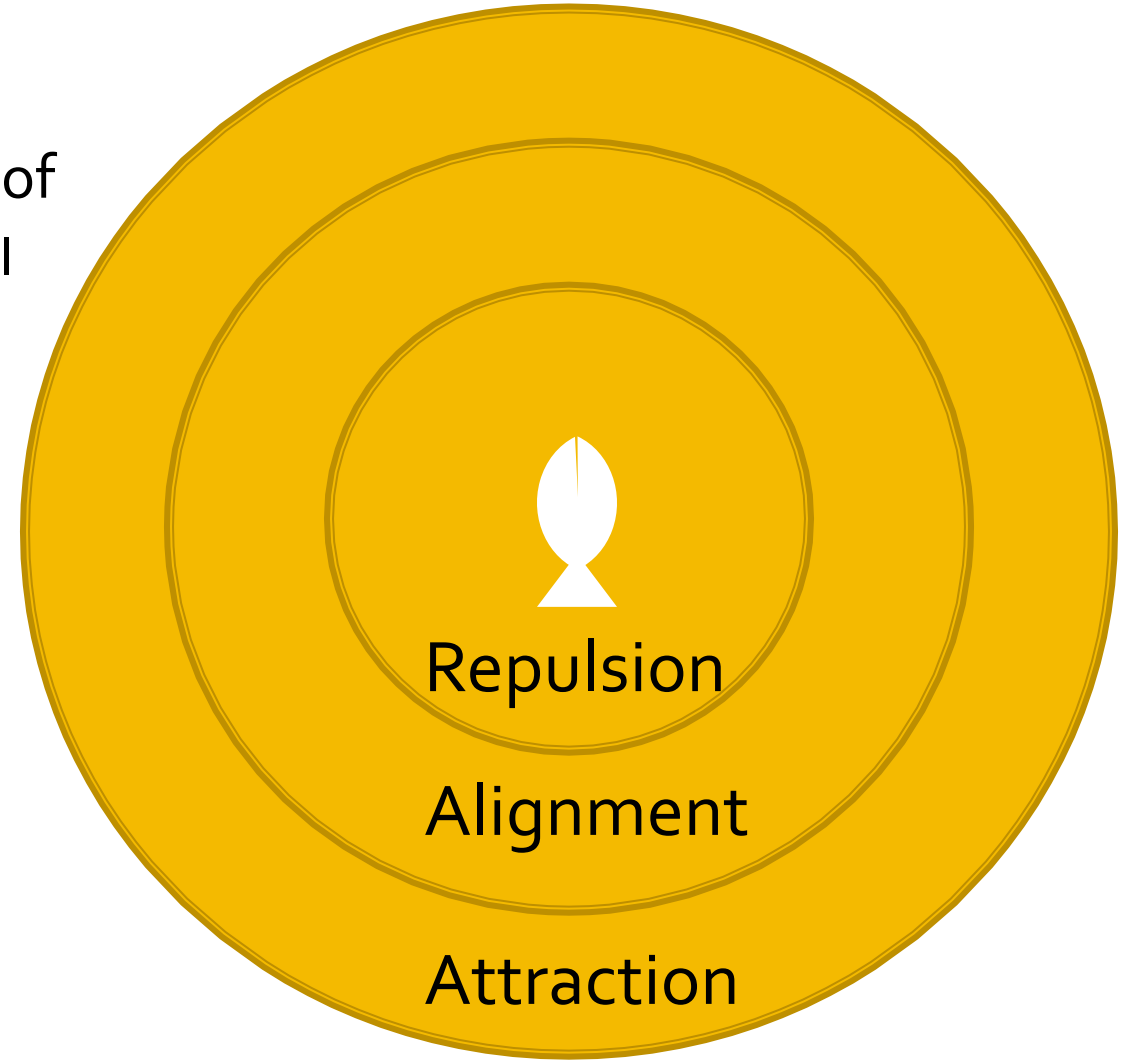
$$F_i = \sum_{j=1}^{N} F_{ij}$$

$$v_i(t+1) = v_i(t) + \frac{F_i}{m_i}$$

Sample Models: Bio-mimetic

- Bio-mimetic
  - Couzin's instantiation of
    - Reynold's "Boids" model
  - Conradt:
    - Split and Steer

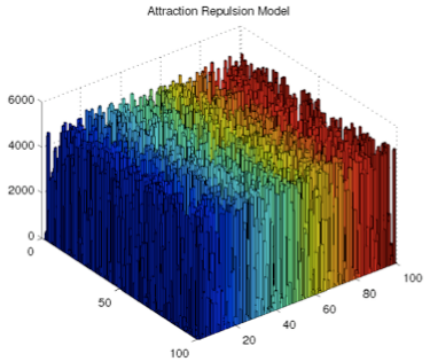




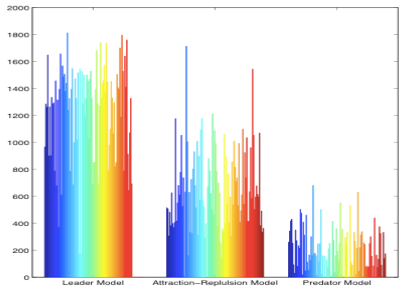
Metrics: time histories

- Adjacency matrix time-histories =
  - evolution of collective structure
  - under human influence

$$\mathcal{A}_t = \sum_{\tau=0}^{T} A_{t-\tau}$$



$$\mathcal{B}_t = \sum_{\tau=0}^{T} B_{t-\tau}$$

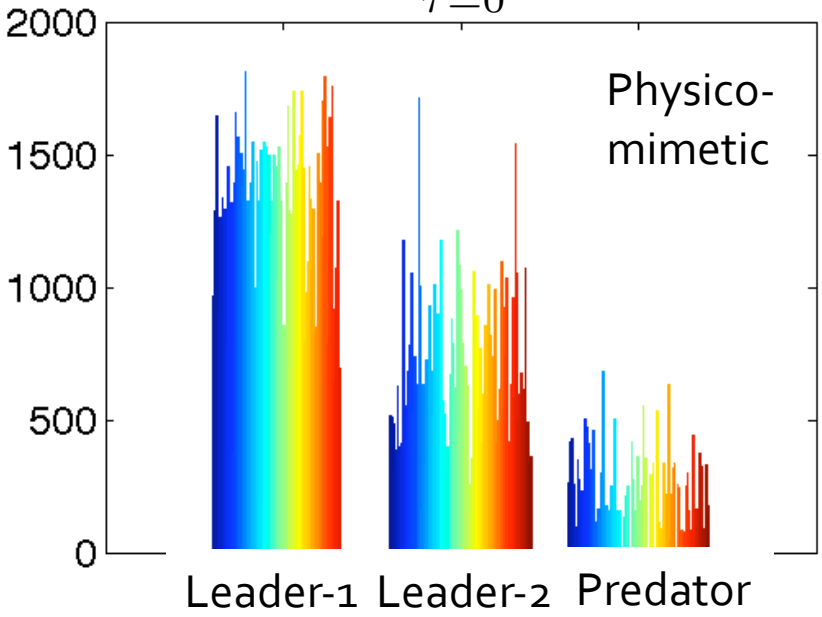


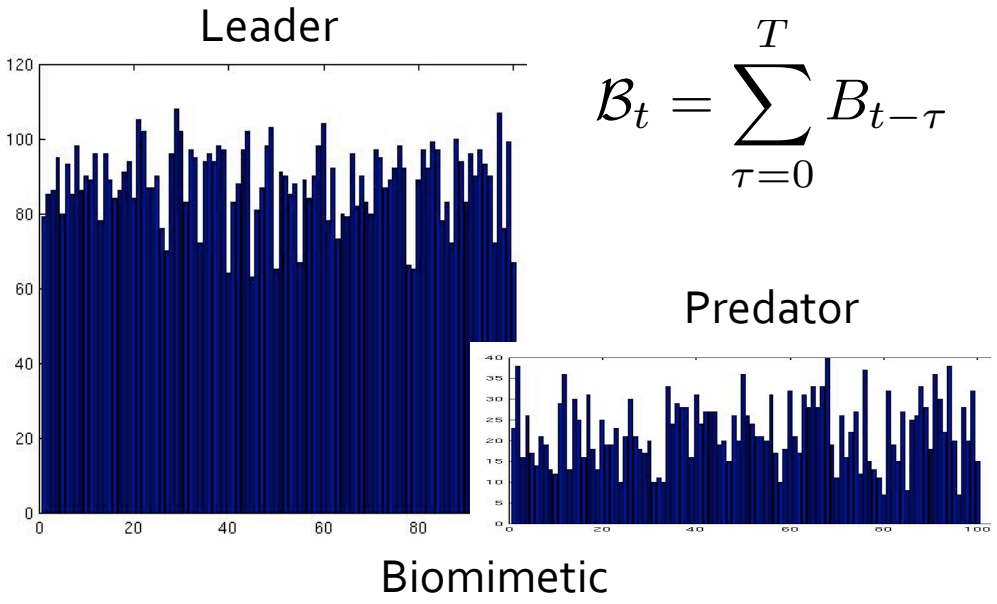
What Types of Human Influence?
Empirical Correlates w/ Performance

Experiments

- Leaders
  - Sustainable human influence
- Predators
  - Unsustainable human influence
  - Need team of predators

$$\mathcal{B}_t = \sum_{\tau=0}^{T} B_{t-\tau}$$



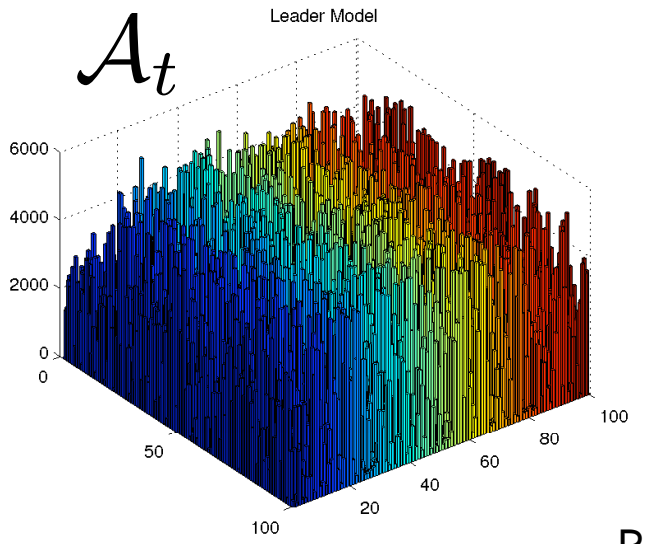


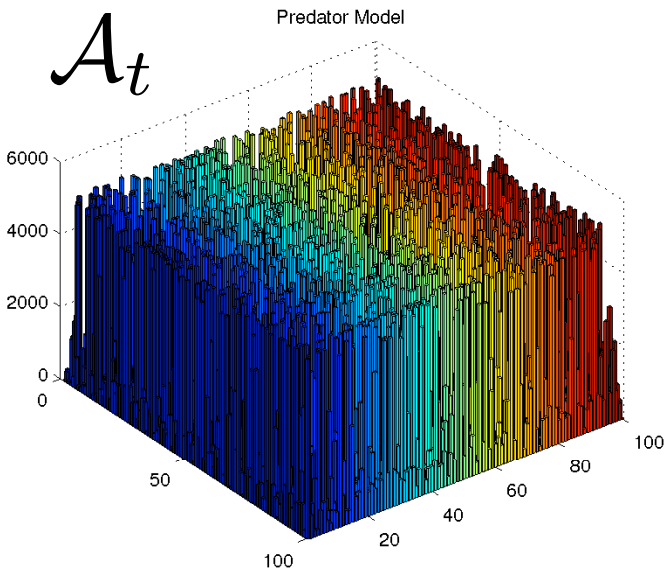
$$\mathcal{B}_t = \sum_{\tau=0}^{T} B_{t-\tau}$$

What Types of Human Influence?
Empirical Correlates?

Experiments

- Leaders
  - Coherent?
- Predators
  - Coherent?



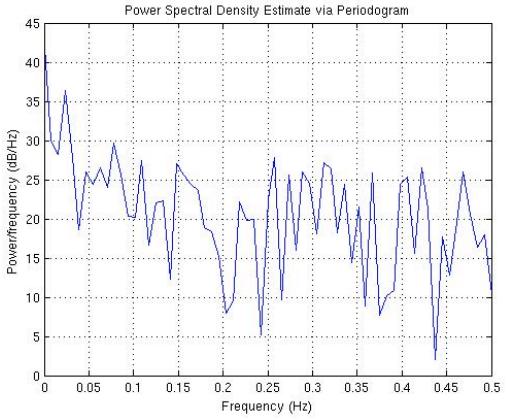


Physicomimetic

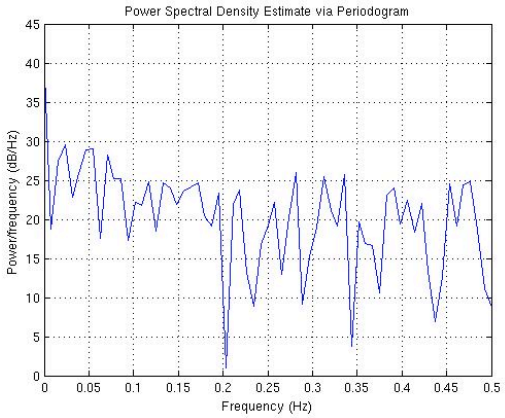
What Types of Topologies?
Empirical Correlates w/ Performance

PSD of $\mathcal{A}_t$

- Metric
  - Less coherent

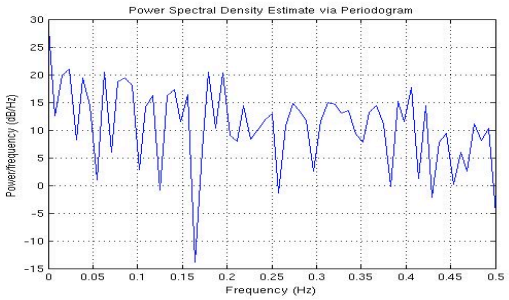


Leader

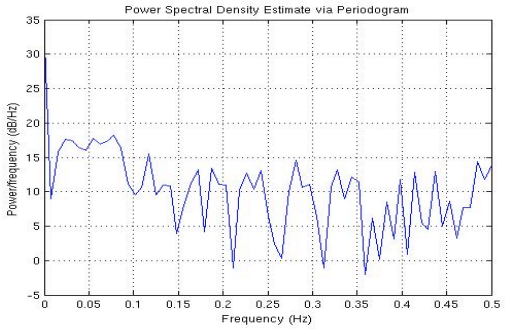


Predator

- Nearest Neighbor
  - Coherent

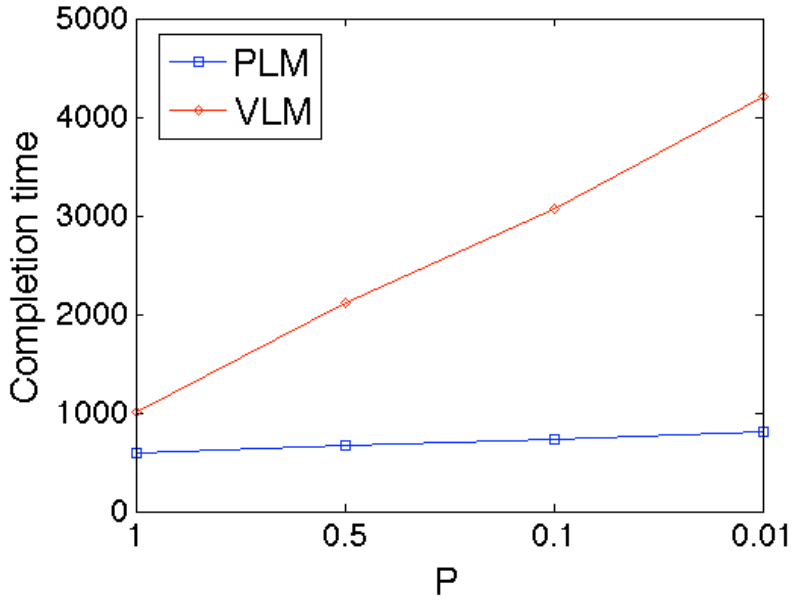


Ballerini's observation



Communication Requirements
Empirical Results

- Robust to communication drop-outs
- Two Leader models
  - Virtual requires sustained remote communication
  - Physical requires intermittent remote and sustained local communication

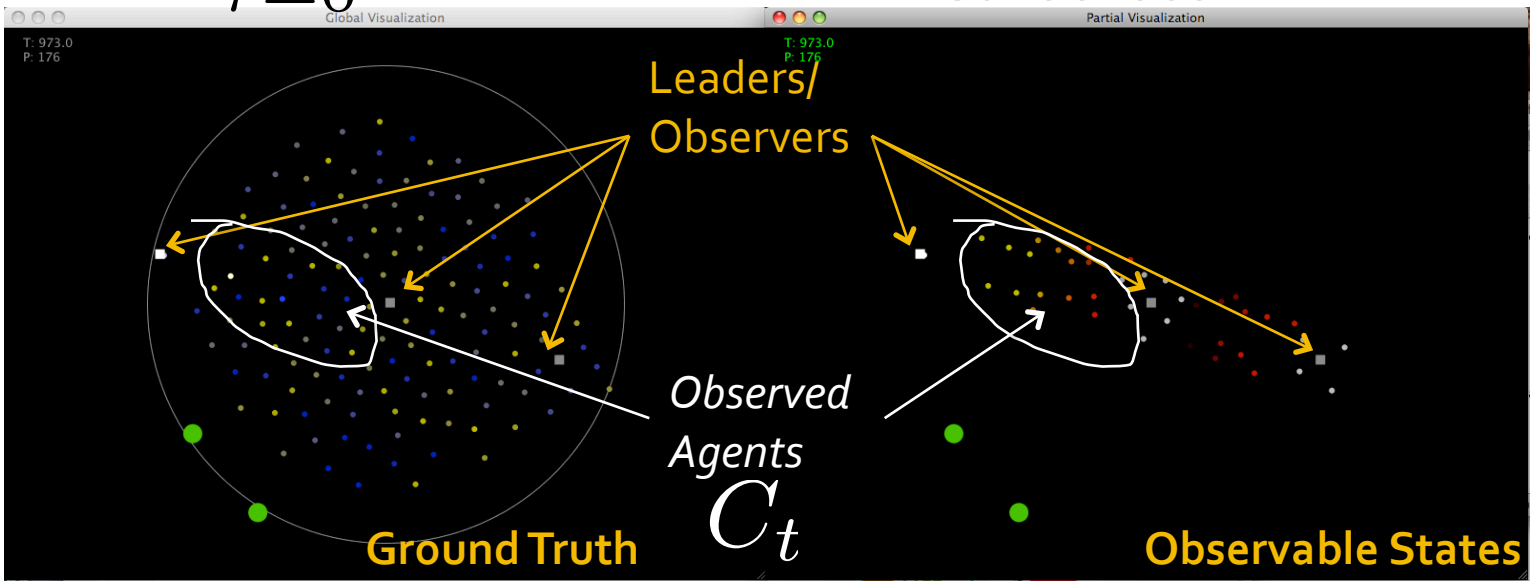


Phase I: Partially Observable Collectives

- A common unrealistic centralization assumption
- Partially observable with time delays

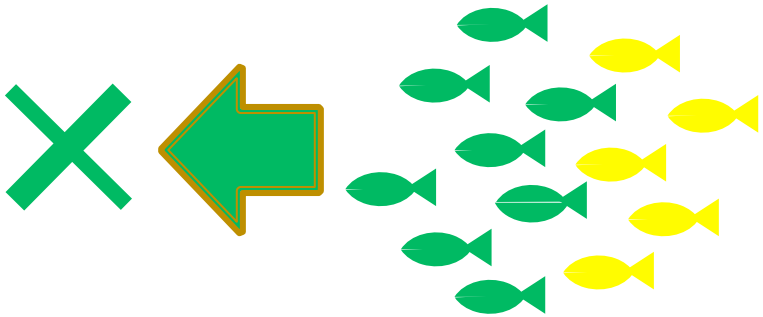
$$\mathbf{z}_t = \sum_{\tau=0}^{T} C_{t-\tau}\mathbf{x}_{t-\tau}$$

- Active Sensing
  - Leaders = Observers
  - Centroid and fringe agents
  - Zig-zag agents
  - Consensus

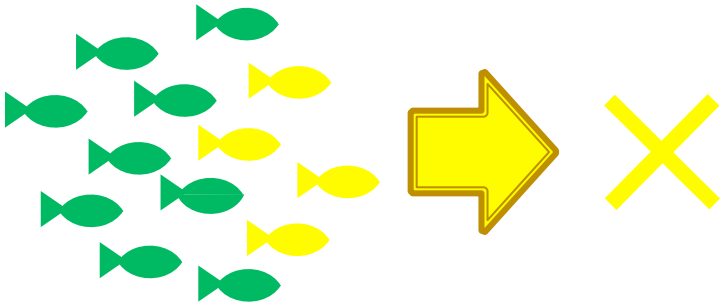


Phase II:
Multi-operator Management

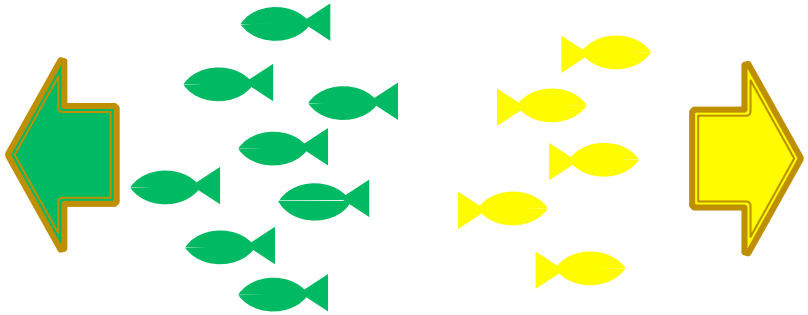
- Conradt et al. 2009



Operator 1 Leads



Operator 2 Leads

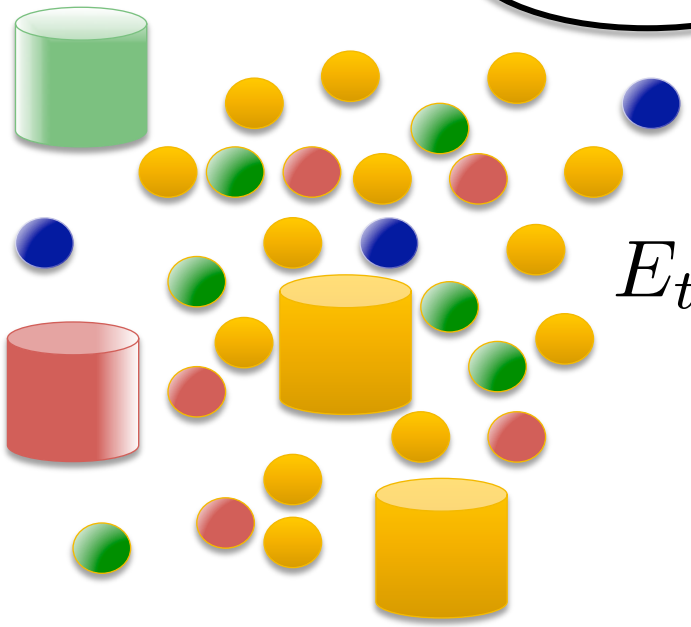


Task Assignment

Phase III: Include Autonomy

- Autonomy and Heterogeneity

$$g^i(x_t^i, u_t) = d^i(x_t^i, u_t^{\text{op}}) + e^i(x_t^i, u_t^{\text{env}})$$



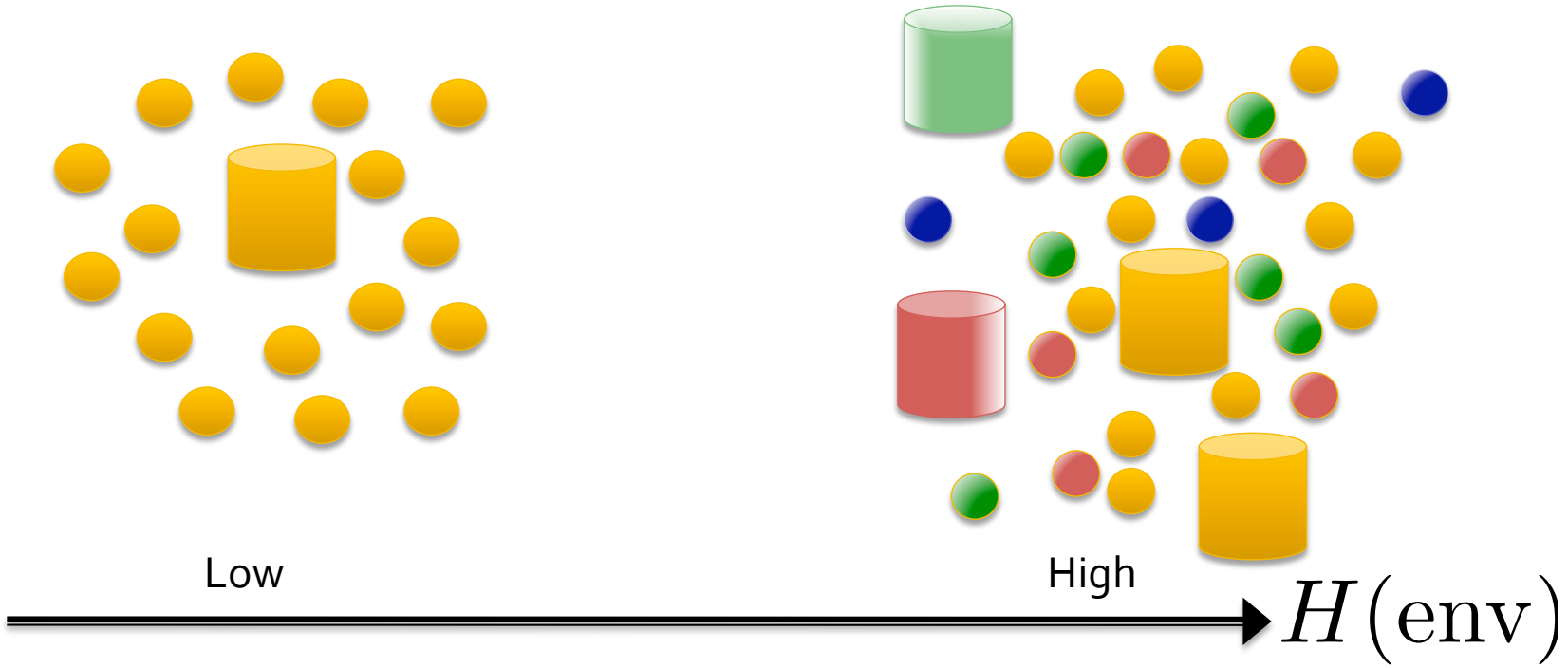
$$E_t = \begin{bmatrix} E_t^{\text{task 1}} \\ \vdots \\ E_t^{\text{task M}} \end{bmatrix}$$

$$E_t^{\text{task j}} = [0\ 1\ 1 \ldots 0\ 0]$$

Information and HuBIRT:
Phase III continued …

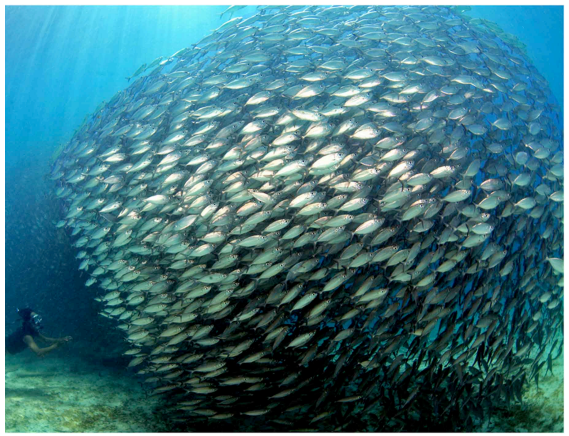
- Semi-random processes

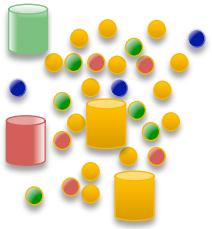
$$\begin{aligned} \text{env} &= [\text{position}, \text{task type}] \\ p(\text{env}) &= p(\text{position})p(\text{task type}) \\ H(\text{env}) &= H(\text{position}) + H(\text{task type}) \end{aligned}$$

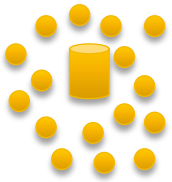


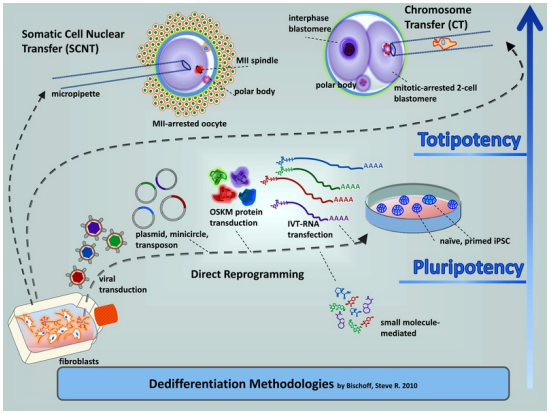
Filling out the Spectrum:
Phase III continued …

- Complexity of Required Collective Behavior





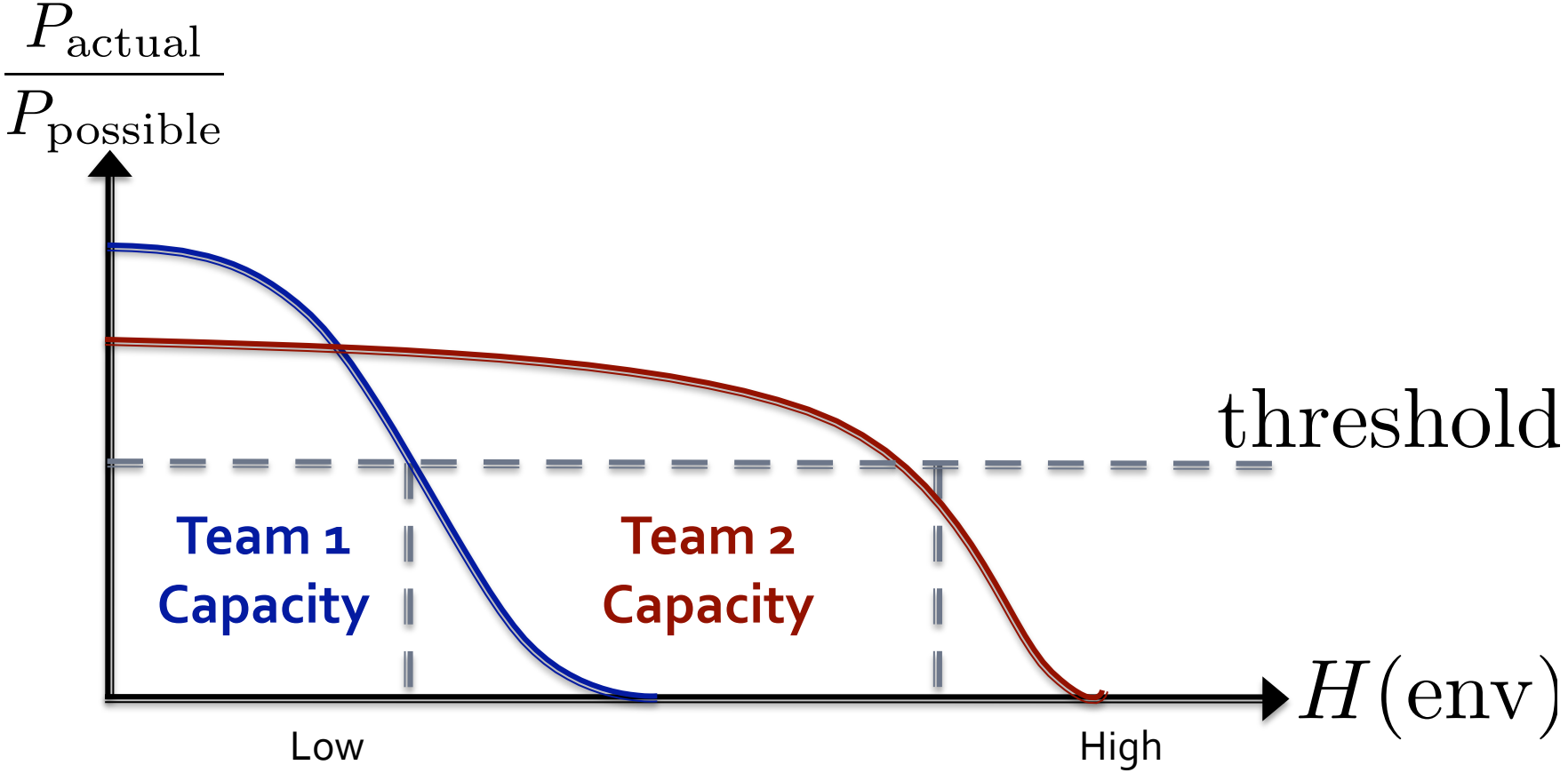




Low → High $H(\text{env})$

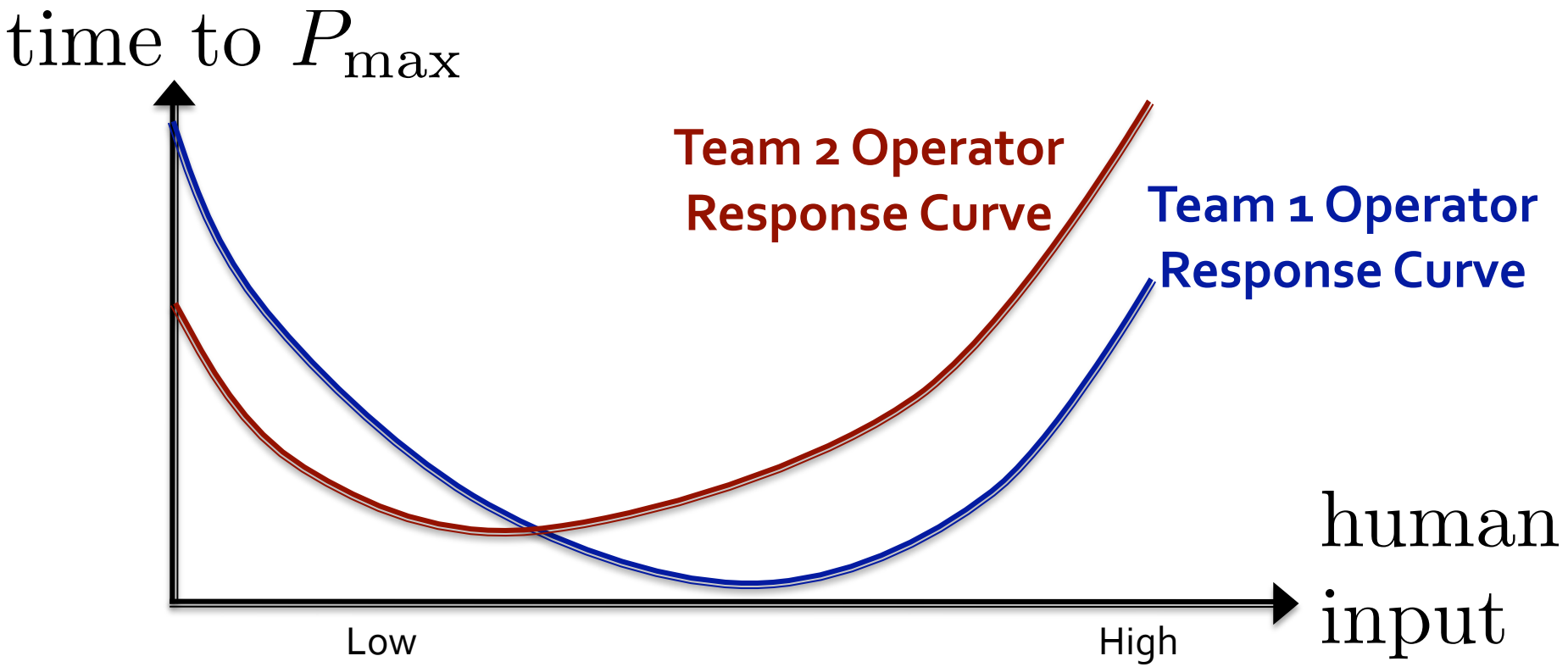
Team Capacity:
Phase III continued …

- Hypothesis: BIRT structures (A_t, E_t) have invariant information-processing capacities



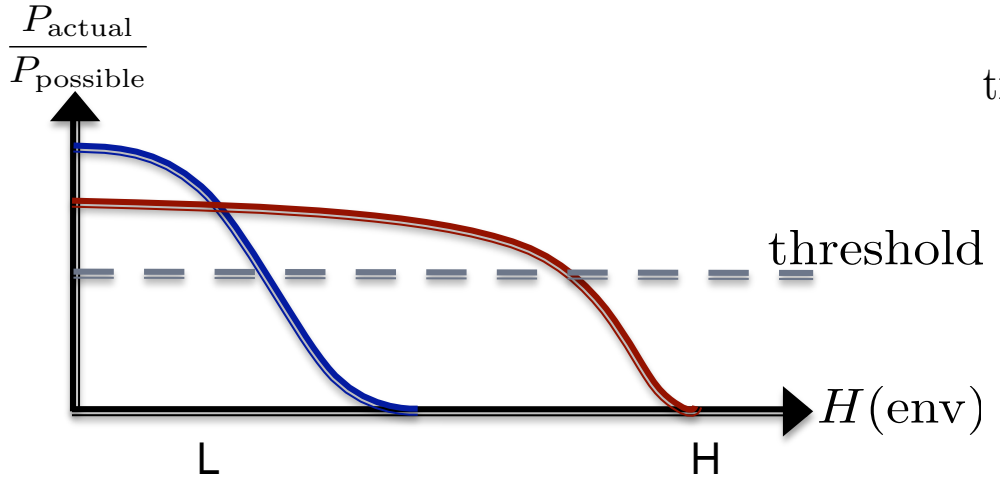
Operator Modulation:
Phase III continued …

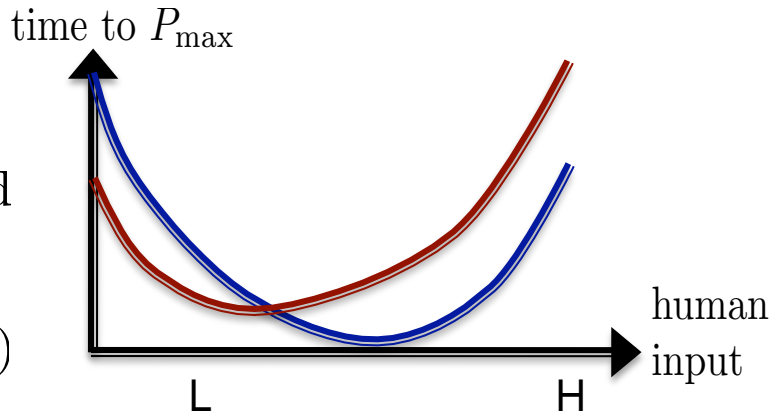
- Hypothesis: HuBIRT structures (A_t, E_t, B_t, C_t) have invariant operator response curves
  - Responsiveness = amount of entropy removed by human



HuBIRT Organizational Tolerance:
Phase III continued …

- Match BIRT structure to environment
- Match HuBIRT structure to human factors constraints





- Organizational tolerance is worst case task rate
- ***Design*** to match organizational and task tolerances

Insights

- *It's easier for a human to manage neighborhood-based teams*
- *Predator-based and Leader-based human interactions offer different advantages*
  - Leader-based models guide a coherent team
  - Predator-based models decohere a team to allow multi-tasking
- *Graph theory formulation and metrics offer design vocabulary for HuBIRT organizations*

Phase IV: Necessity & Sufficiency

- Sufficiency
  - Observability Matrix

$$O(\mathcal{A}_{t,t-1,\ldots t-T}, \mathcal{C}_{t,t-1,\ldots t-T})$$

  - Controllability Matrix

$$R(\mathcal{A}_{t,t-1,\ldots t-T}, \mathcal{B}_{t,t-1,\ldots t-T})$$

  - Characteristic Polynomial and Graph Valence

- Correlates w/ necessity
  - Signal propagation time
  - Probability of decoherence
  - Coherence strength
  - Robustness
  - Mutual Information

Sometimes 2<2x1: Environment Constraints

- Task Saturation
  - Adding more robots won't improve performance
  - Example: 4 small boxes carried by 4 robots versus 4 small boxes carried by 5 robots
- Task Diffusion
  - Task gets harder as sub-tasks are accomplished
  - Example: Mine-sweeping