Scalable models of multi-stream interaction

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Outline

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2. Algorithms and sequential interaction
3. Indirect interaction and multi-agent systems
4. Models

1. Introduction

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

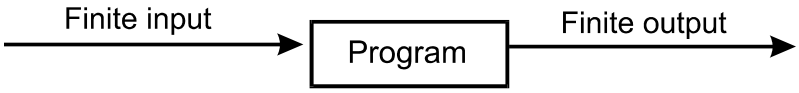
This research

- We assert that the *mission* of this multi-agent system can only be accomplished using *indirect interaction* via the ants' environment (stigmergy)
- We seek to define a class of such missions requiring *scalability*
- Current models of mobile systems are based on *direct interaction* (message passing)
- We show that these models are *unscalable*
- Our interest is in *expressiveness of models of computation;* an expressiveness hierarchy may be defined

2. Algorithms and sequential interaction

Algorithms

***Algorithmic computation* (Knuth):**
The effective transformation of a finite, pre-specified input, to a finite output, in a finite number of steps.



- Algorithms *compute functions*
- A system that executes an algorithm is *closed*
- Algorithms are equivalent to Turing-machine computation

Scalability in algorithms and interaction

- Time efficiency of algorithms is expressed as scalability (rise in running time relative to quantity of data operated on)
- *Intractable* problems are completely unscalable in that running time seems to be exponential in data size
- A robust reactive system likewise should respond in time that does not increase "too much" in proportion to size of its input

Communication

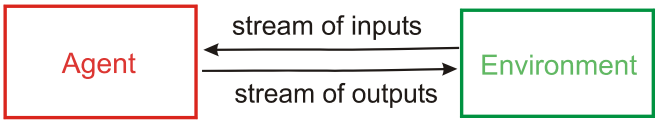
- *One-way communication* is the sending of strings, over a finite alphabet of symbols, from one entity to another
- *Two-way communication* is the concurrent activity of two entities engaged in one-way communication with each other
- Two-way communication does not assume that either entity waits for an input string before emitting output, or that either entity has an exclusive communication relationship with the other.

Interaction and synchrony

- *Direct interaction* is two-way communication in which some outputs of each entity may causally affect the entity's later inputs from the other
- Computing entity *interacts synchronously* with environment *E* if *A* interacts with *E* and both *A* and *E* wait for only one input token before emitting an output token.
- *Asynchronous interaction* occurs in the absence of synchrony as defined here

Sequential interaction

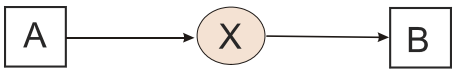
(Synchronous) sequential interactive computation: Interaction involving two participants, at least one of which is a finite computing agent (machine, device).



- Characterized by a single interaction stream of input alternating with output
- If one participant is an agent, the other is its *environment*
- Interaction may involve changes of state

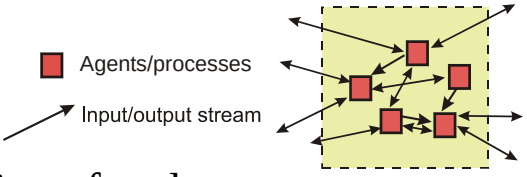
Multi-stream and indirect interaction

- *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.



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



3. Indirect interaction and multi-agent systems

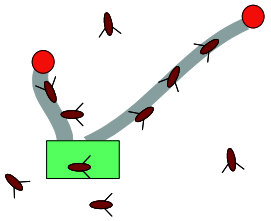
Direct and indirect interaction

Direct interaction: interaction via *messages*, where the identifier of the recipient is specified in a message.

Indirect interaction: interaction via persistent, observable changes to a *common environment*; recipients are any agents that will *observe* these changes.

- Sequential interaction is direct
- Preconditions for indirect interaction:
  - Agents share access to parts of the environment
  - Persistence of environment
- *Example of indirect interaction:* use of semaphores in process synchronization (critical section problem)

Stigmergy in nature



1. Ants foraging (see slide 4)

2. 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*)

3. 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?

Ubiquity of indirect interaction

- **Social biology**: Social insects interact by modifying common structures or through pheromones
- **Operating systems**: Processes communicate via *semaphores* in shared memory
- **Coordination languages**: Shared *tuple spaces* enable coordination in Linda
- **Anatomy**: Cells exchange information via *hormones* in the blood stream
- **Economics**: A *market* is an environment for buyers and sellers that serves as a medium for indirect interaction

Properties of indirect interaction

- **Time decoupling (asynchrony):** State changes persist
- **Anonymity:** Recipient ID not used in access
- **Space decoupling:** Agents need not meet
- **Non-intentionality:** Agents need not have goal of communicating
- **Hybrid nature:** Physical environment may play role
- **Late binding** of recipient

The power of persistence

- *Discussion:* It can be shown that computing agents with persistent state are capable of a wider range of behaviors than ones without persistent state
- *Example*: By remembering past answers, prosecutor may ask questions that force a witness to tell the truth or contradict self
- Persistence of environment is what enables termites, ants, slime mold to coordinate actions

Mission of a multi-agent system

- Algebra and propositional logic provide rules for *evaluation* of formulas
- Algorithms compute recursively definable *functions*
- Sequential-interactive agents offer *services*
- Multi-agent systems accomplish *missions* requiring *quality of service* for all users
- Interaction in MASs may be *asynchronous*
- Mission may require a minimum QoS regardless of number of users (*scalability*)

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)

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.

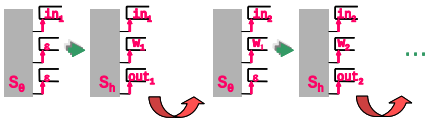
Decentralized system: a multi-agent system whose components do not respond to commands from an active director or manager component, and do not execute prespecified synchronized roles under a design or plan.

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. Models

Persistent Turing Machines

- A minimal extension of TMs expressing *sequential* interactive behavior (Goldin, *et al*)
- A *PTM* is a 3-tape TM with
  - I/O as dynamically generated *streams of interleaved inputs and outputs*
  - TM executions (*macrosteps*) iterated
  - A persistent worktape, called a *memory*, preserved between macrosteps



- *Example:* automatic car

Stream behavior of PTMs

- The *persistent stream language* (PSL) of a PTM is the set of streams $L \subseteq (\Sigma^* \times \Sigma^*)^\infty$ observable on it
- The set of all I/O streams over alphabet Σ: $(\Sigma^* \times \Sigma^*)^\infty = \{ (a, x) \mid a \in (\Sigma^* \times \Sigma^*), x \in (\Sigma^* \times \Sigma^*)^\infty \}$
- PSL is the set of all persistent stream languages
- *Amnesic* PTMs do not make use of their memory, i.e., are equivalent to TMs in that sense
- ASL: The set of *amnesic* stream languages
- *Theorem:* $ASL \subset PSL$ (Goldin, Smolka et al, 2004), hence PTMs are more expressive than TMs

Formal specification of problems

- Algorithmic problem: a set of (*input*, *output*) string pairs
- Sequential-interaction problem: a set of dynamically generated *streams* of I/O pairs
- Multi-stream interaction problem: a set of possibly asynchronous I/O streams, possibly in real time and with dynamic creation/destruction of connections
- Part of spec for multi-stream interaction problem may include number of streams, constraints on computing power of agents, and time constraints

Autonomous agents and models of sequential interaction

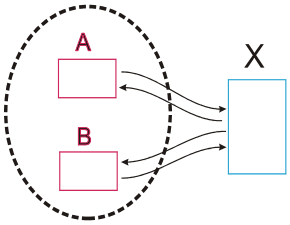
- Unified Modeling Language (UML) models sequential-interactive systems not supported by algorithm-based notations like flowcharts, module hierarchies, pseudocode
- *Autonomous agents* may initiate actions and may or may not synchronize with their environments
- To model autonomous agents, standard UML must be extended (Bauer, Muller, Odell, 2000)

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*



Research goals

- We seek formal results to establish some limitations of the message-passing model
- We seek an *expressiveness result* analogous to the one for sequential interaction by Goldin-Smolka et al.
- *Setting:* A large system of simple agents
- We propose to use three proof approaches:
  - Unscalability
  - Formal behavioral specifications
  - Simulation asymmetry

Showing unscalability of message passing

- *Motivation:* As unscalable architectures in AI are *brittle* and will fail in realistic settings (R. Brooks), so 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

Scalability in parallel systems

- A scalable pair, (*parallel system*, *parallel algorithm*), is one in which speedup is roughly linear in number of processors (Gustafson's Law)
- This requires small *serial fraction* (fraction of unparallelizable steps in algorithm); many algorithms have significant serial fraction
- *Speedup:* serial time / parallel time
- *Efficiency:* speedup / # processors
- *Isoefficiency:* a metric of scalability, the ratio of problem size to minimum # processors *p* needed to obtain an increase in speedup proportional to *p*

Scalability in distributed systems

- *Communication time* is a more significant factor in determining scalability of distributed systems
- *Quality of service* must be maintained for many data streams in a scalable system
- By one definition, scalable systems are ones whose productivity (throughput times average value of response, divided by cost per second) is maintained as scale varies
- By another definition, relative scalability is proportion of power-cost ratios of two systems at different scales

Scalability in multi-agent systems

- Notions of *autonomy* and *asynchrony*, as implied in the notion of *agents*, shape concept of scalability of MASs
- *Condition:* Each agent must provide a level of quality of service
- Models of scalability note *mesh* and *hierarchy* topologies, but not topologies made possible by *shared variables*
- Research notes that scalability is limited by any extra load that is due to increase in number of agents in the system

Unscalability of message passing

- When the system's mission requires adaptability under conditions where each agent is simple, the massive communication load requires use of the agents' environment (indirect interaction)
- *Example:* Under message-passing assumption, all agents may communicate with all other agents, requiring O(n) memory overhead per agent and $O(n^2)$ connections among agents, prohibitive where *n* is large

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

Scalable architectures and models

- *Scalable MAS architecture* (w.r.t. a class of missions): a design architecture whose instances are all scalable w.r.t. that class of missions
- *Scalable computational model* of multi-stream interaction: one capable of serving as the formal foundation of MAS architectures and instances that are scalable w.r.t. nontrivial classes of missions

Formal specification of problems that entail indirect interaction

- We propose to find a class of useful *missions or tasks* that would require indirect interaction
- *Setting:* A large system of simple agents
- *Initial idea:* to look at insect stigmergy examples – would tasks be impossible without stigmergy?
- If indirect interaction is *needed* to meet these specs, then an adequate model must represent that interaction explicitly
- *A tool:* specification languages and notations

An asymmetric simulation relation

- … exists between message-passing-based models and models based on indirect interaction
- *Motivation:* Simulation asymmetry would imply that current models are inadequate
- *Hypothesis:* Direct interaction *cannot* simulate indirect interaction in setting of large system of simple agents
- One possible simulation of direct interaction by indirect:
  - An agent puts a tuple into the shared environment
  - Tuple contains the both message and addresses
  - Recipient reads tuples that contain its ID

Summary

- Sequential interaction is a variant of asynchronous communication; sequential interaction may be *direct* or *indirect via the environment*
- We present evidence that *multi-stream interaction* is richer than sequential interaction
- We define *missions* that can only be accomplished using indirect interaction (stigmergy)
- We have argued that for systems that accomplish these missions, message-passing models of interaction are inadequate because they are unscalable

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