

**Decentralization  
and stigmergy**

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**Abstract**

Human and computational systems increasingly rely on

- decentralized structures
- communication via the environment (stigmergy) rather than only via messages.

We look at

- communication among social insects
- changes in business and social structures made possible by Internet computing

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**Related topics**

- Problems of mathematically modeling stigmergic and decentralized computational behavior
- swarm computing
- evolutionary computation
- emergent behavior
- self-organization

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**Outline**

1. The network society
2. Bees and ants
3. Power of indirect interaction
4. Power of decentralization

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**1. The network society**

*Hypotheses about the information revolution*

- individualization of work (Castells)
- fragmentation of society (Castells)
- evolution of education as collaboration and as learner’s construction of own knowledge
- centralization and **decentralization** of power and production
- social polarization (Castells)
- “culture of real virtuality” (Castells)

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**Decentralization of work**

- A fundamental change in work: “the individualization of labor in the labor process” (Castells)
- A reversal of the socialization of production
- **Management becomes decentralized**, markets become customized, work segmented, and societies fragmented
- Work time, job stability, location of work, and the social contract between employer and employee undergo changes

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## The global networked economy

- *Key new element:* In a self-feeding spiral, progress in management, knowledge, and technology is applied to these same three things
- Compare with individual human learning, in which key element is *self-reflection*
- *Conjecture:* As the brain's neurons and their local connections provide infrastructure for self-reflection, likewise information technology provides infrastructure for the self-feeding spiral of the networked economy

## The network enterprise

- *Thesis:* Informational-global economy is associated with “a new organizational logic” that converges and interacts with new technological paradigm
- Mass production is converted to flexible production
- **Crisis, not of the large corporation, but of its traditional form of hierarchical, vertical integration and functional management**

## Organizational forms

- Inter-firm networking
- Corporate strategic alliances for specific aims, coexisting with competition
- Shift from vertical bureaucracies to the horizontal corporation
  - flat hierarchy
  - organization around process not task
  - team management
  - customer-satisfaction-driven
  - retraining of employees
  - decentralization

## Networks restructure society

- Power relationships are made susceptible to major change by network organization of society
- Power is held by people at the interfaces between networks
- Global capitalist society is structured around a network of financial flows
- Dominant functions in society are organized in networks, subordinate ones are fragmented

## Wisdom of crowds

- *Necessary conditions:*
  - Diversity
  - Independence
  - A “certain kind” of decentralization (Surowiecki, 2004)
- Decentralized communication requires support media for collective wisdom to develop; e.g., stock market

## 2. Bees and ants

- Bees communicate direction and distance of pollen sources by “waggle dance”, an example of *message passing*
- Ants communicate via pheromone trails; the “message” is the entire trail followed by an ant, i.e., no single ant sends a message to another single ant
- *Conjecture:* Difference in means of communication is due to difference in foraging environments

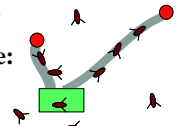
## Food foraging problem for ants

- Food is scattered randomly
- Task is to take it to the nest
- Ants are small and limited in intelligence and communicating power
- Food may appear or disappear dynamically
- *A solution:*
  - Ants walk semi-randomly dropping pheromone
  - Ants tend also to follow pheromone trails
  - Ants carrying food drop special pheromone
  - Trails evolve toward short paths between nest and food

## Stigmergy in nature

### 1. Termites gathering chips into pile:

Move at random, pick up chip when encountered, put down when another chip found; the pile structure is used to coordinate creation of pile (*StarLogo*)



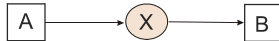
### 2. Slime mold dividing and aggregating:

These amoeba may aggregate by emitting a chemical, migrating toward its greatest concentration

**Q: Is stigmergy essential for some missions?**

## Multi-stream and indirect interaction

- *Multi-stream interaction* occurs when an entity is concurrently interacting with more than one other entity
- Let  $A$  and  $E$  interact asynchronously. If  $E$  may be decomposed into  $E'$  and  $B$ , where  $E' = E - \{B\}$ , then  $A$  and  $B$  *interact indirectly* via  $E$  iff mutual causality holds between the behaviors of  $A$  and  $B$ .



## 3. Power of decentralization

- The brain
- Markets
- Democracy
- Growing military strength of networks
- *Is decentralized coordination more powerful than centralized hierarchy?*

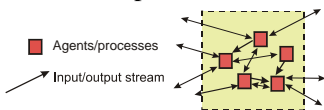
## Decentralized “design”

- *Example artifacts:*
  - The Internet
  - Natural language
  - Human society and culture
  - Evolution of life
- Are any *centralized* processes capable of producing equally good results as current *decentralized* processes?

## Multi-stream interaction

- In contrast to sequential interaction, multi-stream interaction may feature:

- *Nondeterminism* when attempts to write collide
- *Dynamic linking and unlinking, creation/destruction of nodes*
- *Indirect interaction via a shared environment*



## Decentralized, self-organizing systems

- Decentralized and self-organizing systems lend themselves to flexibility and adaptiveness
- Where required:* in environments that are dynamic, persistent, multi-agent, decentralized, and self-organizing.

**Decentralized system:** a multi-agent system whose components do not respond to commands from an active director or manager component, and do not execute prespecified synchronized roles under a design or plan.

**Self-organizing system:** a multi-agent system with a coherent global structure or pattern shaped by local interactions among components, rather than by external forces.

## 4. Power of indirect interaction

- Stigmergy enables agents to interact with more other agents without communications and storage overhead
- Asynchronous multi-stream interaction entails nondeterminism, an element of evolutionary adaptation
- Example:* creation of a pheromone trail *exploits* past experience and *explores* an unknown foraging trail space

## Indirect interaction and multi-agent systems

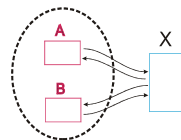
- In a MAS characterized by *locality* of interaction and *mobility* of agents, it is only possible for agents to influence overall system behavior by use of indirect interaction
- Richness of multiagent interaction:
  - It is due partly to ability of each agent to interact with multiple others
  - Hence each agent interacts indirectly with *all* others (otherwise system partitions)

## The message-passing model of concurrency

- Due to Robin Milner: CCS,  $\pi$  Calculus; associated with theory of concurrency and with process algebra
- These models capture the notion of *direct interaction* by *message passing*
- Axiom of concurrency theory: *interaction = message passing* i.e., atomic communication of a *message* from one *process* to another (targeted send/receive)
- Shared variables are deemed *processes*

## Limitations of the message-passing model

- Message passing does not support properties of indirect interaction: anonymity, asynchrony, space decoupling, non-intentionality, and late binding
- Embedded and situated systems aren't supported
- Suppose agents *A* and *B* communicate via shared variable *X*
  - The message-passing model accounts for *direct*  $A \leftrightarrow X$  and  $B \leftrightarrow X$  interaction .
  - ...but not between *A* and *B* via *X*



## Unscalability of message passing

- Motivation:* As unscalable architectures in AI are *brittle* and will fail in realistic settings (R. Brooks), likewise for unscalable MAS architectures and models
- Hypothesis:* As the number of agents rises asymptotically, either number of connections grows too fast, or else paths between agents become too long
- Other dimensions to show unscalability:
  - Synchronization vs. asynchrony
  - Centralized vs. decentralized storage

## Some notions of MAS scalability

- *Scalable MAS instance*: one that can perform a class of missions (hence satisfying their constraints) regardless of the number of agents  $nA$  or environmental entities  $nE$
- *Statically-scalable MAS* (w.r.t. a class of missions): one that is scalable under the assumption that agents and environmental entities are present at startup time
- *Dynamically-scalable MAS*: one that is scalable under the more rigorous assumption that agents and environmental entities may appear or disappear during execution

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