Interaction, Evolution, and Intelligence

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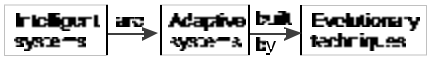
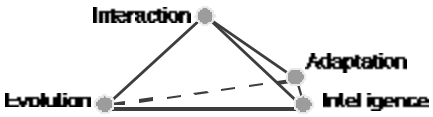
- Intelligence: "the capability of a system to adapt its behavior to meet its goals in a range of environments." – *David Fogel, 'Evolutionary Computation'* (2000)
- "Interaction with the world is the key to intelligence." – *Rodney Brooks, MIT AI lab*
- "The interactive Turing test allows questioned machines to adapt and learn, and to adapt answers to the needs of the questioner, just as a good lecturer adapts lecturing style to the needs of the audience." – *Peter Wegner,* 1999

Four related concepts

- Research in three areas tends to link up:



- A common feature is *interaction:* the exchange of messages by computing agents, or an agent's response to its environment

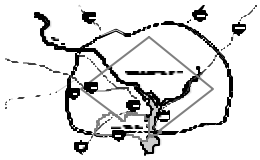


The paradigm shift to interaction

Algorithmic	***Interactive***
Structured design	Object-oriented design
Logic and search in AI	Agent-oriented AI
Rule-based reasoning	Planning, simulation, control
Closed systems	Open systems
Compositional behavior	Emergent behavior
Computation: Transforming input to output (by TMs)	Providing a service over time by agents

Driving is nonalgorithmic

- The problem of driving a car is interactive, not reducible to an algorithm
- External conditions can affect car's motion during driving



Enriching our models of computation

- Must solve problems whose inputs cannot be completely specified a priori
- Must encompass
  - *persistence of agent state*,
  - infinite *interaction streams*, and
  - ongoing interaction with a (possibly uncomputable) *environment*
- "The classical TM paradigm may no longer be fully appropriate to capture all the features of present-day computing" (Van Leeuwen-Wiedermann, 2000)

An interactive model

- Persistent Turing machines and Interactive Transition Systems
- State is persistent between TM computations
- Inputs (percepts) and outputs (actions) are interleaved

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Interaction and EC

- Interactions of three kinds occur:
  - Adaptation by individuals
  - Competition in a population
  - Evolution of a species
- An agent or phenotype or genotype evolves interactively
- Living and artificial agents interact with their dynamic environments through streams of percepts and actions

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Intelligence and adaptation

- *Adaptation* is an example of history-dependent behavior that requires an interactive conceptualization of computation
- *Intelligence:* an evolved ability to adapt to one's environment (Piaget)
- Kinds of intelligence are shaped by different environments
- *Example:* An intelligent interrogation can exploit weaknesses in a story, lead to inconsistencies

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The *Turing test*

- Stipulates that a system is intelligent if it cannot be distinguished from a human through question-answering
- Interactive model permits stronger criteria for intelligence than an algorithmic model
- An interactive Turing test would enable observer to make use of earlier questions and replies, exploiting history dependence
- Consider the difference between open and closed minds: interaction versus algorithms
- Note: Turing suggested that intelligent machines might evolve under the artificial-selection regime of the experimenter

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Multi-agent systems and emergent behavior

- *Complex systems* exhibit *emergent behavior,* which requires interaction
- Example: Multi-agent software systems
- Termites may build piles of chips without a coordinating algorithm (*Starlogo,* MIT)
- Evolution and intelligence are kinds of emergence: e.g., species evolve in complex ways as individuals carry out simple functions
- Evolutionary frameworks enable study of agent interactions and emergent properties of agent systems. (J. Wiles and J. Hallinan, 4/01)

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Summary and future work

- *Summary:* Interactive models of computation offer a theoretical foundation for work building intelligent systems through EC
- Natural evolution has solved the problem of intelligence, by use of *reinforcement learning*
- Shall EC address RL?
- Evolution must involve reactive *anytime* processes

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New mathematical tools are needed

- *Coinduction* provides a mathematical framework for formalizing systems that have infinite interaction sequences
- Associated with *coalgebras*, and *non-well-founded sets*
- If t is a stream over an alphabet S, and $a \in$ S, then (a, t) is a stream over S: $S^{\infty} = \{(a, t) \mid a \in \Sigma, t \in \Sigma^{\infty}\}$.

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Multi-stream interaction machines (MIMs)

- State-transition systems that interact with autonomous multiple streams
- An agent may be composed of multiple interacting components
- Multi-agent computing is more expressive than the sequential kind because it can express collaboration or delegation

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Interactive computing is stream based

- The algorithmic Turing-machine model of computation computes functions ($\Sigma^* \rightarrow \Sigma^*$), or ($\mathbf{N} \rightarrow \mathbf{N}$)
- A *stream over S* is an infinite sequence of values (tokens)
- A stream over a countable set S is circularly defined as a pair (s, t), where $s \in S$ and t is a stream over S
- *Coinduction* provides a mathematics of streams

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Learning, evolution, adaptation

- Learning is an example of *history-dependent behavior*
- Learning is part of adaptation

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- Robotics, social structures, economic phenomena, military situations, "society of mind"
- is an example of the power of parallel and concurrent (multi-stream) interaction
- The study of intelligent systems implies the study of multi-stream interaction

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