Entropy and Self-Organizing in Edge Organizations

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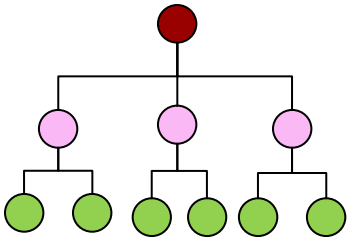
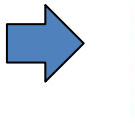
Background

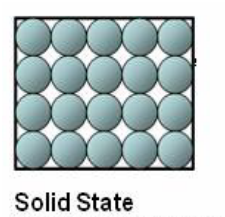
- Edge Organization Research
  - "Power to the Edge", Drs. Alberts & Hayes, 2003
  - Center for Edge Power @ NPS, Dr. Nissen (Director)
- Edge Organization – four tenets (Alberts, 1996)
  - A robustly networked force → Info sharing
  - Info sharing & collaboration → Shared situation awareness
  - Shared situation awareness → Self-synchronization
  - → Drastically increased mission effectiveness
- Edge Organization – Question
  - What is really at work that makes it effective?

Edge Org: An Physical Metaphor

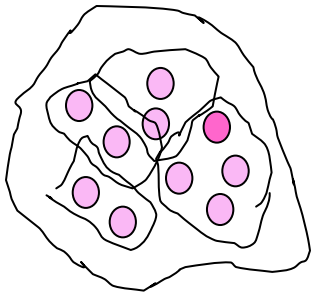


Hierarchical Org

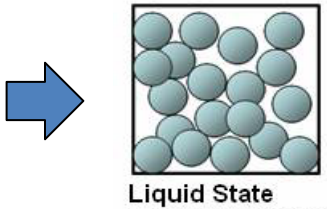




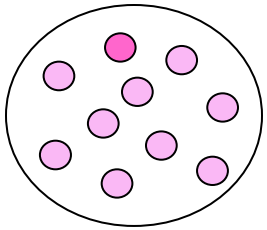
Entropy: Low
Variety: Low
Uncertainty: Low
Complexity: Coherent
Controllability: High



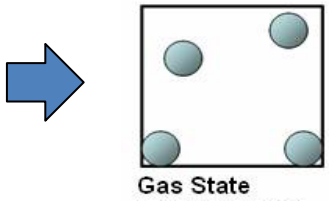
Edge Org

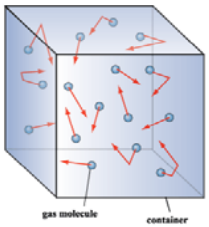


Entropy: Medium
Variety: Medium
Uncertainty: Medium
Complexity: High
Controllability: Low



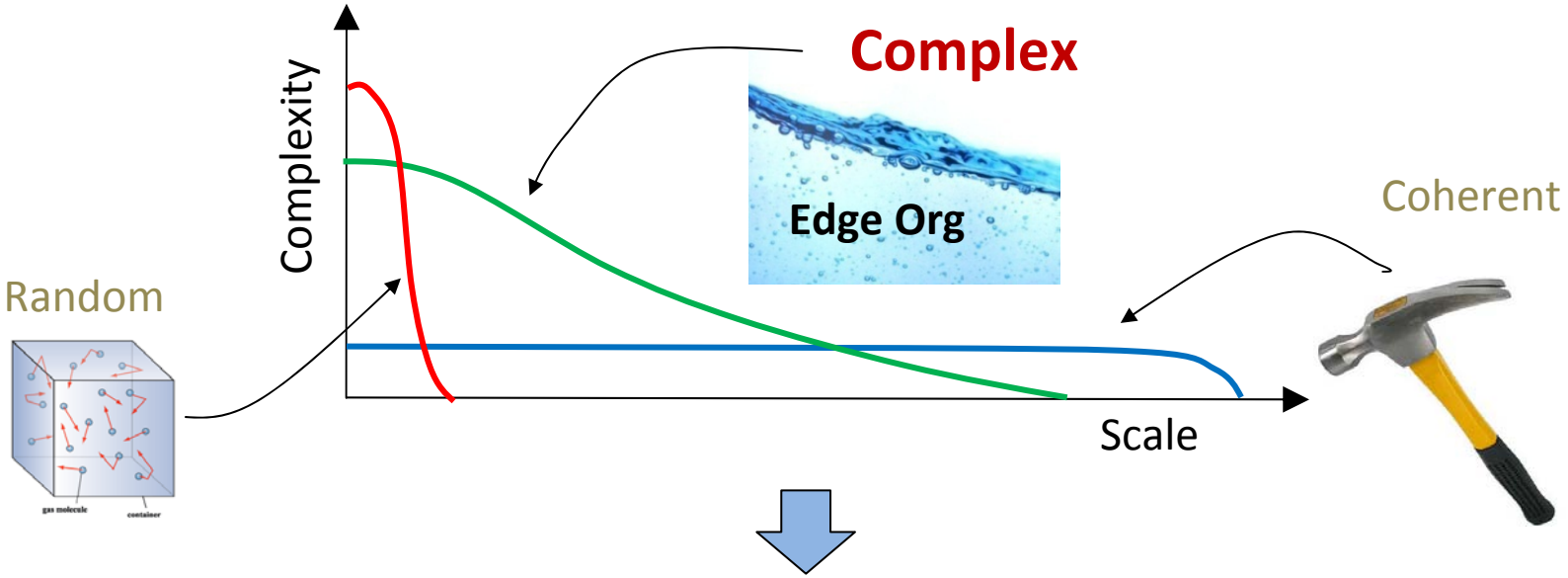
Anarchy





Entropy: High
Variety: High
Uncertainty: High
Complexity: Random
Controllability: None

Edge Org as a Complex System

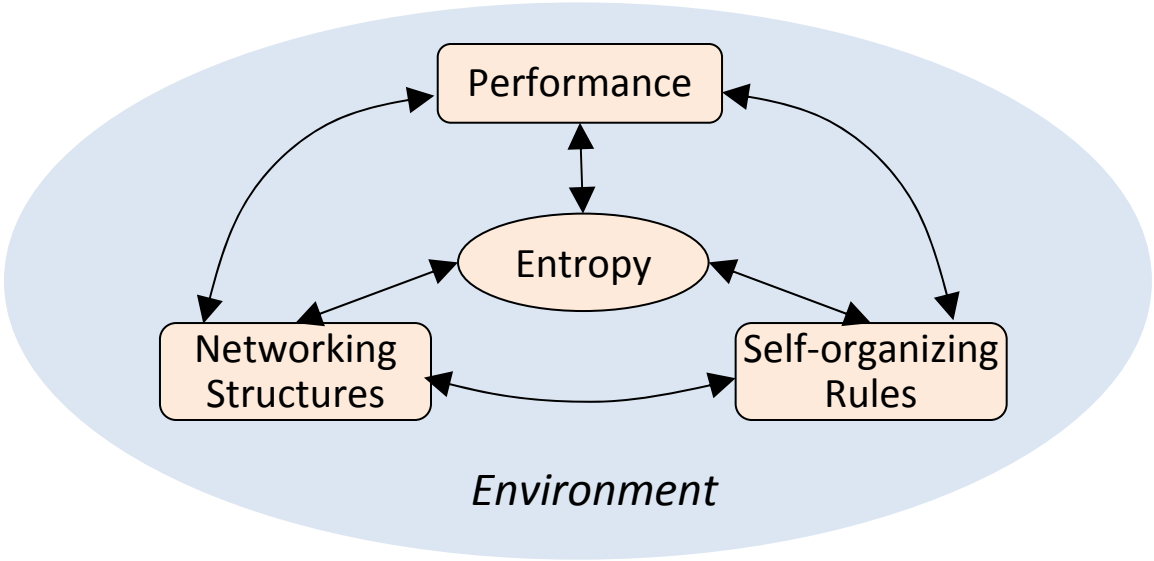


Self Organizing

There must be (dynamically formed) sub/sub-sub and interacting units that can form a variety of "patterns"

A Complex Systems Approach

- Edge organizations as self-organizing complex systems
  - Apply complex systems concepts and methods
  - Conceptualize, characterize, measure, & analyze Edge organizations as complex systems



Hypotheses

- "Fluid" task-dependent structures
- "Fluidity" comes from
  - Low-level freedom and
  - Shared focus/foci
- Effective self-organizing mechanisms
  - Info & energy is needed to sustain self-organizing
  - Work in EOs is done through self-organizing

A Self-Organizing System

$$S_{so} = \{Agt, R_{comm}, R_{cont}, U_{act}, U_{iact}, K_{sh}; T, Env\}$$

where

$Agt = \{a_1, a_2, ...a_N\}$: A finite set of agents

$R_{comm} = \{rm_{a_1a_2}, rm_{a_1a_3}, ..., rm_{a_ia_j}, ..., rn_{a_{N-1}a_N}\}$: Agent comm relations

$R_{cont} = \{rn_{a_1a_2}, rn_{a_1a_3}, ..., rn_{a_ia_j}, ..., rn_{a_{N-1}a_N}\}$: Agent control relations

$U_{act} = \{ua_{a_1a_2}, ua_{a_2}, ..., ua_{a_N}\}$: Agent action rules

$U_{iact} = \{ui_{a_1a_2}, ui_{a_1a_3}, ..., ui_{a_ia_j}, ..., ui_{a_{N-1}a_N}\}$: Agent interaction rules

$K_{sh} = \{k_{a_1a_2a_5a_6}, k_{a_1a_3}, ..., k_{a_ia_ja_ka_la_m}, ...\}$: (Partially) shared knowledge

$T = \{ts_1, ts_2, ..., ts_L\}$: A set of tasks

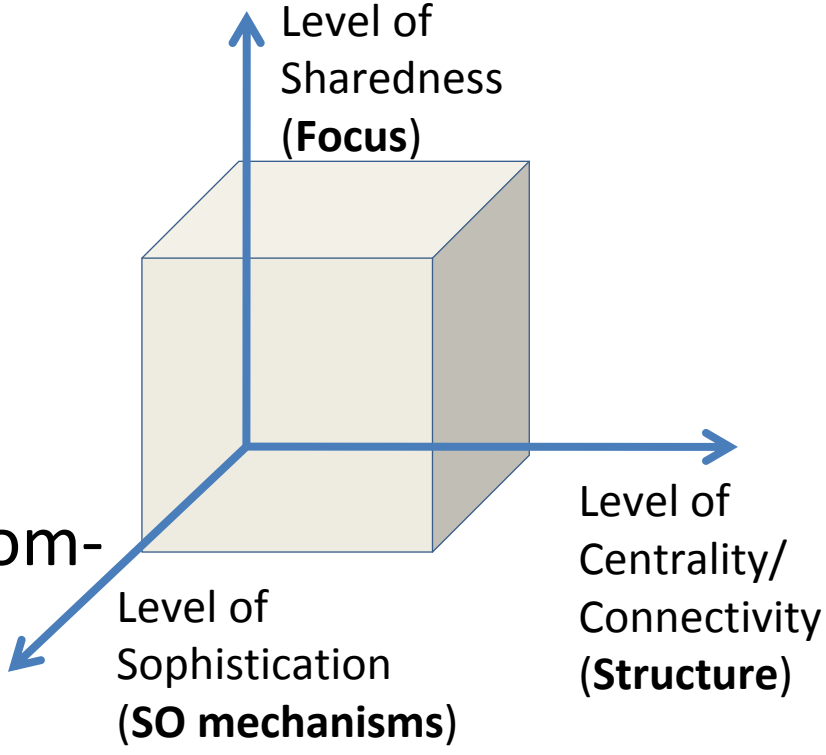
$Env = \{srce_1, srce_2, ...; snke_1, snke_2, ...; srci_1, srci_2, ...; snki_1, snki_2, ...\}$: Environment

Characteristics of SOS/EOs

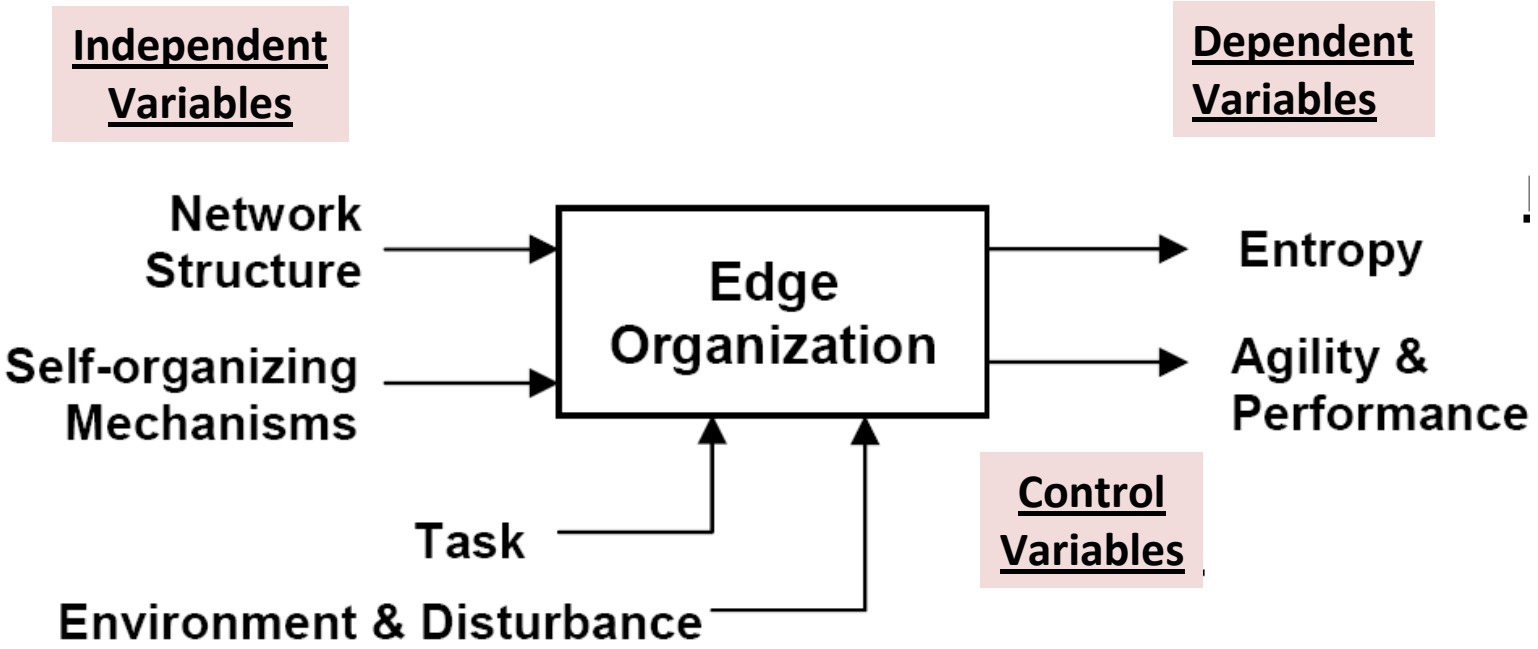
- Homogeneity (homogenous vs. heterogeneous)
  - Degree to which agents share Relations, Rules, & Knowledge
- Connectedness (loosely vs. tightly connected)
  - The level of connections (e.g., degree) of comm and control
- Centrality (centralized vs. decentralized)
  - Degree, closeness, betweenness, clustering coef.
- Sophistication (simple vs. sophisticated)
  - Small Rule sets & Knowledge sets vs. large ones
- Sharedness (weak vs. strong sense of the whole)
  - Level and/or amount of shared knowledge/norm/culture

Explore Space of Edge Organizations

- Focus as sharedness
  - Focus is the key for EO to function effectively
- Structure
  - Fluidity comes from random-ness at bottom level
  - Structure has a big role
- Self-organizing mechanism
  - Simple vs sophisticated SO mechanisms



Model and Simulation Study



Measurement Categories

- Category 1: State of Organizations
  - Organizational Entropy
    - Attrition based measures
    - Spatial situation based measures
    - **Decision-making capability based measures**
  - Situation Awareness
    - Current information distribution
- Category 2: Performance & Agility
  - Performance
    - Mission effectiveness & efficiency
  - Agility
    - Performance agility and fundamental agility

Organization Entropy

- Measure the decision difficulty of the whole organization of N agents

$$Q = \sum_{i}^{N} Q_i = \sum_{i}^{N}\sum_{j}^{K} C(ts_j) \times (AmountOfInformationNeeded)$$

$$= \sum_{i}^{N}\sum_{j}^{K} C(ts_j) \times \left[\sum_{m}^{M} p_{ij}(m) \log(\frac{1}{p_{ij}(m)}) + \sum_{n}^{N-1} p_{ij}(n) \log(\frac{1}{p_{ij}(n)}) \right]$$

where:

M : number of information sources

$p_{ij}(m)$: probability of receiving needed info wrt task ts_j from info source m;

N: total number of agents;

$p_{ij}(n)$: probability of receiving needed info wrt task ts_j from agent n.

Entropy: What Does It Mean for Organizations?

- High level of entropy
  - More chaotic, uncertain, and less functional
  - More adaptive to change, more freedom to discover and innovate
- Low level of entropy
  - More orderly, certain, functional
  - Less opportunities & motivations to change, discover and innovate
  - Less adaptive to environmental changes

Implications

- Equilibrium state
  - When $p_i(n)$'s and $p_i(m)$'s are evenly distributed for all tasks → "No structure at all!", "Anarchy!"
- Information potential
  - Having information potential is a prerequisite for reducing organization entropy
  - More info discovery from the field, input from the environment → more info potential
- Structural entropy vs. potential entropy
  - Hierarchical orgs reduce entropy mostly through fixed structures and top-down flow/potential of information
  - Edge orgs reduce entropy mostly through discovery of field info and dynamically forming local structures
    - Dynamical structuring is driven by dynamical info potential creation

Information Potential

- For a situation item s_l:

$$PI_{s_l} = \frac{2}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}|a_i s_l - a_j s_l| \quad \text{where} \quad a_i s_l = \begin{cases} 1, \text{ if } a_i \text{ is aware of } s_l \\ 0, \text{ if } a_i \text{ is not aware of } s_l \end{cases}$$

$$= \frac{4Ks_l(N - Ks_l)}{N^2} \quad \text{where } Ks_l \text{ is the \# of agents who know } s_l$$

- For all situation items in the field

$$PI = \frac{2}{L \cdot N^2}\sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{j=1}^{N}|a_i s_l - a_j s_l| = \frac{4\sum_{l=1}^{L} Ks_l(N - Ks_l)}{L \cdot N^2}$$

Situation Awareness

- For a given situation item s_l, we have

$$As_{s_l} = \frac{1}{N}\sum_{i=1}^{N} a_i s_l; \quad a_i s_l = \begin{cases} 1, \text{ if } a_i \text{ is aware of } s_l \\ 0, \text{ if } a_i \text{ is not aware of } s_l \end{cases}$$

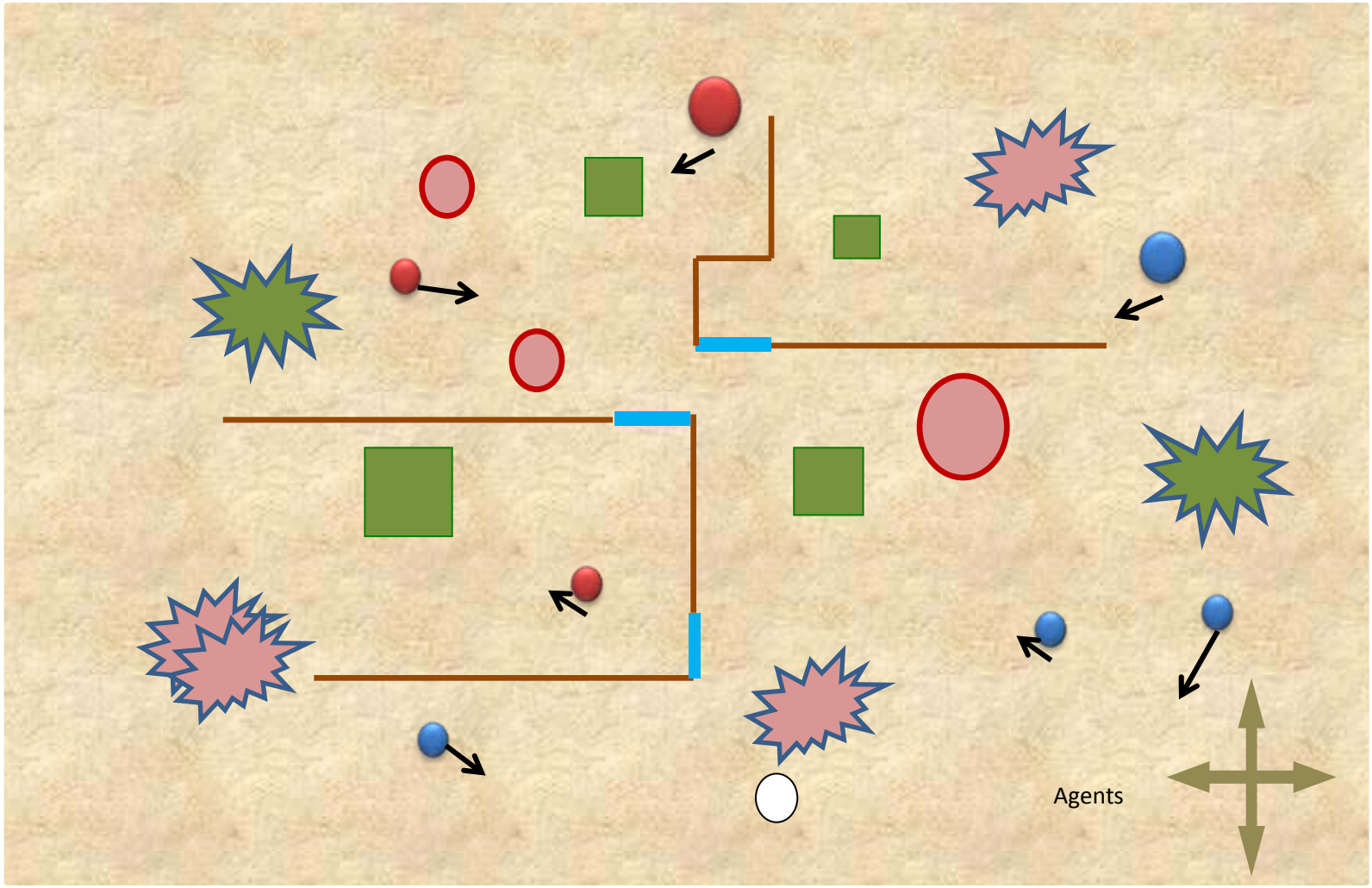
- For all situation items in a field

$$As = \frac{1}{L \cdot N}\sum_{l=1}^{L}\sum_{i=1}^{N} a_i s_l; \quad a_i s_l = \begin{cases} 1, \text{ if } a_i \text{ is aware of } s_l \\ 0, \text{ if } a_i \text{ is not aware of } s_l \end{cases}$$

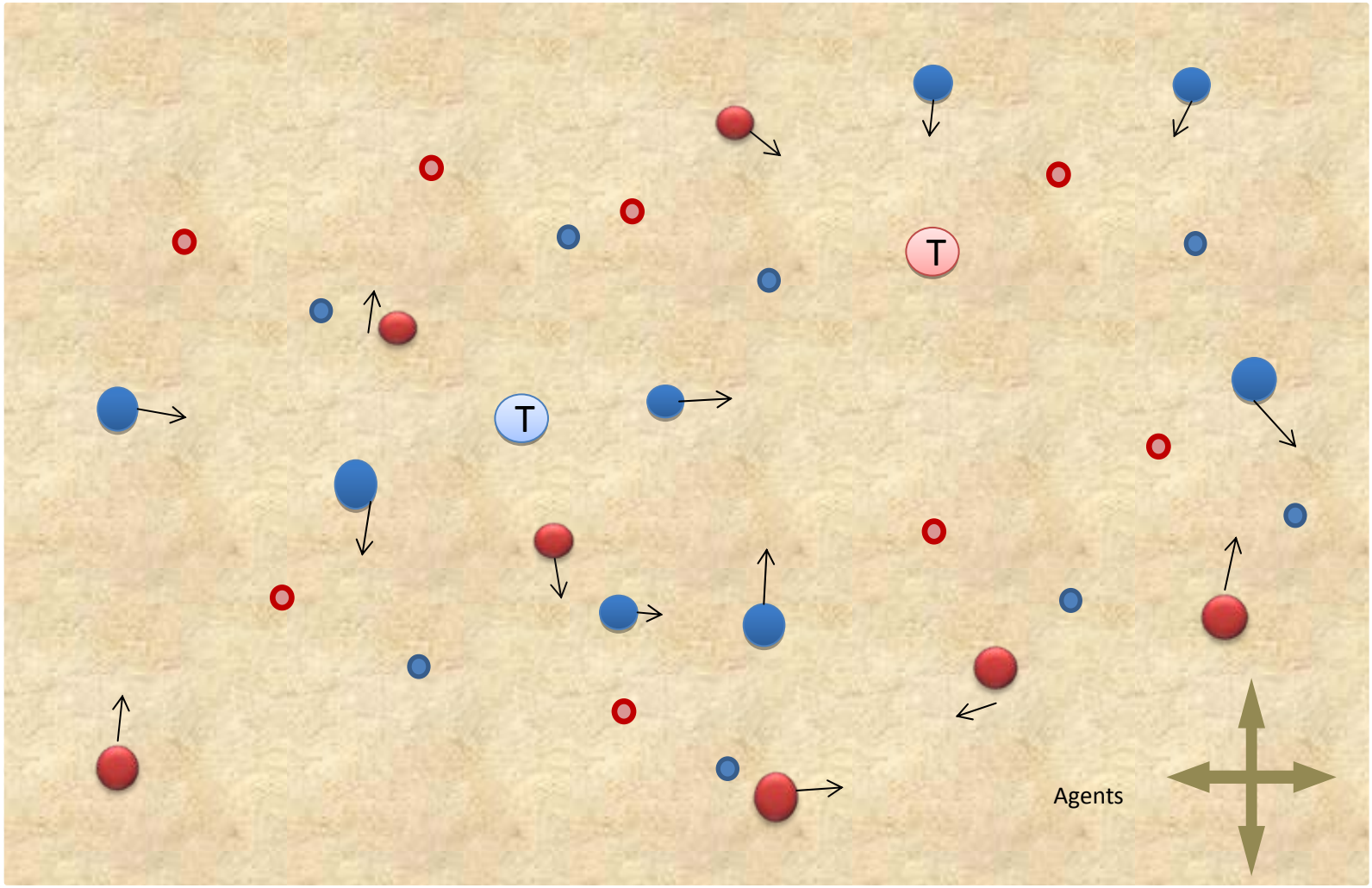
Implications

- Matching structure and info potential
  - Info flow depends on not only structure & info potential, but also the matching between the two
  - Mismatch leads to higher level of entropy
  - Dynamic situation changes cause mismatch
- Equilibrium state
  - No one knows anything → no info potential
    - No one can do anything -> no sense of org/order
  - Everyone knows everything → no info potential
    - Everyone knows what to do -> no sense of org/order

Simulation Scenario

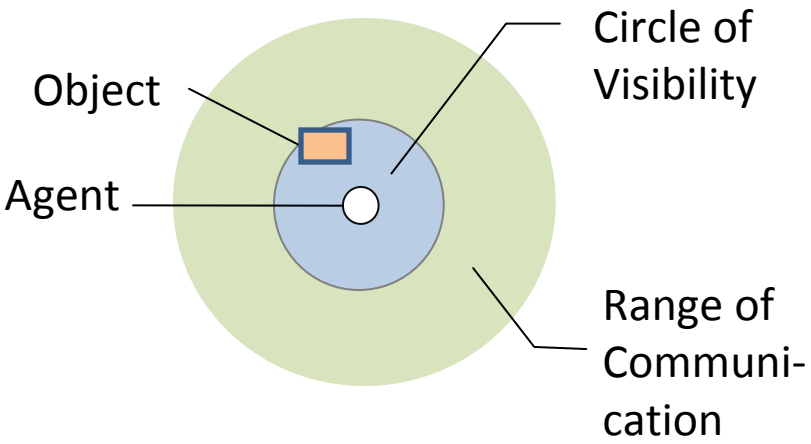


Simulation Scenario

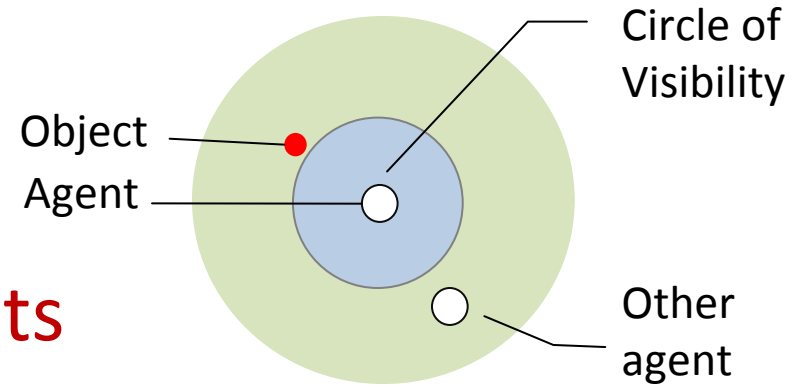


Agent

- Properties
  - Party: friend & enemy (color coded)
  - Capability: low level & high level (circle size coded)
  - Location & speed: (x, y) & (vx, vy) (grid coded)
- Basic actions
  - Sensing
    - Visible range
      - Identify objects
    - Communication range
      - Identify other agents
  - Moving
    - Random move on X and Y direction
    - Attracted to the attractors, move away from traps



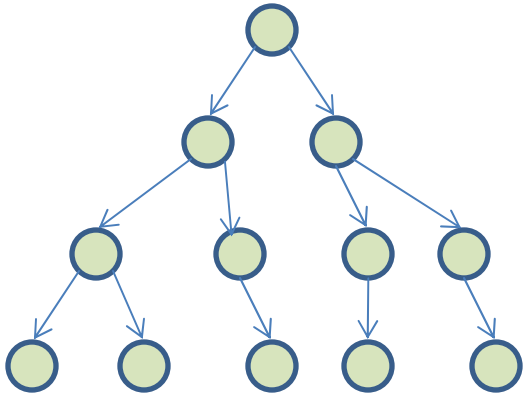
Agent Interactions



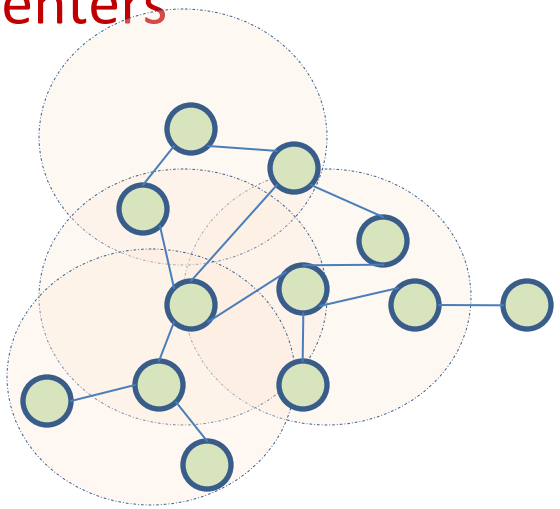
- Identify each other
  - Identify others
- Register connected agents
  - Keep a list of currently in-range agents
  - Remove an agent from the list once it moved away
- Send/receive information to/from each other
  - Broadcast info to connected agents once available
- Emerge dynamical structures
  - Such additive structuring tends to create “scale free” networks → potential local hierarchies

Hierarchy vs. Self-Organizing

- Hierarchy
  - Plan based
  - Static
  - Control structure ≈ Comm structure
  - Commander is the center



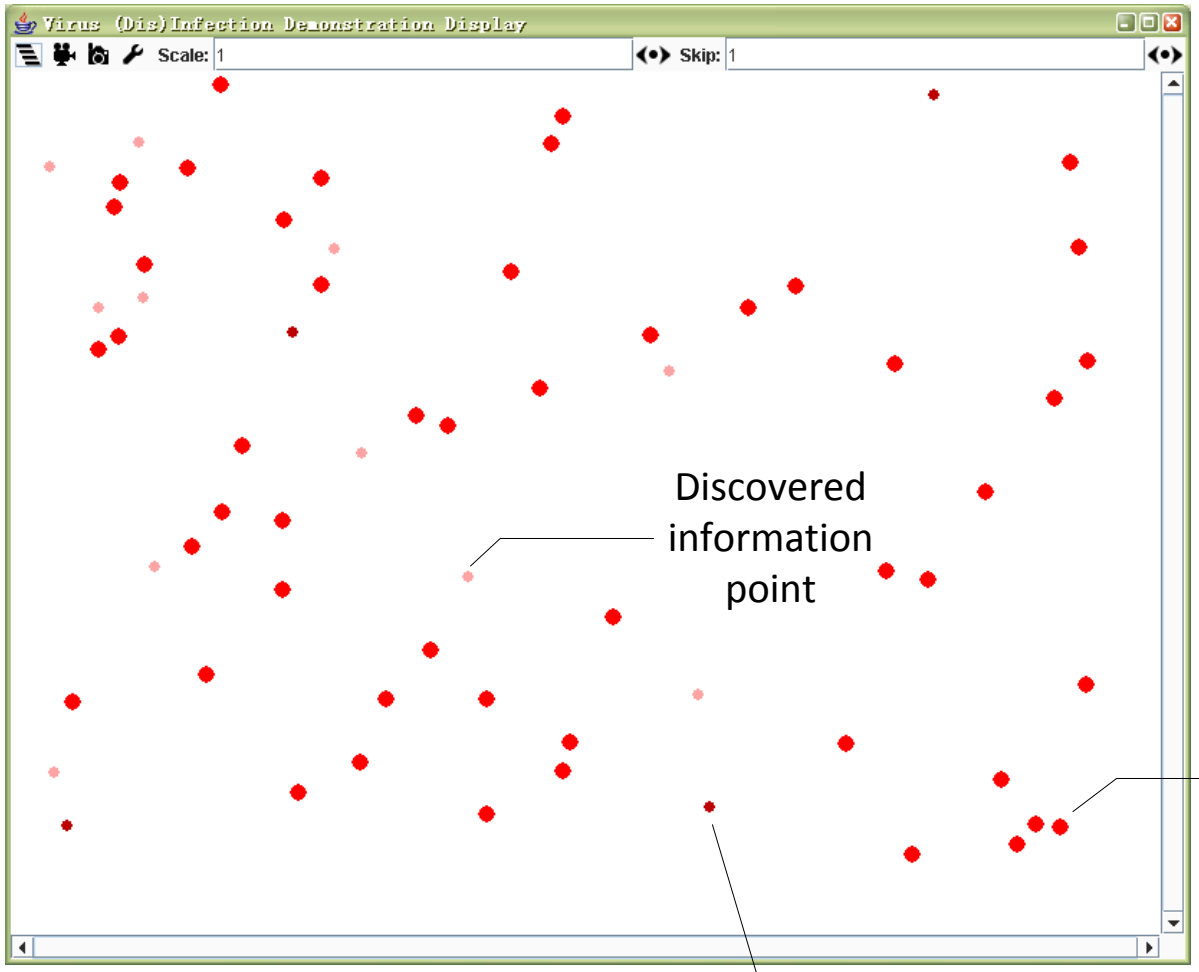
- Self-organizing
  - Field/task driven
  - Dynamic
  - Control depends on SO rules
  - Ones who have more info and connections are the centers



Actions & Interactions

Actions/i-Actions	Rules
Sense: Recognize situation items and agents	1) Put all situation items within the visibility range into the *recognized-situation-list*. 2) Remove situation items out of the recognized list when they are out of the range 3) Put all agents within the communication range into the *recognized-agent-list*. 4) Remove agents out of the recognized list when they are out of the range
Move: Change location (x,y) one step at a time	1) Move randomly in x or y direction if no valuable area, trap or block is recognized. 2) Move toward the closest valuable area if one or more valuable areas are recognized. 3) Move away from traps if recognized. 4) Avoid blocks and find passages toward valuable areas if needed.
Communicate: Pass *Ko* & *Ks* to others when potential exists	1) In *Hierarchy* setting, communicate only with those who are on a pre-defined hierarchical communication list. 2) In *Edge* setting, communicate with all those who are on *recognized-agent-list*.
Collaborate: Help other when requested	1) In *Hierarchy* setting, collaborate with only those with whom a pre-defined control link exist. 2) In *Edge* setting, collaborate with all those who are on *recognized-agent-list*.
Stay: No action for the next move	1) Stay with a valuable areas whenever the agent is in the area. 2) Stay with a trap whenever the agent is trapped.

Simulation 1



Organizational Properties:

Homogeneity

Homogeneous

Connectedness

R=20/40/60

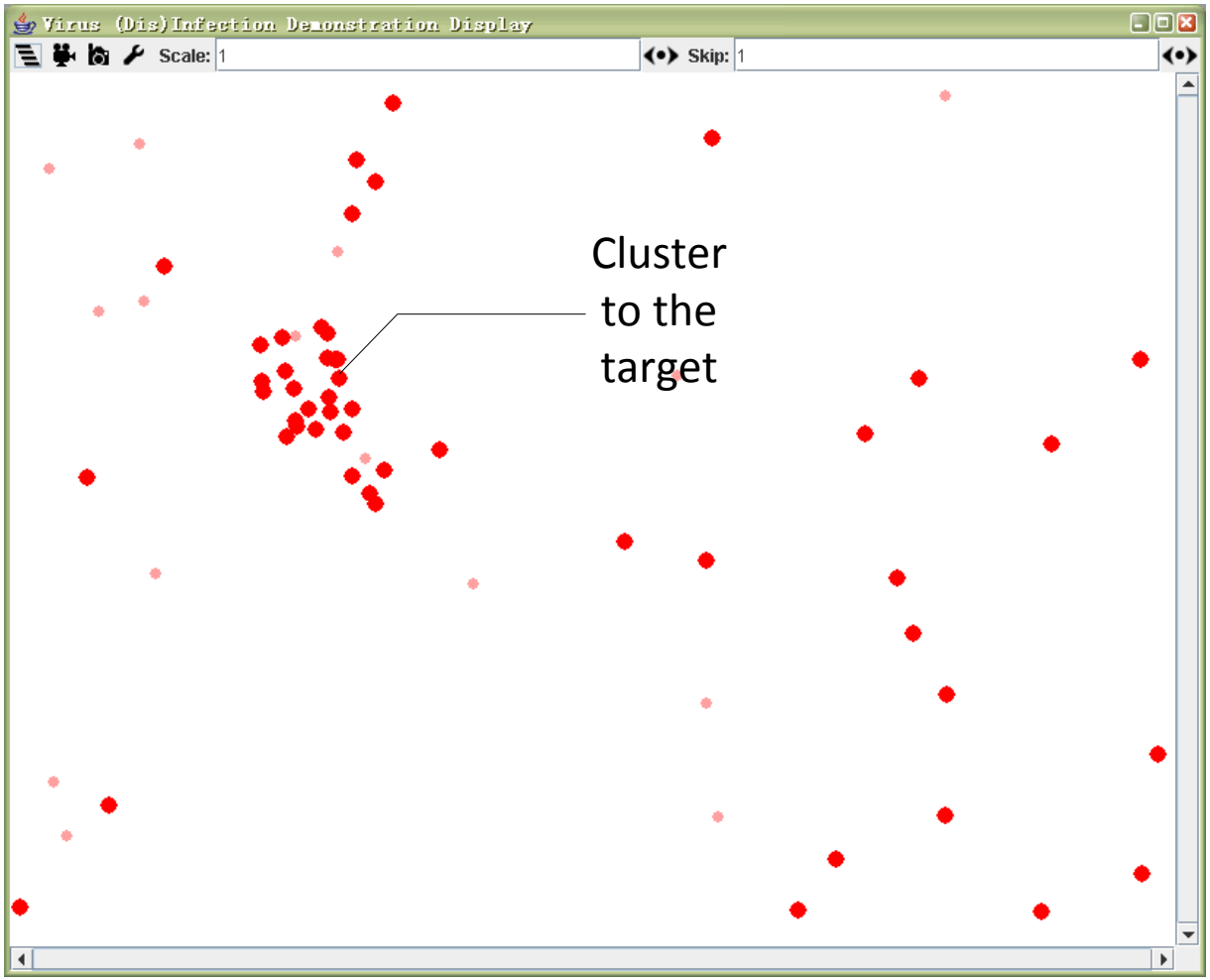
Centrality

Fully decentralized

Sophistication

None

Simulation 1



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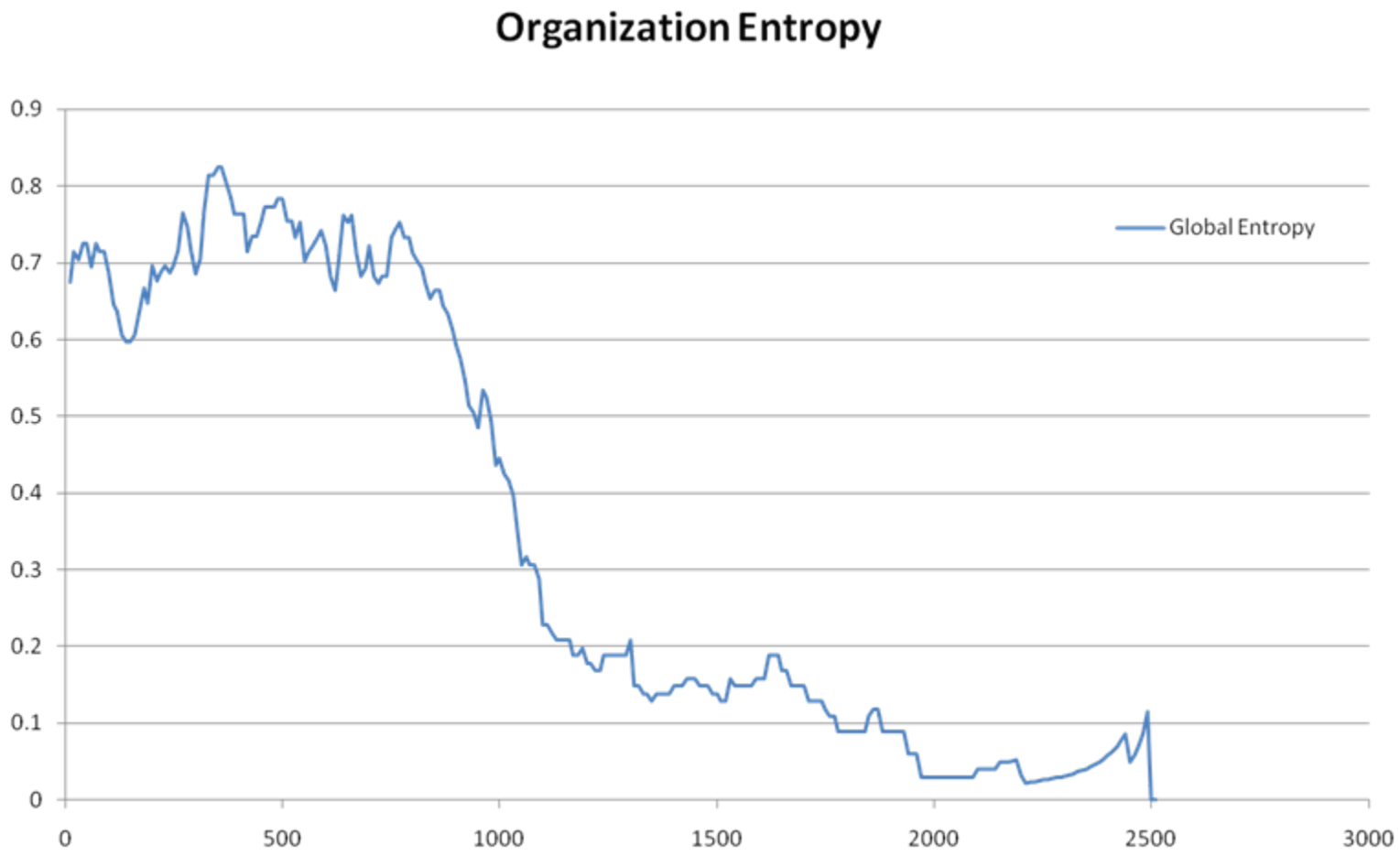
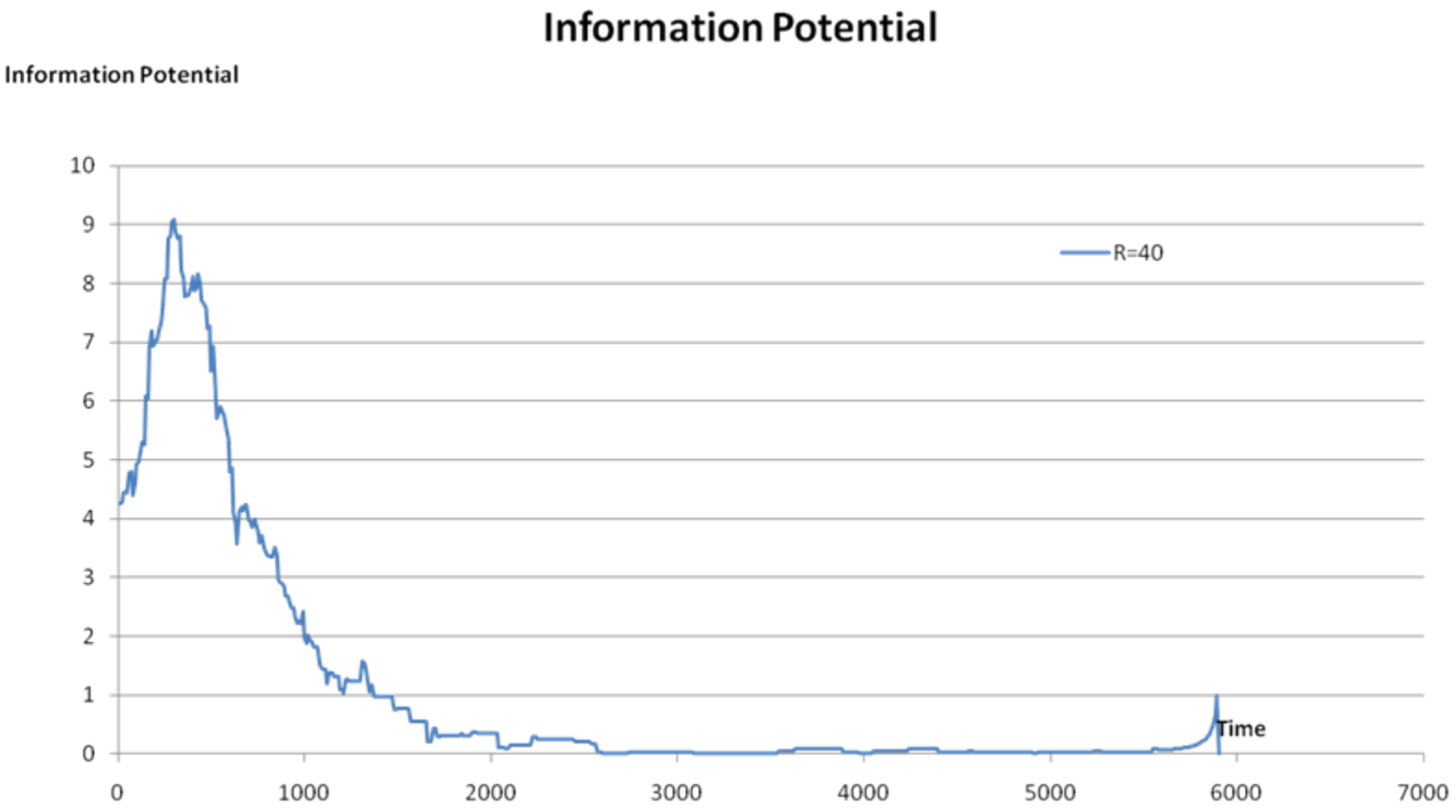
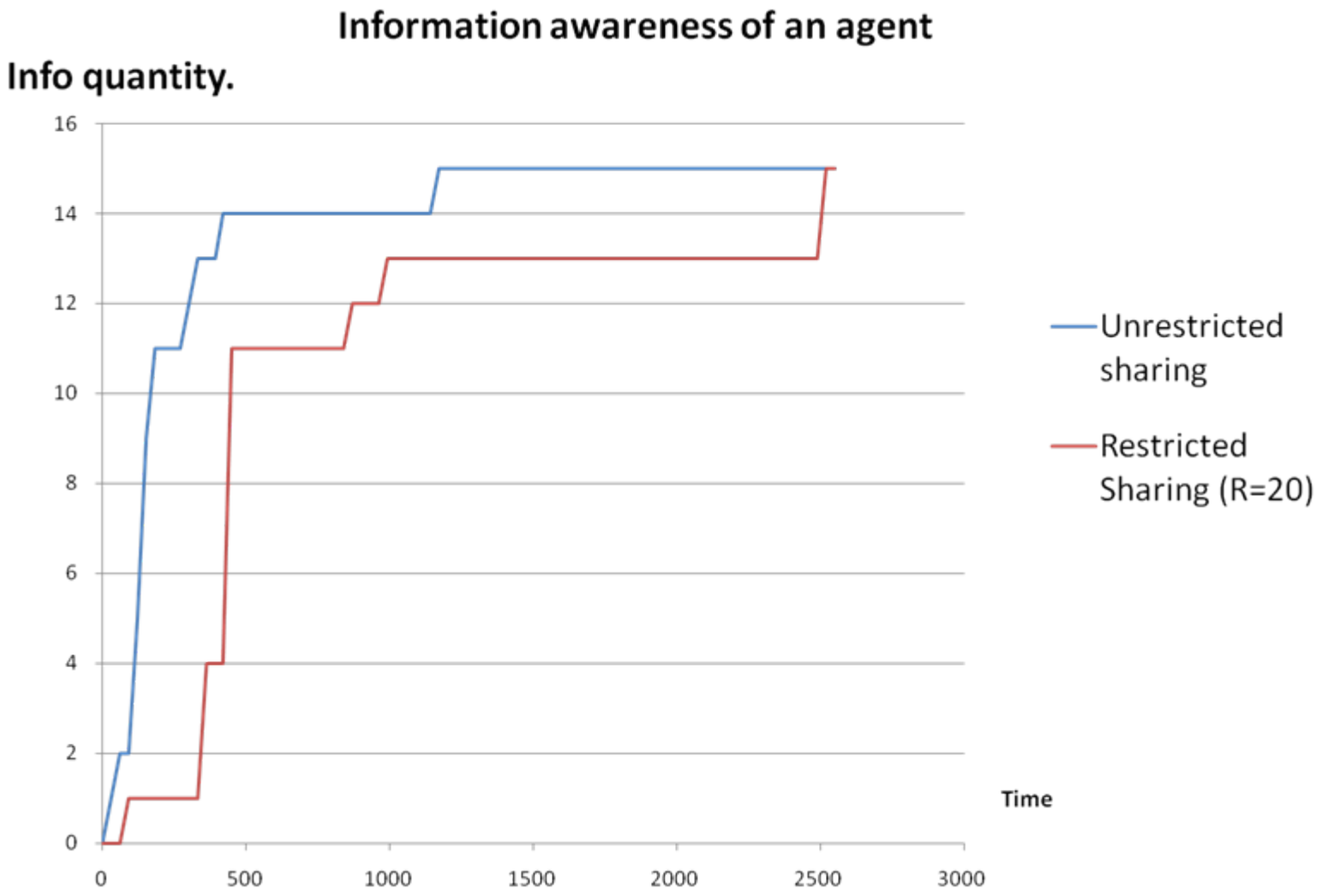
Organization Entropy



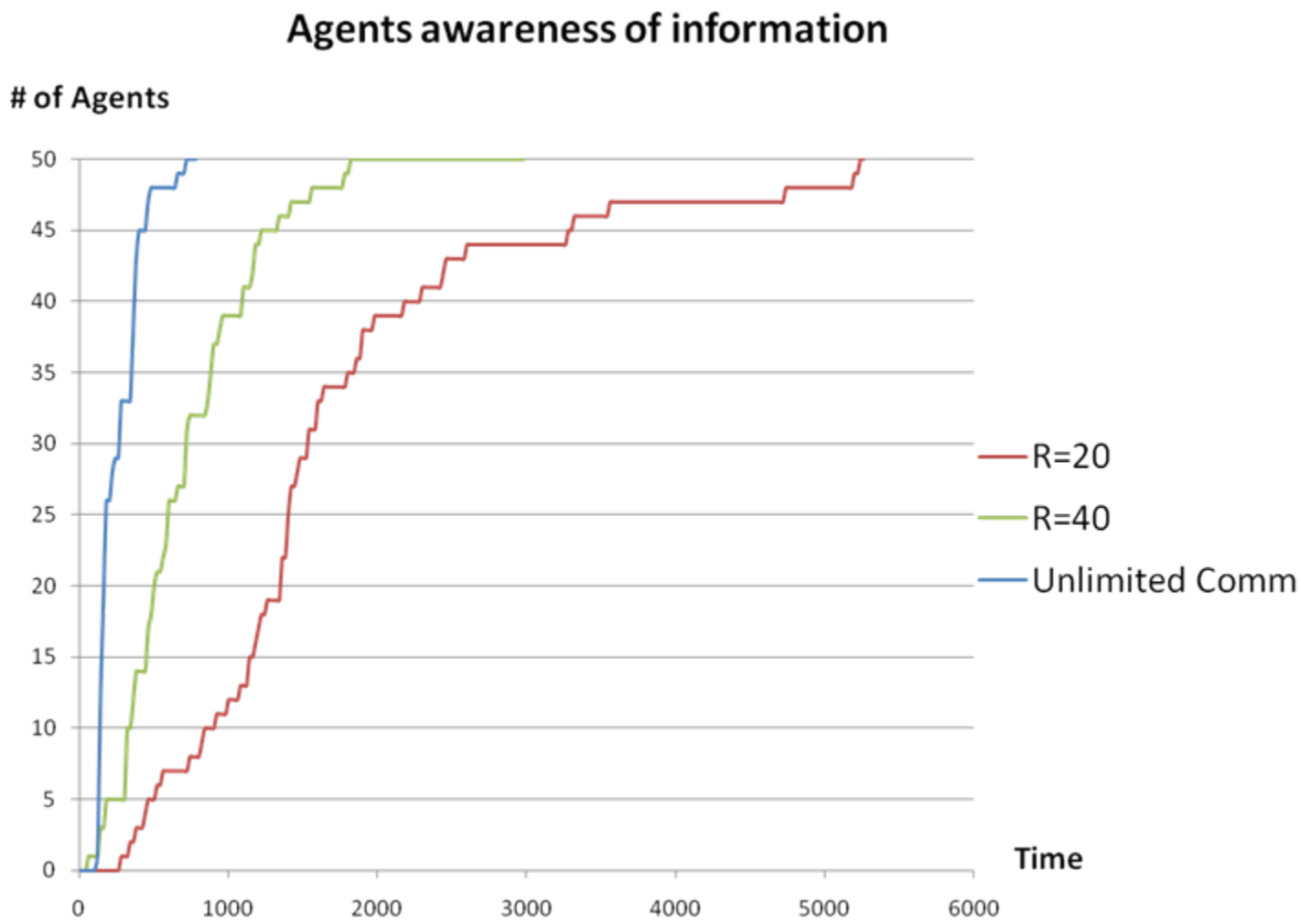
Information Potential



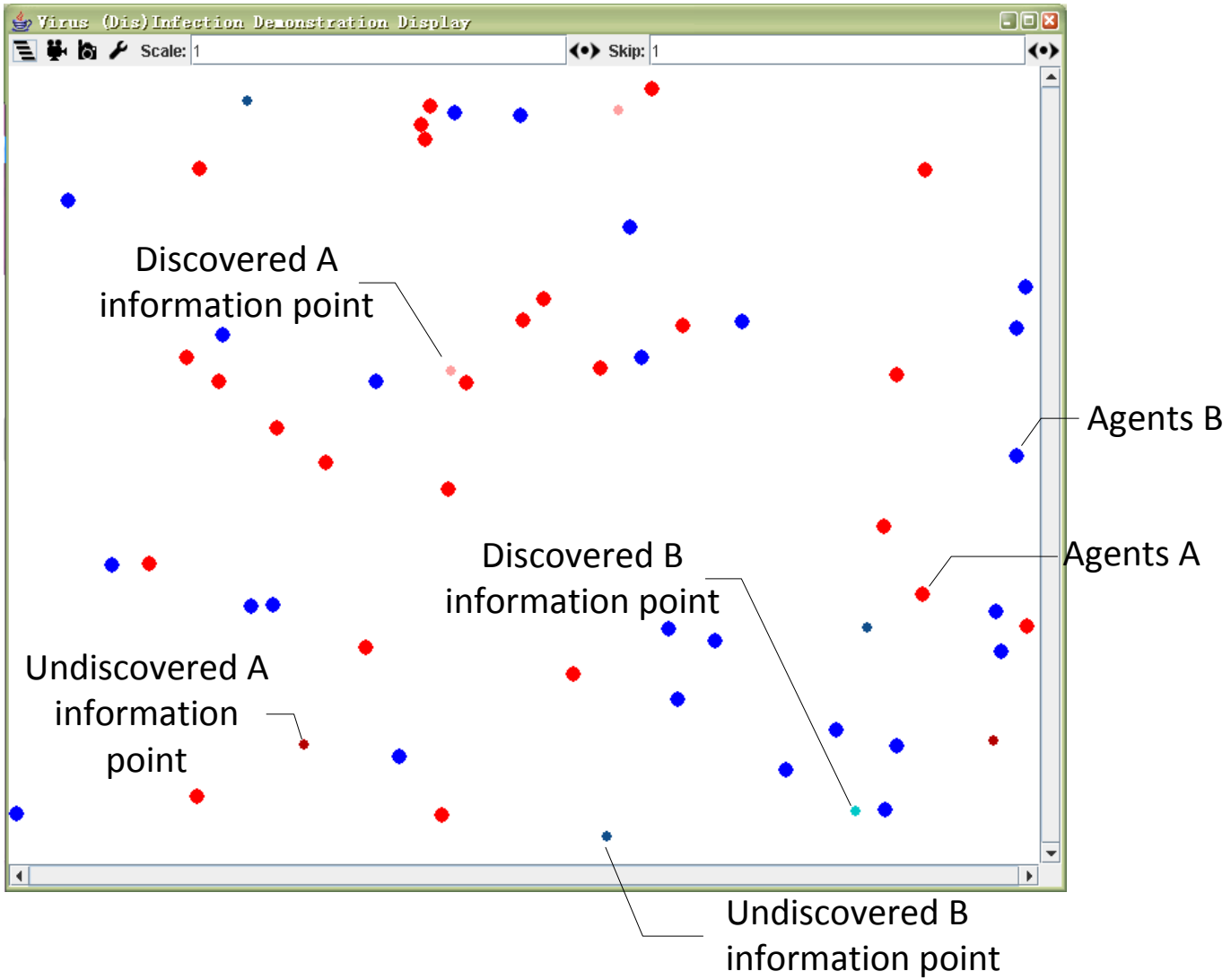
Situation Awareness of Agents



Agents Situation Awareness



Simulation 2



What Brings Fluidity & Order?

- Situated & dynamical communication
  - Situation driven networking and structuring
  - When situation is unknown
    - Entropy is high, order is low
    - Agents do what they are locally motivated to do → high level of fluidity/variety
  - As the picture of the field situation emerges
    - Self-organizing rules start to "move" information and reduce EO entropy → high level of order
- High-level of sharedness/focus
  - Brings in more order and reduces entropy through self-organizing

How to Make Entropy Low?

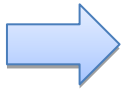
- Self-organizing
  - Dynamically create local structures
  - Low degree or scale free structures are preferable
- Create information potential
  - New information supplied to Edge Orgs from Env leads to externally created info potential
  - Discoveries by agents generate new information to be propagated to others → internal information potential

What Is at Work?

- Edging, Converging, and Focus/Foci
  - Dynamic & effective combination of Edging and Converging guided by Focus/foci is the key to effective Edge Organizations
- Edging
  - A process to discover new info and tasks – High entropy
- Converging
  - A self-organizing process to execute tasks – Low entropy
- Focus/Foci
  - The knowledge that translates info into tasks
  - Can be either predefined or discovered dynamically
  - Can be either local or widely shared

Ongoing Studies

- More complete mission process
  - Info discovery
  - Info sharing
  - Info processing
  - Decision making
  - Action & Interaction
  - Result assessment
  - Learning and institutionalization



Edge Approach
Vs.
Hierarchical Approach

- Comparative Studies
  - Compare Hierarchies and Edge Organizations
  - Compare results with other EO research groups: ELICIT and POW-ER

Summary

- A physical metaphor of edge organizations
- An information flow based organizational entropy measure
- Measures of information potential and situation awareness
- Edging and converging processes for agility
- An agent-based simulation framework and scenarios