7. Distributed AI

1. What is distributed artificial intelligence?
2. Multi-agent systems
3. Stigmergy and self-organizing systems

Inquiry

• Is intelligence *emergent* and *decentralized*?
• Do persistent, dynamic, physical environments pose problems solvable only with multi-agent systems and distributed AI?
• What is the role of indirect interaction in intelligence?
7. Distributed AI

Objectives

7a. Describe multi-agent solution approaches
7b. Explain the relationship of intelligence to indirect interaction, self organization, and emergent behavior

1. What is distributed AI?

• DAI is intelligent (rational, adaptive) behavior of multi-agent systems in an interactive environment
• A multi-agent system is a set of agents that coordinate for a common mission
• Multi-stream interaction may produce self-organization and emergent behavior
Distributed AI and other AI

<table>
<thead>
<tr>
<th>Old AI</th>
<th>New AI</th>
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<tbody>
<tr>
<td>Find a computational path</td>
<td>Learn a policy, using coordination</td>
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<tr>
<td>Reasoning in a closed world</td>
<td>Open systems</td>
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<td>Human intervention</td>
<td>Autonomy</td>
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<td>Heuristics</td>
<td>Emergent behavior</td>
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<td>Toy environment</td>
<td>Real-world environment</td>
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<td>Brittle solutions</td>
<td>Scalable solutions</td>
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Changes in AI

- AI has moved away from algorithmic computing and reasoning, in a closed world, toward rational-agent behavior.
- AI is more and more associated with distributed and multi-stream systems.
- A hierarchy of difficulties of interactive problems:
2. Multi-agent systems

- A system of problem solvers situated in interactive environments
- Features of agents:
  - Situated
  - Autonomous
  - Flexible
  - Social

Adaptation and multi-agent systems

- MASs enable *distributed AI*
- *Behavior*: action to change the environment
- *Adaptation*: learning that changes behavior; occurs in dynamic persistent environments
- MASs are often flexible enough to adapt well
- *Sociogenetic adaptation*, contrasted, with *ontogenetic* (simple-agent) and *phylogenetic* (evolutionary) is adaptation by multi-agent systems
Multi-agent planning

- *Joint plans* are solutions if they achieve the goal when all agents act according to plan
- Agents need a way to *coordinate* execution of joint plan
- Environment is *dynamic* because multiple agents are present and may act
- *Synchronization* is necessary
- Joint plan is a partially ordered graph of joint actions (tuples of actions by multiple agents)

Concurrent action planning

- *Concurrent action list* specifies actions that must be executed concurrently
- Examples:
  - For A to hit the ball, other agents must *not* concurrently do so
  - For agents to carry a large container, two agents must do so concurrently
- *Time relations* of <, >, and = are valid
- *Conventions* such as “stay on the right side of the road” are required
Multi-stream interaction

- **Definition:** Interactive computation involving more than two entities
- Multi-stream interaction may include:
  - *Asynchrony*
  - *Nondeterminism* when attempts to write collide
  - *Dynamic linking* and unlinking, creation/destruction
  - *Indirect interaction* via a shared environment

Indirect interaction and multiagent systems

- In a MAS characterized by locality of interaction and mobility of agents, it is only possible for agents to influence overall system behavior remotely, i.e., indirectly
- Richness of multiagent interaction:
  - due partly to ability of each agent to interact with multiple others
  - hence indirectly with *all* others (otherwise system partitions)
Multi-agent evolutionary computation

• *Swarm* or *ant* computing
• *Coevolution*: Evolution of species whose instances interact in multi-agent systems
• *Particle swarm optimization*: Particles are candidate solutions to a problem in *n*-dimensional space, particles are accelerated through this space in relation to each other and to objective function

3. Stigmergy and self-organizing systems

• *Stigmergy*: A variety of self-organization in which mobile agents interact via their shared environment
• *Contrast to*: direct interaction; centralized interaction
• Examples:
  – termites gathering chips,
  – ants foraging,
  – slime mold aggregation
Stigmergy in nature

1. **Ants foraging for food**: Ants leave pheromone trail, prefer existing trails, blaze shorter and shorter trails to and from food

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 tasks?**

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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
Indirect interaction

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

- Features:
  - anonymity (recipient ID not used in access)
  - time delay (state changes persist)
  - space decoupling (agents $A$, $B$ need not meet)

- Agents $A$ and $B$ (below) may interact with each other indirectly via shared variable $x$.

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 bloodstream.

- 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

Environments for multi-agent systems

*E4MAS 2005 Proceedings* cited as examples the environments of:

- visitors to a web site;
- a system of autonomous guided vehicles;
- a system of manufacturing control;
- a PDA-based system of agents to help support activities of museum visitors.

*All involve indirect interaction*
A taxonomy of environments

<table>
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<tr>
<th>Amnesic vs.</th>
<th>Static vs.</th>
<th>Virtual vs.</th>
</tr>
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<tbody>
<tr>
<td>Persistent</td>
<td>Dynamic</td>
<td>Physical</td>
</tr>
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</table>

- An environment is **amnesic** if its outputs depend only on its *immediately preceding* inputs.
- An environment $E$ is **static** with respect to an agent or MAS $A$ if its outputs to $A$ are *strictly dependent* on its previous inputs from $A$.
- A **virtual** environment is accessed digitally; a **physical** environment is observable only by analog sensors.

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).
Self-organizing system

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

Decentralized 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.
### Concepts

- anonymity
- asynchrony
- autonomy
- behavior
- concurrent action list
- configuration space
decentralized system
distributed AI

- emergent behavior
- emergent intelligence
- indirect interaction
- joint plan
- mobility
- model based approach
- multi-agent system

- multi-stream interaction
- self-organizing system
- social biology
- sociogenetic adaptation
- space decoupling
- stigmetry

### References


