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

Related topics

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

Outline

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

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)

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

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

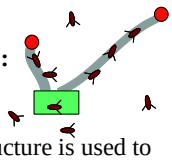
2. Bees and ants

- 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



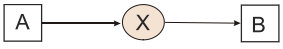
1.Termites gathering chips into pile: Move at random, pick up chip when encountered, put down when another chip found; the pile structure is used to coordinate creation of pile (*StarLogo*)

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

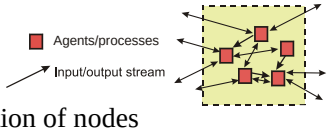
- The brain
- Markets
- Democracy
- Growing military strength of networks
- *Is decentralized coordination more powerful than centralized hierarchy?*

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

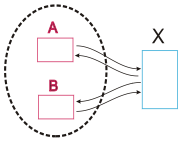
- In a MAS characterized by *locality* of interaction and *mobility* of agents, it is only possible for agents to influence overall system behavior by use of indirect interaction
- Richness of multiagent interaction:
  - It is due partly to ability of each agent to interact with multiple others
  - Hence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

The message-passing model of concurrency

- Due to Robin Milner: CCS, π 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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