Modeling Indirect Interaction in Open Computational Systems

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Our contribution
- Motivation: Design requires models
- Inspiration: Examples from natural systems
- We identify two distinct kinds of interaction
- Indirect interaction makes possible a richer set of behaviors in open computational systems than direct interaction alone
- Models that represent indirect interaction explicitly are more expressive

Some interaction patterns in natural systems
1. Termites gathering chips into a pile
   Protocol: Move at random, pick up chip when encountered, put down when another found
2. Ants foraging for food forming trails
   Ants leave chemical trail, prefer existing trails, blaze shorter and shorter trails to and from food
3. Slime mold dividing and forming aggregate
   These amoeba may aggregate by emitting chemical, migrating toward its greatest concentration

What is the common feature?
In these systems, organisms communicate
- to coordinate their behavior
- in a decentralized way
- via their shared environment

Interactive computation
- Open systems are interactive
- Interaction features interleaved, dynamically generated stream I/O (Goldin et al, 2001)
- Contrasts to algorithmic computation, such as that modeled by Turing machines, in which inputs are all precomputed

Direct interaction
- This is the only kind of interaction modeled in concurrency theory
- Agent accesses to shared memory are represented by elevating shared memory to process status (Milner, 1993)
Indirect interaction

Interaction via persistent, observable state changes, in which the destination of output is any agent that observes these state changes.

- Agents A and B (right) may interact with each other indirectly via shared variable $x$.
- Features:
  - anonymity (recipient ID not used in access)
  - time delay (state changes persist)
  - space decoupling (agents A, B need not meet)

Blackboard systems (Corkill, 1991):
- a collaboration technology that uses indirect interaction to support:
  - flexible interfaces
  - anonymous communication
  - for common objectives

Evolutionary computation:
- Researchers include particle swarm optimization as a form of evolutionary computing.
  - (Goldin-Keil, 2001) pointed in general way to indirect interaction; defined properly here.

Interaction via the real world

- Indirect interaction among computational entities introduces the possibility for the real world to be used as the interaction medium.
- Examples:
  - Robot societies in which robots collaborate by moving physical objects.
  - Sensor networks in which sensor motes move or leave markers.

Persistent state increases power

- Environment-agent relation features a symmetry in which each has persistent state.
- Agents without persistent state (memory) are reflex (Russell-Norvig) and less adaptive, less powerful.
- Indirect interaction uses the persistent state of the environment as a medium of communication:
  - It is what enables anonymity, time decoupling, space decoupling.
- Formal modeling:
  - Semantically, persistent state is data, not a process.
  - Persistent Turing Machines (Goldin et al, 2001) use persistent state to achieve greater expressiveness.

Self-organization and emergent behavior

- Persistent state enables a wider range of behaviors.
- Self-organization: the interaction of a set of processes or structures at a lower level of a system to yield global structures or behavior at a higher level.
- Example: Chemical reactions.
- The higher-level system behavior is often called emergent.

Stigmergy

- Definition: A variety of self-organization in which agents are mobile, interacting via the environment.
- Examples: from nature (slide 3).
- Stigmergy is an instance of indirect interaction that enables a wider behavior range due to emergence.
- Design idea: Use stigmergy in design of collaboration technologies.
Theorem

*Indirect interaction via the real world enables richer system behavior than is possible with direct interaction alone.*

*Proof:* The real world may be assumed to be analog. Therefore its response to actions by computing agents may be uncomputable (Siegelmann).

Power of indirect interaction

*Corollary to above theorem:* Models that explicitly represent indirect interaction, including via the real world, are more expressive than models that don’t.

*Conjecture:* Even when modeling indirect interaction that does not use the real world as a medium, models that represent indirect interaction (via shared memory) explicitly are more expressive than those that don’t.

*Proof:* future work

Future work

- Prove the richness conjecture
- Define a formal semantics of indirect interaction
- Place collaboration technologies on a firm theoretical foundation by modeling indirect interaction explicitly

Selected references