Multiagent Systems (SMA-UPC)

3. Reasoning in Agents
Part 1:
Introduction to Reasoning

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What is Reasoning?

- More than thinking
- Taking a set of facts and deriving new ones in a fixed way
- More specifically (usefully):
  - Reasoning to achieve a goal – planning
  - Problem Solving
  - Working out how to get world state A to world state B

What is Reasoning?
An example

- How do I achieve my dream of owning a house by the seaside?
  - Starting world state:
    - I have X amount of money
    - I have many facts about land, the city, planning permission, the housing market etc.
  - How do I achieve my goal state:
    - Where I have a house
    - (preferably one which is the BEST I could get with my money)
- The possibilities in the real world are (nearly!) infinite!

Automated Reasoning

- Objective: carry out such inference automatically - without the need for human intervention
- This is very hard because:
  - The real world is complex (huge number of factors)
    - **inaccessible**
  - Resources are bounded (finite time and finite memory)
  - Things change (while I am thinking or acting the world may change)
    - **dynamic**
  - The world is uncertain (I cannot be sure that an action I take will have the expected outcome)
    - **non-deterministic**
  - There are other actors that might try to (intentionally or unintentionally) thwart my plans!
    - **non-deterministic**

Multiagent Systems (SMA-UPC)

Reasoning Paradigms

- **Key distinctions between paradigms**
- **Concrete approaches**

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Key distinctions btw. Reasoning Paradigms

Monotonic vs. Non-Monotonic (I)

- **Monotonic**
  - A logical inference relation is *monotonic* if and only if, for all sets of propositions S and T, and for all propositions A, if S entails A (e.g. $S \vdash A$) then $(S \cup T) \vdash A$
  - First order logic is monotonic
  - Classical deduction - suitable for reasoning in open-ended situations
  - Absence of x implies x is unknown
  - A proposition A is false with respect to a set of propositions S when $S \vdash \neg A$.

Key distinctions btw. Reasoning Paradigms
Monotonic vs. Non-Monotonic (II)

- **Non-monotonic**
  - Logics in which the set of implications determined by a given group of premises does not necessarily grow, and can shrink, when new well-formed formulae are added to the set of premises
  - Absence of x implies x is false - closed world assumption
  - Prolog is non-monotonic
  - Reasoning to conclusions on the basis of incomplete information. Given more information, we are prepared to retract previously drawn inferences.
  - Agents are in general non-monotonic systems.

Key distinctions btw. Reasoning Paradigms
Abductive vs. Deductive

- **Abductive**
  - A form of inference that works forward to the best explanation
  - Example:
    - D is a collection of data (facts, observations, givens),
    - H explains D (or would, if true, explain D),
    - No other hypothesis explains D as well as H does.
    - Therefore, H is probably correct.
  - Good for diagnosis, plan recognition, natural language understanding, vision
  - Explanation is not necessarily true
- **Deductive**
  - Predictive
  - Works from premises to conclusion
  - Inference rules drive the process
  - Uses the existence of facts to infer (via rules) the existence of new facts
  - Conclusion is proven with respect to available facts

Key distinctions btw. Reasoning Paradigms

Forward Chaining vs. Backward Chaining

- **Forward Chaining**
  - An implementation of deduction
  - Rules are used to deduce new facts from existing facts
  - Process continues until no more rules apply
- **Backward Chaining**
  - Works backwards from goal to current situation
  - Rules are used to infer that a (sub)goal holds then the preconditions (left hand side of rule) also hold
  - Process moves backwards down chain of reasoning until no more rules apply
  - Prolog style

Reasoning Paradigms: Concrete Approaches

Essential elements

- A description of the world
- A specification of the goal
- A search space of things to do (possibly vast)
- Some way to traverse the search space
  - Need of some algorithm/strategy/heuristic function to guide the traversal.

Reasoning Paradigms: Concrete Approaches

- Approaches
  - Case-Based Reasoning
  - Model-Based Reasoning
  - Qualitative Reasoning
  - Planning Systems
  - Constraint Satisfaction Reasoning
  - Rule-Based Reasoning
  - Ontological Reasoning
  - Symbolic Reasoning
  - Logic Programming
- These are not disjoint. One can have combined approaches such as Constraint Logic-Based Planning Systems.

Reasoning Paradigms: Concrete Approaches
Case-Based Reasoning

- *"I remember solving a problem like this some time ago ... "*
- Functions:
  - A case-base of previous problem-solution pairs
  - An indexing scheme which classifies problems and cases
- When a new problem arises:
  - Find the closest previous problem(s) and solution(s)
  - Try to adapt the solution(s) to the new problem
  - Apply the new solution
  - Optionally add the new experience to the case-base
- Challenge is how to create initial case base

Reasoning Paradigms: Concrete Approaches

Model-Based Reasoning

- *"I understand how this system and its components work based on their input parameters"*
  - Component models (e.g. failure modes)
  - Differential equations, logical models, ...
- Combined:
  - Brute force search algorithms
- Often used for system diagnosis:
  - Why is my washing machine not working?
  - Why is this electric circuit failing?

Reasoning Paradigms: Concrete Approaches

Qualitative Reasoning

- *"Gravity works downwards, if I jump out of this plane I will probably fall"*
- Approximate way of reasoning
  - Useful to reason about too complex (e.g. chaotic, fractal) problems
  - E.g. physical world properties
  - Use "naïeve" (but often useful) deduction rules

Reasoning Paradigms: Concrete Approaches
Planning

- *"From my current world state I can apply a sequence of possible actions to get to the goal"*
- Different types:
  - **State based planning** - we search the combinations of all actions (Domain driven)
  - **Hierarchical Task Network** - we search the possible plans (Knowledge based)
- A lot of different search techniques, world models and reasoning approaches are used
  - Linear/non-linear
  - Continuous/discrete
  - Temporal issues

Reasoning Paradigms: Concrete Approaches
Constraint Satisfaction

- *"The world is a set of interdependent choices. If I make one, it may affect another"*
- Problem:
  - A **set of variables** V (each with a possible set of values vi1-vin)
  - A **set of constraints** linking variables C(vi1, vi2, vi3) such as "if my trousers are green my shirt should not be blue"
  - What are the legal combinations of values for each variable? Or, which choices fit together given the constraints
- Many search techniques
  - Propagating constraint effects, subdividing the constraint graph etc.
  - Related problems: dynamically changing choices/options, uncertainty, ...
  - But algorithms are typically quite expensive (complexity)
  - Domain specific SAT solvers relatively efficient
  - Good heuristics

Reasoning Paradigms: Concrete Approaches
Rule-Based Reasoning

- *"If the light is red STOP, if it is raining I must be wet, ..."*
- Functions by:
  - Accumulating a **set of rules** relating PRE-conditions to inferences or actions
  - A **fact base** allowing the rules to fire iteratively when the facts fit the rule preconditions
  - **Heuristics** to select one rule when several satisfy the preconditions
- Reasoning happens by traversing the facts available
- We will see more of this later

Reasoning Paradigms: Concrete Approaches
Ontological Reasoning

- There are two approaches
  - **Description logic reasoning** over ontological knowledge (e.g. class membership inference) - such as RACER etc.
  - Adapting the data models in each of the other schemes to **use objects in agreed ontologies** - that is, using any of the previous approaches, but the facts are represented via ontologies

Reasoning Paradigms: Concrete Approaches
Symbolic Reasoning

- The world or a portion of it is represented in terms of *formulae in some logic*
- Reasoning is based on inference.
- Different types of logic are used
  - description logic
  - temporal logic
  - BDI logic
  - epistemic logic
  - deontic logic
  - …
- We will come back on this later

Reasoning Paradigms: Concrete Approaches
Logic Programming

- "Given this set of rules with pre and post conditions which information can I obtain from it"
- Based in model theoretic principles
- Provides possible views of solutions
- Prolog (with closed world assumption)
- **Answer Set Programming** (no closed assumption)

Reasoning Paradigms
Evolution in Agent Architectures

- Originally (1956-1985), pretty much all agents designed within AI were *symbolic reasoning* agents
- Its purest expression proposes that agents use *explicit logical reasoning* in order to decide what to do
- Problems with symbolic reasoning led to a reaction against this — the so-called *reactive agents* movement, 1985–present
- From 1990-present, a number of alternatives proposed: *hybrid* architectures, which attempt to combine the best of reasoning and reactive architectures

Deductive Reasoning Agents

- **Rule-Based Systems**
- **Simbolic Reasoning Agents**
- **Deductive Reasoning Agents**
- **Agent Oriented Programming**

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Foundations: Rule-based systems

Expert Systems and rules

- **Expert Systems** provide expert quality advice, diagnoses and recommendations on real world problems
- Designed to perform function of a human expert. E.g. Medical diagnosis - program takes place of a doctor; given a set of symptoms the system suggests a diagnosis and treatment
- The knowledge base of an expert system is often **rule based**
  - the system has a list of rules which determine what should be done in different situations
  - These rules are initially designed by human expert(s)
  - The rules are called **production rules**

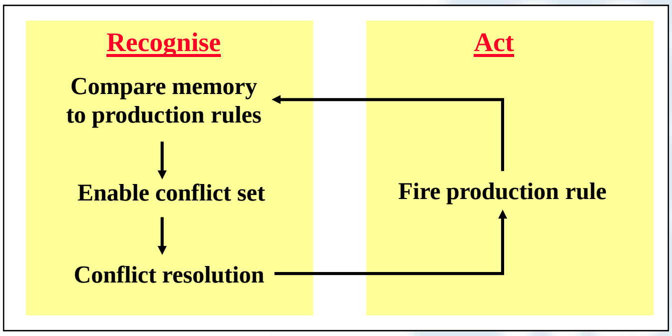
Foundations: Rule-based systems

Rules

- Each rule has two parts, the **condition-action pair**
  - **Condition** - what must be true for the rule to fire
  - **Action** - what happens when the condition is met
- Can also be thought of as IF-THEN rules
  - IF sunny(weather) AND outdoors(x)
THEN print “Take your sunglasses x”
  - IF >30(temperature)
THEN print “take some water”
- The contents of the **working memory** are constantly compared to the production rules
- When the contents match the condition of a rule, that rule is *fired*, and its action is executed
- More than one production rule may match the working memory - **conflict set**

Foundations: Rule-based systems
Recognise-Act Cycle

- The system cycles around in the **recognise-act cycle**
- Whenever a condition is matched, it is added to the **conflict set** - all the rules which are currently matched
- The system must then decide which rule within the conflict set to fire - **conflict resolution**



Symbolic Reasoning Agents

- The classical approach to building agents is to view them as a particular type of *knowledge-based system*, and bring all the associated (discredited?!) methodologies of such systems to bear
- This paradigm is known as ***symbolic AI***
- We define a deliberative agent or agent architecture to be one that:
  - contains an explicitly represented, symbolic model of the world
  - makes decisions (for example about what actions to perform) via symbolic reasoning

3.Reasoning in Agents

Symbolic Reasoning Agents
Problems to solve

- If we aim to build an agent in this way, there are two key problems to be solved:

1. *The transduction problem*:
that of translating the real world into an accurate, adequate symbolic description, in time for that description to be useful…vision, speech understanding, learning

2. *The representation/reasoning problem*:
that of how to symbolically represent information about complex real-world entities and processes, and how to get agents to reason with this information in time for the results to be useful…knowledge representation, automated reasoning, automatic planning

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3.Reasoning in Agents

Symbolic Reasoning Agents
Problems to solve

- Most researchers accept that **neither problem is anywhere near solved**
- Underlying problem lies with the complexity of symbol manipulation algorithms in general: many (most) search-based symbol manipulation algorithms of interest are ***highly intractable***
- Because of these problems, some researchers have looked to alternative techniques for building agents...

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Deductive Reasoning Agents

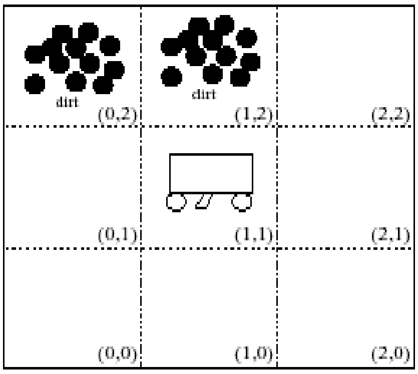
- How can an agent decide what to do using theorem proving?
- Basic idea is to use logic to encode a theory stating the ***best*** action to perform in any given situation
- Let:
  - ρ be this theory (typically a set of rules)
  - Δ be a logical database that describes the current state of the world
  - Ac be the set of actions the agent can perform
  - $\Delta \vdash_\rho \phi$ mean that ϕ can be proved from Δ using ρ

Deductive Reasoning Agents
Action selection

/* *try to find an action explicitly prescribed* */
for each $a \in Ac$ do
    if $\Delta \vdash_\rho Do(a)$ then
        return a
    end-if
end-for
/* *try to find an action not excluded* */
for each $a \in Ac$ do
    if $\Delta \nvdash_\rho \neg Do(a)$ then
        return a
    end-if
end-for
return $null$ /* *no action found* */

Deductive Reasoning Agents
Example: the Vacuum World

- Goal is for the robot to clear up all dirt



Deductive Reasoning Agents
Example: the Vacuum World

- Use 3 *domain predicates* to solve problem:

$In(x, y)$	agent is at (x, y)
$Dirt(x, y)$	there is dirt at (x, y)
$Facing(d)$	the agent is facing direction d

- Possible actions:

  $Ac = \{turn, forward, suck\}$

  P.S. *turn* means "turn right"
- Rules ρ for determining what to do:

$$\begin{aligned} In(0,0) \wedge Facing(north) \wedge \neg Dirt(0,0) &\longrightarrow Do(forward) \\ In(0,1) \wedge Facing(north) \wedge \neg Dirt(0,1) &\longrightarrow Do(forward) \\ In(0,2) \wedge Facing(north) \wedge \neg Dirt(0,2) &\longrightarrow Do(turn) \\ In(0,2) \wedge Facing(east) &\longrightarrow Do(forward) \end{aligned}$$

- …and so on!
- Using these rules (+ other obvious ones), starting at (0, 0) the robot will clear up dirt

Deductive Reasoning Agents
Example: the Vacuum World

- Problems:
  - How to convert video camera input to $Dirt(0, 1)$?
  - decision making assumes a *static* environment: *calculative rationality*
  - decision making using first-order logic is ***undecidable*!**
- Even where we use *propositional* logic, decision making in the worst case means solving co-NP-complete problems (PS: co-NP-complete = bad news!)
- Typical solutions:
  - weaken the logic
  - use symbolic, non-logical representations
  - shift the emphasis of reasoning from *run time* to *design time*
- We will look at some examples of these approaches

Agent Oriented Programming

- Yoav Shoham introduced “Agent Oriented Programming” in 1990:
  - “new programming paradigm, based on a societal view of computation”.
- Key idea: directly programming agents in terms of intentional notions like belief, commitment, and intention.
- The motivation behind such a proposal is that, as we humans use the intentional stance as an abstraction mechanism for representing the properties of complex systems.
  - In the same way that we use the intentional stance to describe humans, it might be useful to use to describe the programming of machines.
- Shoham suggested that a complete AOP system will have 3 components:
  - a logic for specifying agents and describing their mental states
  - an interpreted programming language for programming agents
  - an ‘agentification’ process, for converting ‘neutral applications’ (e.g., databases) into agents
- Relationship between logic and programming language is *semantics*

Agent Oriented Programming
AGENT0

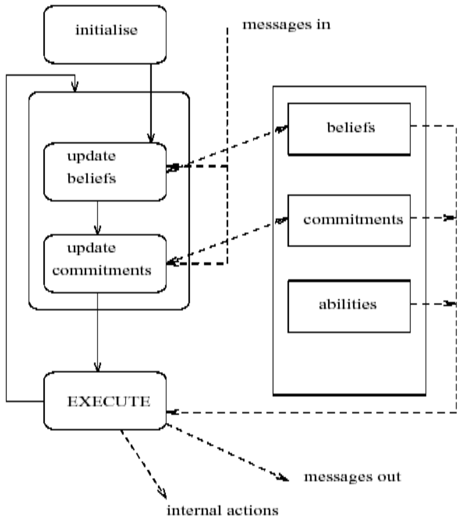
- AGENT0 is the first AOP language.
- AGENT0 is implemented as an extension to LISP
- Each agent in AGENT0 has 4 components:
  - a set of capabilities (things the agent can do)
  - a set of initial beliefs
  - a set of initial commitments (things the agent will do)
  - a set of ***commitment rules***
- The key component, which determines how the agent acts, is the commitment rule set
- Each commitment rule contains
  - a *message condition*
  - a *mental condition*
  - an action

3.Reasoning in Agents

Agent Oriented Programming
AGENT0

- On each 'agent cycle'…
  - The message condition is matched against the messages the agent has received
  - The mental condition is matched against the beliefs of the agent
  - If the rule fires, then the agent becomes committed to the action (the action gets added to the agent's commitment set)
- Actions may be
  - *private*:
    an internally executed computation, or
  - *communicative*:
    sending messages
- Messages are constrained to be one of three types:
  - "requests" to commit to action
  - "unrequests" to refrain from actions
  - "informs" which pass on information

Agent Oriented Programming
AGENT0



Agent Oriented Programming
AGENT0

- A commitment rule:

```
COMMIT(
   (agent, REQUEST, DO(time, action)), ;;; msg condition
   (B,
        [now, Friend agent] AND
        CAN(self, action) AND
        NOT [time, CMT(self, anyaction)]
   ), ;;; mental condition
   self,
   DO(time, action)
)
```

- This rule may be paraphrased as follows:
  if I receive a message from *agent* which requests me to do *action* at *time*, and I believe that:
  - *agent* is currently a friend
  - I can do the action
  - At *time*, I am not committed to doing any other action

  then commit to doing *action* at *time*

Agent Oriented Programming

AGENT0 and PLACA

- AGENT0 provides support for multiple agents to cooperate and communicate, and provides basic provision for debugging…
- …it is, however, a *prototype*, that was designed to illustrate some principles, rather than be a production language
- A more refined implementation was developed by Thomas, for her 1993 doctoral thesis
- Her Planning Communicating Agents (PLACA) language was intended to address 2 severe drawbacks to AGENT0:
  - the inability of agents to plan,
  - the inability of agents to communicate requests for action via high-level goals
- Agents in PLACA are programmed in much the same way as in AGENT0, in terms of *mental change* rules

Agent Oriented Programming

AGENT0 and PLACA

- An example mental change rule:

```
(((self ?agent REQUEST (?t (xeroxed ?x)))
   (AND (CAN-ACHIEVE (?t xeroxed ?x)))
      (NOT (BEL (*now* shelving)))
      (NOT (BEL (*now* (vip ?agent))))
   ((ADOPT (INTEND (5pm (xeroxed ?x)))))
   ((?agent self INFORM
      (*now* (INTEND (5pm (xeroxed ?x)))))))
```

- This can be paraphrased as follows:
  if someone asks you to xerox something, and you can, and you don't believe that they're a VIP, or that you're supposed to be shelving books, then
  - adopt the intention to xerox it by 5pm, and
  - inform them of your newly adopted intention

MetateM

- MetateM is a multi-agent language in which each agent is programmed by giving it a ***temporal logic* specification** of the behavior it should exhibit
- These specifications are executed directly in order to generate the behavior of the agent
- Temporal logic is classical logic augmented by *modal operators* for describing how the truth of propositions changes over time

MetateM

Temporal Logic operators

- For example. . .

$\Box important(agents)$

means "it is now, and will always be true that agents are important"

$\Diamond important(ConcurrentMetateM)$

means "sometime in the future, ConcurrentMetateM will be important"

$\blacklozenge important(Prolog)$

means "sometime in the past it was true that Prolog was important"

$(\neg friends(us))\ \mathcal{U}\ apologize(you)$

means "we are not friends until you apologize"

$\bigcirc apologize(you)$

means "tomorrow (in the next state), you apologize".

$\odot \mathrm{prepareSlides(me)}$

means "yesterday (previous run) I prepared my slides".

$post\text{-}doc(me)\ \mathcal{S}\ year(2003)$

means "I am a posdoc researcher since 2003"

MetateM
Execution rules

- MetateM is a framework for *directly executing* temporal logic specifications
- The root of the MetateM concept is Gabbay's *separation theorem*: Any arbitrary temporal logic formula can be rewritten in a logically equivalent *past* $\Rightarrow$ *future* form.
- This *past* $\Rightarrow$ *future* form can be used as *execution rules*
- A MetateM program is a set of such rules
- Execution proceeds by a process of continually matching rules against a "history", and *firing* those rules whose antecedents are satisfied
  - Execution is thus a process of iteratively generating a model for the formula made up of the program rules
- The instantiated future-time consequents become *commitments* which must subsequently be satisfied

MetateM
Example

- An example MetateM program: the resource controller…

$$\forall x \quad \odot ask(x) \Rightarrow \Diamond give(x)$$
$$\forall x,y \quad give(x) \wedge give(y) \Rightarrow (x=y)$$

- First rule ensure that an 'ask' is eventually followed by a 'give'
- Second rule ensures that only one 'give' is ever performed at any one time
- There are algorithms for executing MetateM programs that appear to give reasonable performance

Concurrent MetateM

- Concurrent MetateM provides an operational framework through which societies of MetateM processes can operate and communicate
- It is based on a model for concurrency in executable logics: the notion of executing a logical specification to generate individual agent behavior
- A Concurrent MetateM system contains a number of agents (objects), each object has 3 attributes:
  - a name
  - an interface
  - a MetateM program

Concurrent MetateM
object interface

- An object's interface contains two sets:
  - *environment predicates* — these correspond to messages the object will accept
  - *component predicates* — correspond to messages the object may send
- For example, a 'stack' object's interface:

  stack(pop, push)[popped, stackfull]

  {pop, push} = environment preds
  {popped, stackfull} = component preds

- If an agent receives a message headed by an environment predicate, it accepts it
- If an object satisfies a commitment corresponding to a component predicate, it broadcasts it

3.Reasoning in Agents

Concurrent MetateM
Example

- To illustrate the language Concurrent MetateM in more detail, here are some example programs…
- Snow White has some sweets (resources), which she will give to the Dwarves (resource consumers)
- She will only give to one dwarf at a time
- She will always eventually give to a dwarf that asks
- Here is Snow White, written in Concurrent MetateM:

$$
\begin{array}{l}
\text{Snow-White(ask)[give]:} \\
\qquad \odot\, \text{ask}(x) \Rightarrow \Diamond\, \text{give}(x) \\
\text{give}(x) \wedge \text{give}(y) \Rightarrow (x = y)
\end{array}
$$

3.Reasoning in Agents

Concurrent MetateM
Example

- The ‘eager’ dwarf asks for a sweet initially, and then whenever he has just received one, asks again

$$
\begin{array}{l}
\text{eager(give)[ask]:} \\
\qquad \text{start} \Rightarrow \text{ask(eager)} \\
\odot\, \text{give(eager)} \Rightarrow \text{ask(eager)}
\end{array}
$$

- Some dwarves are even less polite: ‘greedy’ just asks every time

$$
\begin{array}{l}
\text{greedy(give)[ask]:} \\
\text{start} \Rightarrow \Box\, \text{ask(greedy)}
\end{array}
$$

Concurrent MetateM

Example

- Fortunately, some have better manners; ‘courteous’ only asks when ‘eager’ and ‘greedy’ have eaten

$$
\begin{array}{l}
\text{courteous(give)[ask]:} \\
((\neg\, \text{ask(courteous)}\ \mathcal{S}\ \text{give(eager)}) \wedge \\
(\neg\, \text{ask(courteous)}\ \mathcal{S}\ \text{give(greedy)})) \Rightarrow \\
\quad \text{ask(courteous)}
\end{array}
$$

- And finally, ‘shy’ will only ask for a sweet when no-one else has just asked

$$
\begin{array}{rcl}
\multicolumn{3}{l}{\text{shy(give)[ask]:}} \\
\mathit{start} & \Rightarrow & \Diamond\, \text{ask(shy)} \\
\odot\, \text{ask(x)} & \Rightarrow & \neg\, \text{ask(shy)} \\
\odot\, \text{give(shy)} & \Rightarrow & \Diamond\, \text{ask(shy)}
\end{array}
$$

Concurrent MetateM

- Summary:
  - an(other) experimental language
  - very nice underlying theory…
  - …but unfortunately, lacks many desirable features — could not be used in current state to implement ‘full’ system
  - currently prototype only, full version on the way!

3.Reasoning in Agents

References

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[2] Weiss, G. "Multiagent Systems: A modern Approach to Distributed Artificial Intelligence". MIT Press. 1999. ISBN 0262-23203

[3] Y. Shoham, "An Overview of Agent-Oriented Programming", in J. M. Bradshaw, editor, Software Agents, pages 271–290. AAAI Press / The MIT Press, 1997.

These slides are based mainly in [2] and material from M. Wooldridge, J. Padget and M. de Vos