Multi-Agent Oriented Programming

The JaCaMo Platform

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Tutorial Organisation

- Introduction to Multi-Agent Oriented Programming
- Programming Agents
- Programming Agents' Environment
- Programming Agents' Interaction
- Programming Agents' Organisations
- Programming Applications
- Conclusion & Perspectives

Multi-Agent Oriented Programming
Programming Agents

Outline

Literature

Fundamentals

Books: [Bordini et al., 2005], [Bordini et al., 2009]

Proceedings: ProMAS, DALT, LADS, EMAS, AGERE, ...

Surveys: [Bordini et al., 2006], [Fisher et al., 2007] ...

Languages of historical importance: Agent0 [Shoham, 1993], AgentSpeak(L) [Rao, 1996], MetateM [Fisher, 2005], 3APL [Hindriks et al., 1997], Golog [Giacomo et al., 2000]

Other prominent languages: *Jason* [Bordini et al., 2007], Jadex [Pokahr et al., 2005], 2APL [Dastani, 2008], GOAL [Hindriks, 2009], JACK [Winikoff, 2005], JIAC, AgentFactory

But many others languages and platforms...

Some Languages and Platforms

Fundamentals

Jason (Hübner, Bordini, ...); 3APL and 2APL (Dastani, van Riemsdijk, Meyer, Hindriks, ...); Jadex (Braubach, Pokahr); MetateM (Fisher, Guidini, Hirsch, ...); ConGoLog (Lesperance, Levesque, ... / Boutilier – DTGolog); Teamcore/ MTDP (Milind Tambe, ...); IMPACT (Subrahmanian, Kraus, Dix, Eiter); CLAIM (Amal El Fallah-Seghrouchni, ...); GOAL (Hindriks); BRAHMS (Sierhuis, ...); SemantiCore (Blois, ...); STAPLE (Kumar, Cohen, Huber); Go! (Clark, McCabe); Bach (John Lloyd, ...); MINERVA (Leite, ...); SOCS (Torroni, Stathis, Toni, ...); FLUX (Thielscher); JIAC (Hirsch, ...); JADE (Agostino Poggi, ...); JACK (AOS); Agentis (Agentis Software); Jackdaw (Calico Jack); *simpAL*, *ALOO* (Ricci, ...);

...

Theories, Models, Architectures

Fundamentals

- Agents are used to solve problems (e.g. to find solutions, to take decisions, to act on the environment)
- The characteristics of the problem influence the way the agents are built
  - ⇝ we then talk about agent architectures
- It may be the case that some architectures are designed using general principles
  - ⇝ we then talk about agent models
- Some of these models have a theory associated with them that allows the verification of some properties
  - ⇝ we then talk about agent theories

Several agent architectures, models and theories exist in the literature!!!

Outline

Analysis Grid

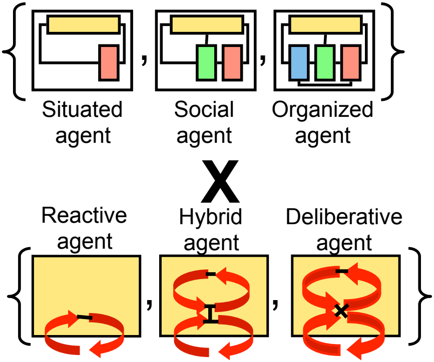
Agent Models Panorama

Agent models depend on:

- the type of inputs that they reason from (external factor)
- the control cycle connecting inputs to actions (coupling)

External factor

Coupling



External Factor Dimension

Agent Models Panorama

- Situated Agents
  - agents that reason about themselves and about their environment
- Social Agents
  - agents that reason about themselves, about their environment and about the interactions with others
- Organized Agents
  - agents that reason about themselves, about their environment and about the interactions with others and about the organizations (e.g. social structures, norms) enforcing these interactions

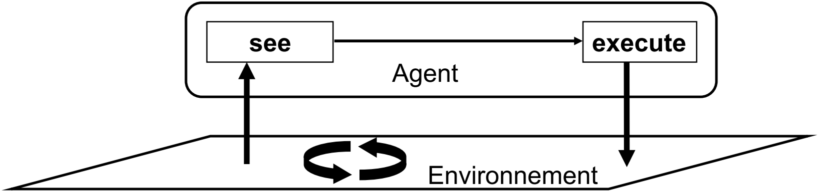
Coupling Dimension

- Reactive Agent
  - tight coupling between perception of the external factors with action
- Deliberative Agent
  - loose coupling between perception and actions: agents deliberate on the actions to execute from their perception of the external factors and from their goals
- Hybrid Agent
  - agents that are mixing reactivity and deliberation

Reactive Agent Models

Agent Models Panorama/ Coupling Dimension

- The process cycle of an agent is a closed loop between "execute" and "see" (Stimulus/Response)
- reaction to the evolution of the environment
- No explicit representation of the environment, of the other agents, of its skills,
- Decisions are done without reference to the past (no history), to the futur (no planning)



Reactive Agent models

Reactive approach arises in opposition to the symbolic reasoning model (AI). Several approaches that are based on :

- behaviours
  - [Brooks, 1986], (Steels 89), (robotic)
  - (Drogoul 93) (ethology)
- interactions
  - (Demazeau 93) (image analysis, cartography, ...)
  - (Bura 91) (games)
- situations
  - (Agre 87) (games)
  - (Wavish 90) (design, manufacturing)

Reactive Agent models

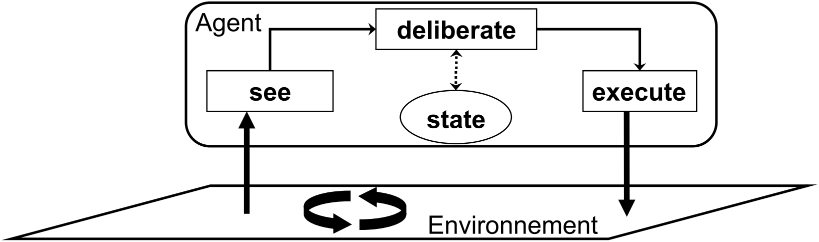
- Example of control cycle of a reactive agent (implemented as a set of condition/action rules):

```
condition-action rules
set of percepts
do {
    percepts := see();
    state := interpret-inputs(percepts);
    rule := match(state,rules);
    execute(rule[action]);
} while (true);
```

Deliberative Agent models

Agent Models Panorama/ Coupling Dimension

- The process cycle of an agent introduces a "deliberate" function between "see" and "execute" in order to choose the "right" action
- Explicit Representation of the environment, of the other agents, of its skills, ...
- History management, ...



Deliberative Agent models

- Goal-based Agents
  - Rich internal state
  - Can anticipate the effects of their actions (e.g. Planning)
  - Take those actions expected to lead toward achievement of goals
  - Capable of reasoning and deducing properties of the world (Knowledge representation)
- Utility-based Agent
  - Decision Theory + Probabilities
  - Use of utility function that maps state (or state sequences) into real numbers
  - Permits more fine-grained reasoning about what can be achieved, what are the trade-offs, conflicting goals, etc

Hybrid Agent Models

Agent Models Panorama/ Coupling Dimension

Hybrid Agent's Model: Reactive and Deliberative Agent

- Reactive agents are too simple - they work well in some scenarios, but they fail to solve complex problems
- Deliberative agents are too complex - they need too much time to deliberate, they fail in very dynamic environments
- The reactive and deliberative behaviors are organized in layers
- Examples: Touring Machines [Ferguson, 1995], InterRaP[Müller and Pischel, 1994],

Situated Agent

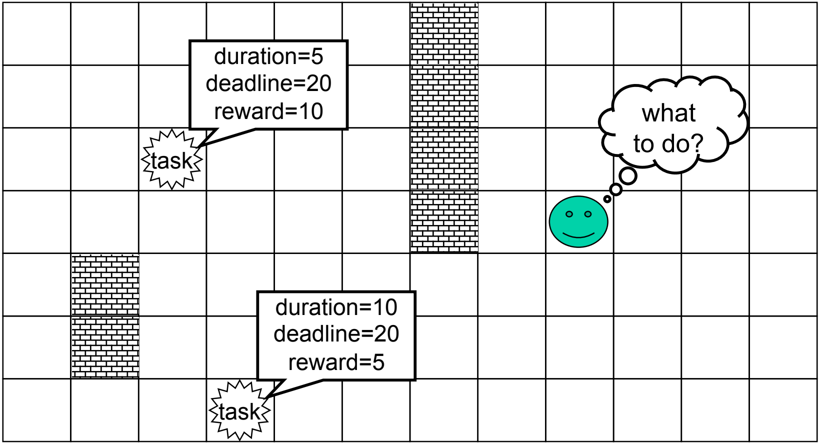
Agent Models Panorama

- Reactive agents: the subsumption architecture [Brooks, 1986]
- Deliberative agents: the BDI model and the PRS architecture
- Hybrid agents: Touring Machines [Ferguson, 1995]

- Reason about themselves and about their environment
- We need to model the environment (subject of the Environment course)
- Our case study:
  - the agents move on a 2D grid
  - there are obstacles blocking their movements
  - an agent should find a path to a task, to execute it, and then to move on to another task
- Note: movement on a grid stands for real movement (e.g., robots) or virtual movement (e.g., searching on Internet)

Case study

Agent Models Panorama/ Situated Agent

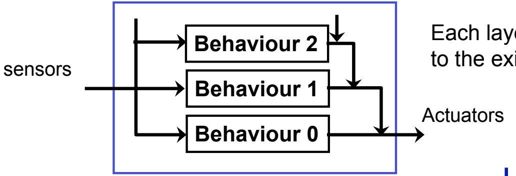


The Subsumption Architecture

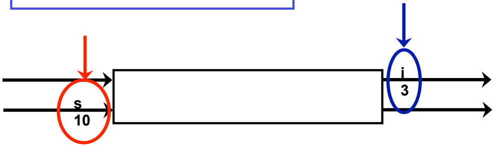
- Agent's decision making is realized through a set of tasks accomplishing behaviors.
- A behavior continually takes perceptual inputs and maps them to an action to perform (finite state machines, no symbolic reasoning, no symbolic representation)
- Many behaviors can fire simultaneously. In order to choose between them, use of a subsumption hierarchy, with the behaviors arranged into layers.
  A higher layer has priority on lower layers (inhibition)

The Subsumption Architecture

Agent Models Panorama/ Situated Agent/ Reactive agents



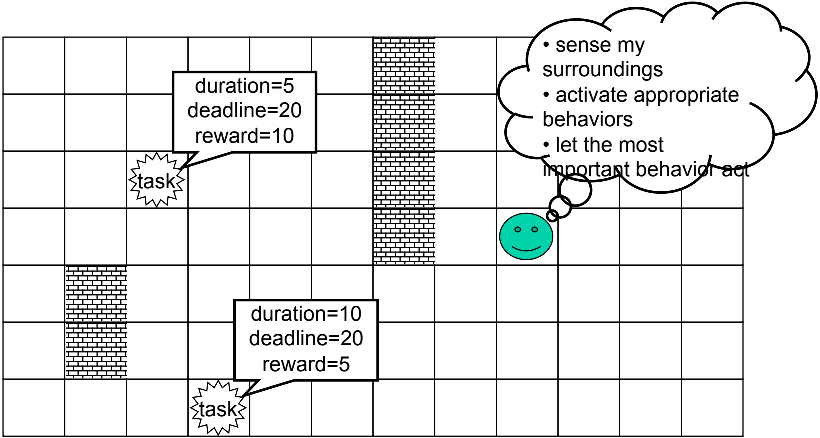
Each layer can be incrementally added to the existing architecture.



Each layer is a set of modules (FSM) which sends messages to each other without central control.
Inputs to modules can be suppressed and Outputs can be inhibited by wires terminating from other modules for a determined time. (subsumption)

The Subsumption Architecture

Agent Models Panorama/ Situated Agent/ Reactive agents



The Subsumption Architecture

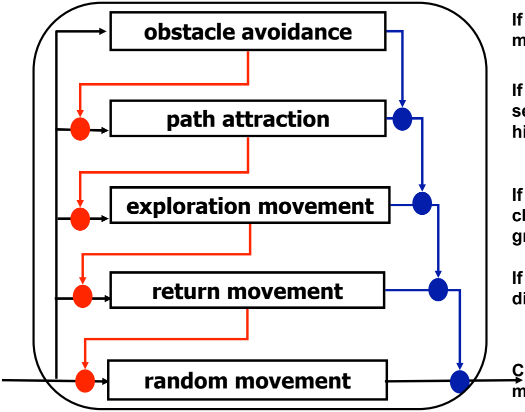
- Does it work? The agents are very simple, there is no symbolic reasoning or representation of their environment...
- It works if there are many agents: "the intelligence is in the system, not in the entities composing it".
- (Steels 89) used this architecture in a scenario very similar with our case study:
  - robots have to collect samples of precious rock (unknown location) and bring them back to a mothership spacecraft.
  - cooperation without direct communication : through the environment.
    - gradient field with a signal generated by the mothership
    - radioactive crumbs are picked up, dropped and detected by robots.

Two sets of behaviors running in parallel:

- Handling behavior
  - If I sense a sample and I don't carry one, I pick it up.
  - If I sense the vehicle-platform and I carry a sample, I drop it.
  - If I carry a sample, I drop 2 crumbs.
  - If I carry no sample and crumbs are detected, I pick up one crumb.
- Movement behaviors organized along a subsumption hierarchy

The Subsumption Architecture

Agent Models Panorama/ Situated Agent/ Reactive agents



If I sense an obstacle in front, I make a random turn.

If I am not carrying a sample and I sense crumbs, I move towards the highest concentration of crumbs.

If I am in exploration mode, I choose the direction of lowest gradient.

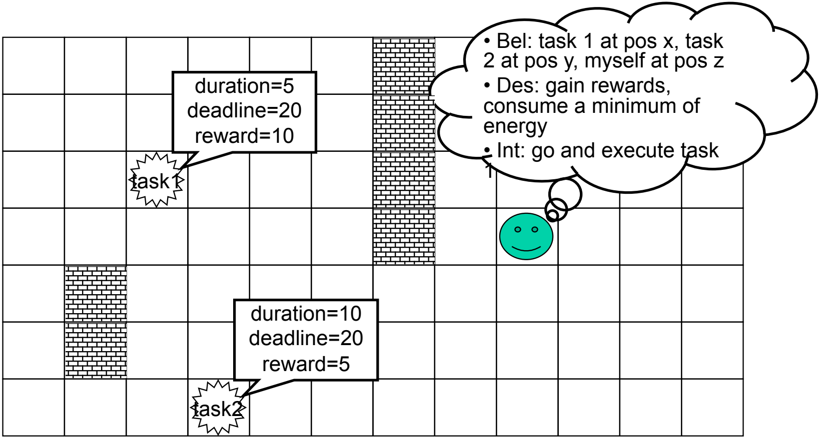
If I am in return mode, I choose the direction of highest gradient.

Choose randomly a direction to move. Move in that direction.

PRS Architecture

- the use of intentions in agent's design [Georgeff and Lansky, 1987, Bratman, 1990]
- the BDI model: an agent contains [Rao et al., 1995]
  - a set of beliefs about itself and the world;
  - a set of (possibly conflicting) desires
  - a set of non-conflicting intentions
  - reasoning mechanisms to update its beliefs, choose the desire(s) to pursue and generate new intentions

PRS Architecture

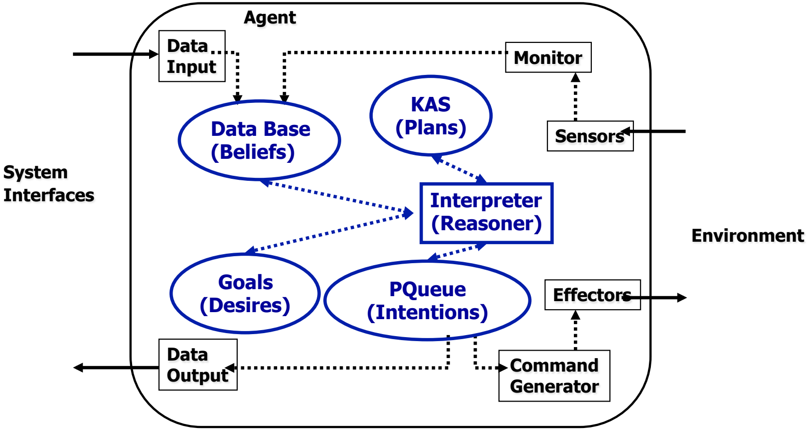


PRS Architecture

BDI Implementations:

- Procedural Reasoning System uses and supports the BDI model [Georgeff and Lansky, 1987]
- BDI-logics - modal operators for Beliefs, Desires and Intentions [Rao et al., 1995]
- BDI applications: Space Shuttle (Diagnosis), Sydney Airport (air traffic control).
- BDI Agents Platform: JACK, Zeus, Jadex, Jason.

PRS Architecture



- The plan-recipes library (KAS) builds the procedural knowledge to satisfy the intentions.
- A plan-recipe (KA) is defined by: a body, triggering condition to activate a plan (Desire), a pre-condition (feasability)

Hybrid agents

Agent Models Panorama/ Situated Agent

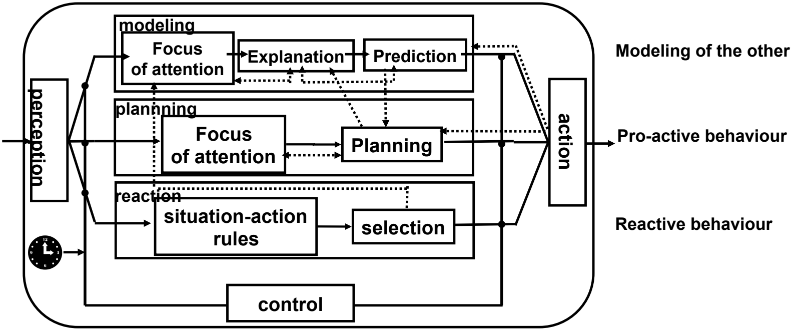
- Reactive agents are too simple - they work well in some scenarios, but they fail to solve complex problems
- Deliberative agents are too complex - they need too much time to deliberate, they fail in very dynamic environments
- Solution: hybrid agents that are both reactive and deliberative, depending on the situation.
- The reactive and deliberative behaviors are organized in layers $\leadsto$ layered architectures.

Touring Machines

- Constrained navigation in dynamic environments
- Consists of three activity producing layers : each layer produces suggestions for the actions to perform.
  - Reactive layer: reactive behaviour
  - Planning Layer: proactive behaviour
  - Modeling Layer: world updates, beliefs; it predicts conflicts between agents and it changes the plans/goals
- Control-subsystem: chooses the active layer: certain observations should never reach certain layers.

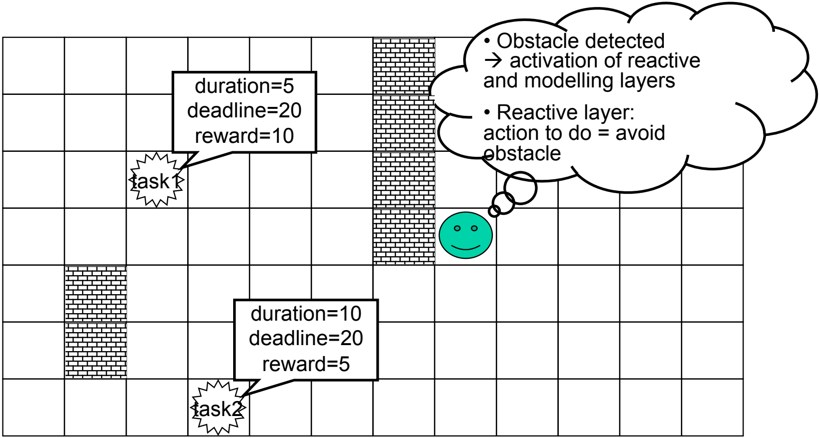
Touring Machines

Agent Models Panorama/ Situated Agent/ Hybrid agents

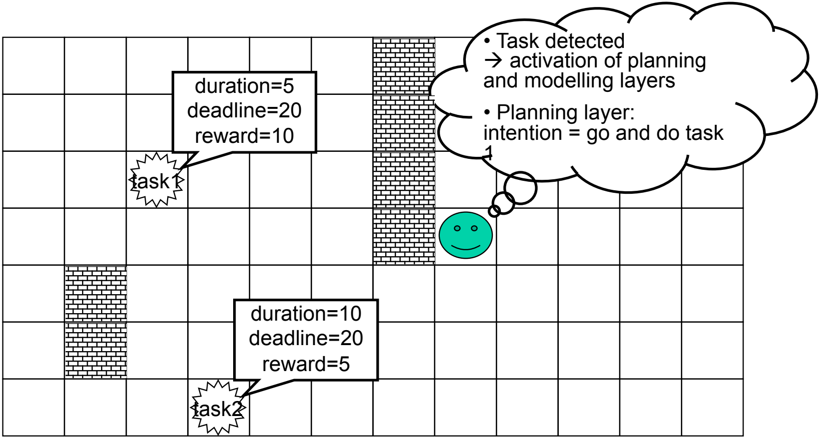


Touring Machines

Agent Models Panorama/ Situated Agent/ Hybrid agents

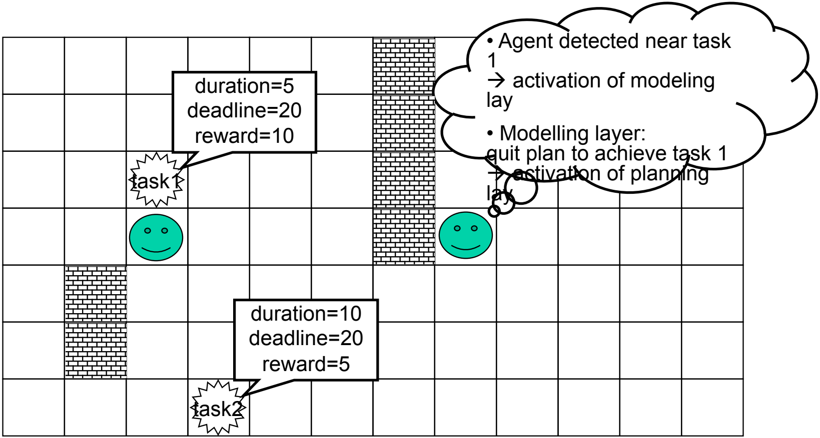


Touring Machines



Touring Machines

Agent Models Panorama/ Situated Agent/ Hybrid agents



Social Agents

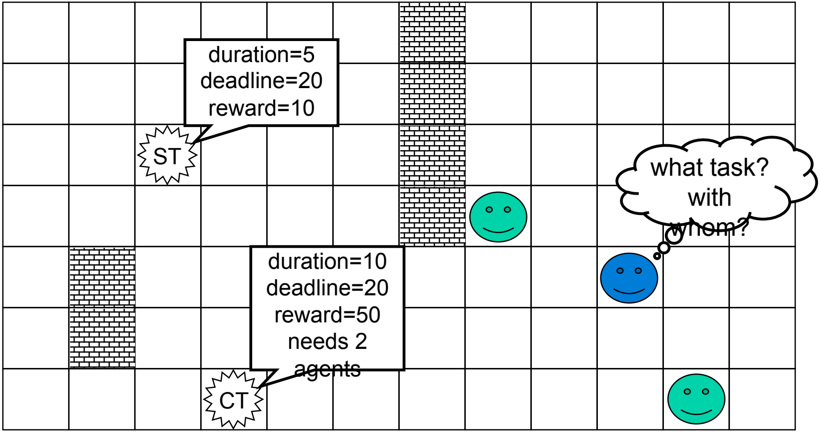
Agent Models Panorama

- AOP/AgentO [Shoham, 1993]
- The InterRaP Architecture [Müller and Pischel, 1994]

- Reason about themselves, their environment and about the interactions with other agents
- We need to model these interactions (subject of the Interaction course)
  - agent interaction is generally done by means of communication via exchanged messages (e.g., request, inform, etc.)
  - how these messages modify the internal state of an agent?
- Our case study:
  - SingleTasks (ST) and CooperativeTasks (CT) that need several agents to execute them and to divide their rewards
  - agents communicate to inform each other about task positions and to form agreements on CT execution.

Case Study

Agent Models Panorama/ Social Agents



Agent0

Three main components :

- a formal language with a syntax and a semantic to describe mental states,
- an interpreted programming language to program agents
- agentification process to convert native applications

Agent : an entity whose state is viewed as consisting of mental components such as beliefs, capabilities, choices, and commitments, (...) What makes any hardware or software component an agent is precisely the fact that one has chosen to analyse and control it in these mental terms. [Shoham, 1993]

Agent0

Agent specified in terms of:

- a set of capabilities (things it can do)
- a set of initial beliefs
- a set of initial commitments (like intentions in BDI)
- a set of commitment rules

Key component, which determines how the agent acts, is the set of commitment rules. Each rule contains:

- a message condition
- a mental condition
- an action

Agent0

- If the message condition matches a message the agent has received and the mental condition matches the beliefs of the agent, the rule fires.
- When a rule fires, the agent becomes committed to the action.
- The operation of an agent is simply:
  1. read all current messages, update beliefs and commitments
  2. execute all commitments where capable of action
  3. goto 1

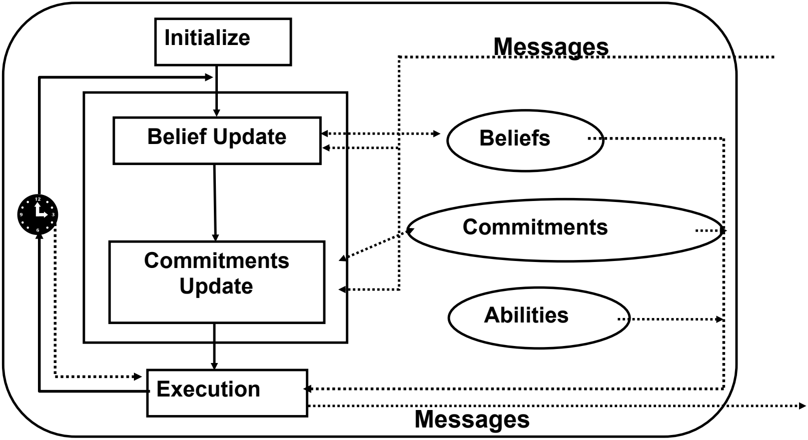
Agent0

- Each action is either:
  - private : an internal subroutine, or
  - communicative : a message sent to other agents
- Messages are constrained to be one of three types:
  - request : perform an action
  - unrequest : refrain from performing an action
  - inform : pass an information

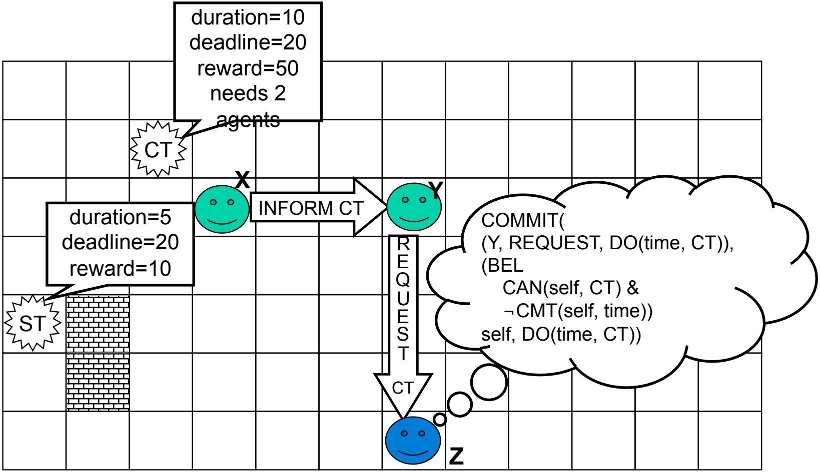
  Request and unrequest messages typically result in a modification of agent's commitments.
  Inform messages result in a change to the agent's beliefs.

Agent0

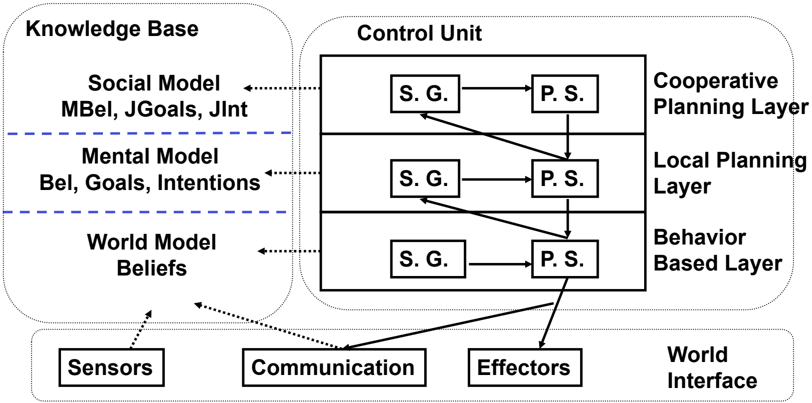
Agent Models Panorama/ Social Agents/ Deliberative Agent



Agent0


duration=10
deadline=20
reward=50
needs 2
agents
CT
X
INFORM CT
Y
duration=5
deadline=20
reward=10
ST
REQUEST
CT
COMMIT(
(Y, REQUEST, DO(time, CT)),
(BEL
CAN(self, CT) &
¬CMT(self, time))
self, DO(time, CT))
Z

The InterRaP architecture

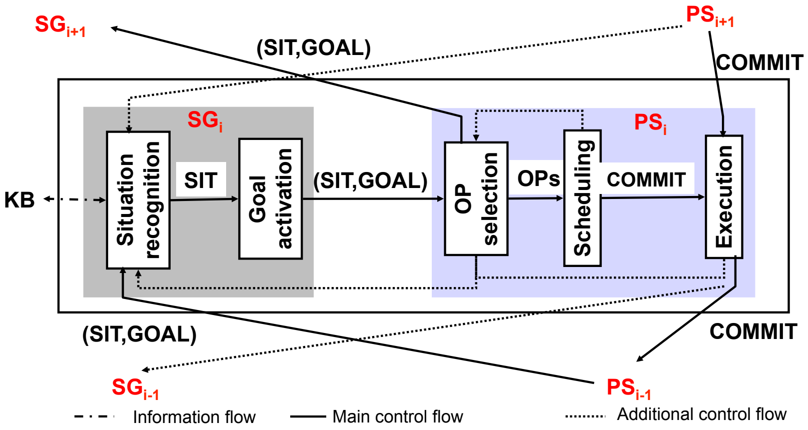


The InterRaP architecture

	BB Layer	LP Layer	CP Layer
Belief Revision	Generation and revision of beliefs (world model)	Abstraction of local beliefs (mental model)	Maintaining models of other agents (social model)
Situation recognition **G**oal activation	Activation of reactor patterns	Recognition of situations requiring local planning	Recognition of situations requiring cooperative planning
Planning **S**cheduling	Reactor: direct link from situations to action sequences	Modifying local intentions; local planning	Modifying joint intentions; cooperative planning.

The InterRaP architecture

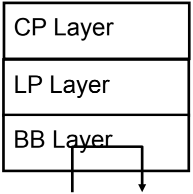
Agent Models Panorama/ Social Agents/ Hybrid Agent



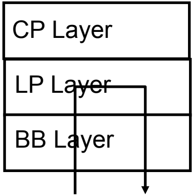
The InterRaP architecture

Agent Models Panorama/ Social Agents/ Hybrid Agent

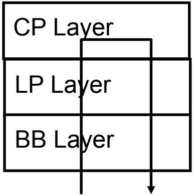
Reactive path



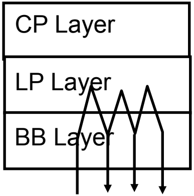
Local planning path (idealized)



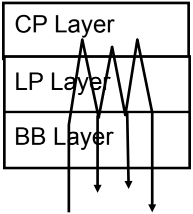
Cooperative path (idealized)



Local planning path (instance)

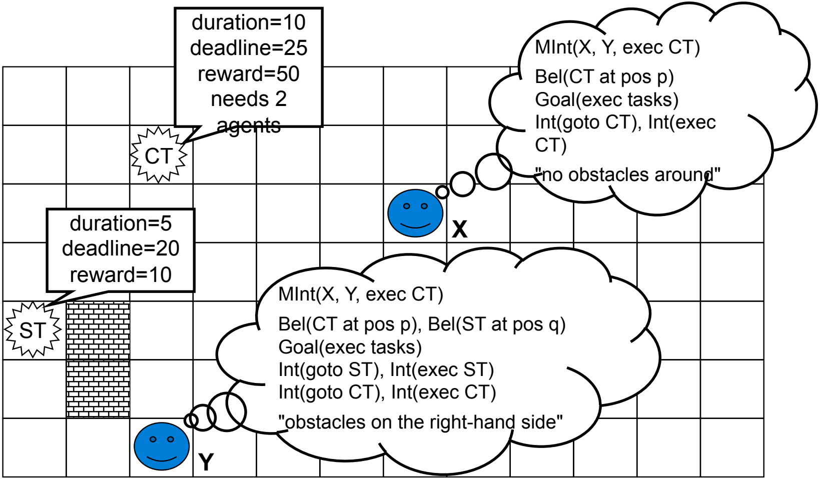


Cooperative path (instance)



The InterRaP architecture

Agent Models Panorama/ Social Agents/ Hybrid Agent



Organized agents

Agent Models Panorama

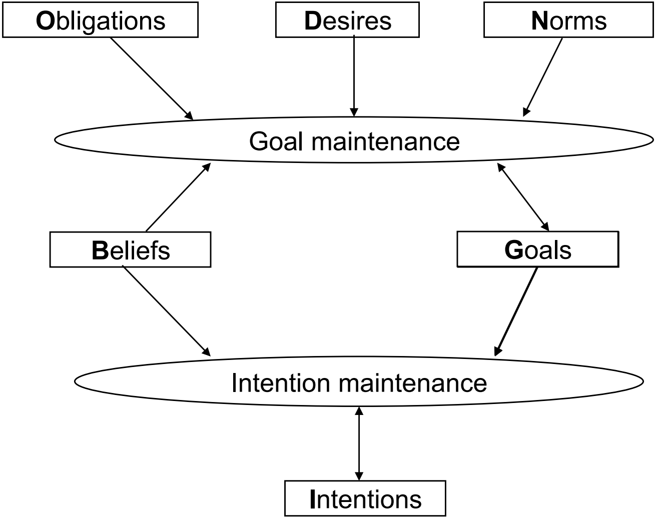
- Reason about themselves, their environment, the interactions with other agents and the organizational structures enforcing these interactions
- We need to model these organizational structures (subject of the Organization course)
  - many notions are used: groups, roles, norms, etc.
  - e.g., a norm saying that a car must stop at the red light
  - agents that violate a norm pay penalities
- Our case study:
  - a norm saying that an agent is forbidden to violate a commitment towards another to cooperatively execute a CT
  - a norm saying that a tax on the reward gained is to be payed

B-DOING

- B-DOING (Dignum 01) extends the BDI model.
- The agent's intentions are generated based on its current beliefs and a set of possibly conflicting goals.
- The goals are generated from:
  - a set of desires: what the agent wants;
  - a set of obligations: what other agents want;
  - a set of norms: what is good for the society.
- B-DOING logic: an extention of BDI-logic with three new modal operators.

B-DOING architecture

Agent Models Panorama/ Organized agents/ Deliberative Agent



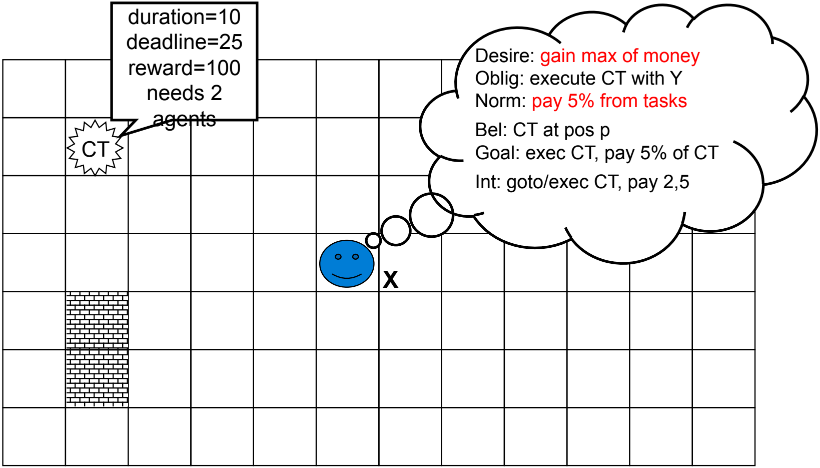
B-DOING architecture

- Example of a control cycle of a BDOING agent
  - *b* : beliefs, *g* : desires, *i* : intentions, *eq* : event queue

(b,g,i) := initialize();
repeat
    options := option_generator(*eq*,*b*,*g*,*i*, **oblEvents**);
    selected := deliberate(*options*, *b*,*g*,*i*, **oblEvents**);
    i := *selected* ∪ *i*;
    execute(*i*);
    eq := see();
    b := update_beliefs(*b*,*eq*);
    (*g*,*i*) := drop_successful_attitudes(*b*,*g*,*i*);
    (*g*,*i*) := drop_impossible_attitudes(*b*,*g*,*i*);
forever

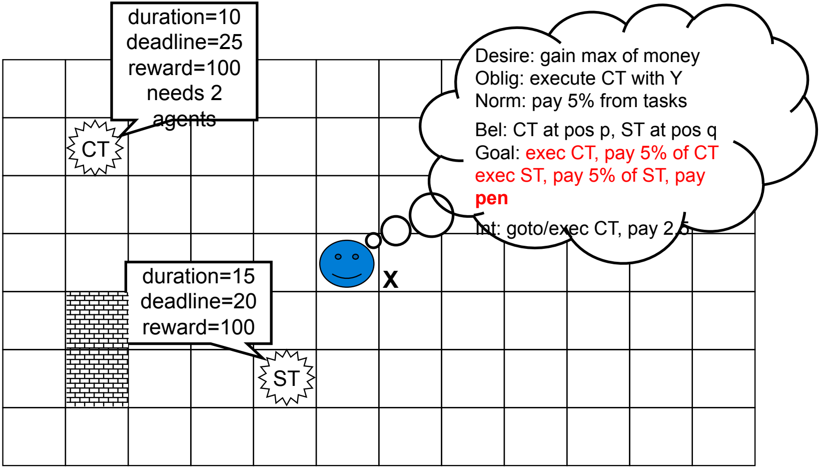
B-DOING architecture

Agent Models Panorama/ Organized agents/ Deliberative Agent



B-DOING architecture

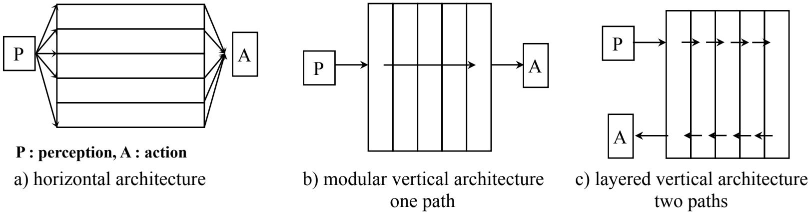
Agent Models Panorama/ Organized agents/ Deliberative Agent



Agent Architectures

Agent Models Panorama

- Modules Organisation:



- Control flow: one / several
- Data flow: broadcast, translation
- Control structure: inhibition, hierarchy, ...

Outline

Agent Oriented Programming

Features

- Reacting to events $\times$ long-term goals
- Course of actions depends on circumstance
- Plan failure (dynamic environments)
- Social ability
- Combination of theoretical and practical reasoning

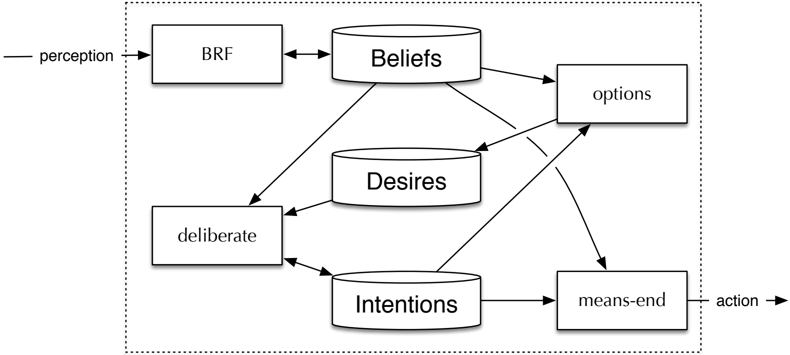
Agent Oriented Programming

Fundamentals

- Use of mentalistic notions and a societal view of computation [Shoham, 1993]
- Heavily influenced by the BDI architecture and reactive planning systems [Bratman et al., 1988]

BDI architecture

(the mentalistic view)



BDI architecture [Wooldridge, 2009]

```
while true do
    B ← brf(B, perception()) ;                         // belief revision
    D ← options(B, I) ;                                // desire revision
    I ← filter(B, D, I) ;                              // deliberation
    π ← plan(B, I, A) ;                                // means-end
    while π ≠ ∅ do
        execute( head(π) )
        π ← tail(π)
```

BDI architecture [Wooldridge, 2009]

```
while true do
    B ← brf(B, perception()) ;                  // belief revision
    D ← options(B, I) ;                         // desire revision
    I ← filter(B, D, I) ;                       // deliberation
    π ← plan(B, I, A) ;                         // means-end
    while π ≠ ∅ do
        execute( head(π) )
        π ← tail(π)
```

fine for pro-activity, but not for reactivity (over commitment)

BDI architecture [Wooldridge, 2009]

```
while true do
    B ← brf(B, perception()) ;                      // belief revision
    D ← options(B, I) ;                             // desire revision
    I ← filter(B, D, I) ;                           // deliberation
    π ← plan(B, I, A) ;                             // means-end
    while π ≠ ∅ do
        execute( head(π) )
        π ← tail(π)
        B ← brf(B, perception())
        if ¬sound(π, I, B) then
            π ← plan(B, I, A)
```

revise commitment to plan – re-planning for context adaptation

BDI architecture [Wooldridge, 2009]

```
while true do
    B ← brf(B, perception()) ;                                   // belief revision
    D ← options(B, I) ;                                          // desire revision
    I ← filter(B, D, I) ;                                        // deliberation
    π ← plan(B, I, A) ;                                          // means-end
    while π ≠ ∅ and ¬succeeded(I, B) and ¬impossible(I, B) do
        execute( head(π) )
        π ← tail(π)
        B ← brf(B, perception())
        if ¬sound(π, I, B) then
            π ← plan(B, I, A)
```

revise commitment to intentions – Single-Minded Commitment

BDI architecture [Wooldridge, 2009]

```
while true do
    B ← brf(B, perception()) ;                                  // belief revision
    D ← options(B, I) ;                                         // desire revision
    I ← filter(B, D, I) ;                                       // deliberation
    π ← plan(B, I, A) ;                                         // means-end
    while π ≠ ∅ and ¬succeeded(I, B) and ¬impossible(I, B) do
        execute( head(π) )
        π ← tail(π)
        B ← brf(B, perception())
        if reconsider(I, B) then
            D ← options(B, I)
            I ← filter(B, D, I)
        if ¬sound(π, I, B) then
            π ← plan(B, I, A)
```

reconsider the intentions (not always!)

Intentions

- Intentions pose problems for the agents: they need to determine a way to achieve them (planning and acting)
- Intentions provide a "screen of admissibility" for adopting new intentions
- Agents keep tracking their success of attempting to achieve their intentions
- Agents should not spend all their time revising intentions (losing pro-activity and reactivity)

Jason

Agent Programming Language

Outline

(BDI & Jason) Hello World – agent bob

```
happy(bob).                                        // B
!say(hello).                                       // D

+!say(X) : happy(bob) <- .print(X).                // I
```

beliefs: prolog like (First Order Logic)

(BDI & Jason) Hello World – agent bob

```
happy(bob).                                  // B
!say(hello).                                 // D
+!say(X) : happy(bob) <- .print(X).          // I
```

beliefs: prolog like (First Order Logic)
desires: prolog like, with ! prefix

(BDI & Jason) Hello World – agent bob

```
happy(bob).                                          // B
!say(hello).                                         // D

+!say(X) : happy(bob) <- .print(X).                  // I
```

beliefs: prolog like (First Order Logic)
desires: prolog like, with ! prefix
plans:

- define when a desire becomes an intention $\rightsquigarrow$ deliberate
- how it is satisfied
- are used for practical reasoning $\rightsquigarrow$ means-end

(BDI & Jason) Hello World – agent bob

desires from perception – options

```
+happy(bob) <- !say(hello).

+!say(X) : not today(monday) <- .print(X).
```

(BDI & Jason) Hello World – agent bob

source of beliefs

```
+happy(bob)[source(A)]
   :  someone_who_knows_me_very_well(A)
   <- !say(hello).

+!say(X) : not today(monday) <- .print(X).
```

(BDI & Jason) Hello World – agent bob

plan selection

```
+happy(H)[source(A)]
   :  sincere(A) & .my_name(H)
   <- !say(hello).

+happy(H)
   :  not .my_name(H)
   <- !say(i_envy(H)).

+!say(X) : not today(monday) <- .print(X).
```

(BDI & Jason) Hello World – agent bob

intention revision

```
+happy(H)[source(A)]
    :  sincere(A) & .my_name(H)
    <- !say(hello).

+happy(H)
    :  not .my_name(H)
    <- !say(i_envy(H)).

+!say(X) : not today(monday) <- .print(X); !say(X).

-happy(H)
    :  .my_name(H)
    <- .drop_intention(say(hello)).
```

(BDI & Jason) Hello World – agent bob

intention revision

```
+happy(H)[source(A)]
    :  sincere(A) & .my_name(H)
    <- !say(hello).

+happy(H)
    :  not .my_name(H)
    <- !say(i_envy(H)).

+!say(X) : not today(monday) <- .print(X); !say(X).

-happy(H)
    :  .my_name(H)
    <- .drop_intention(say(hello)).
```

(BDI & Jason) Hello World – agent bob

intention revision / Features

- we can have several intentions based on the same plans

$\leadsto$ running concurrently

- long term goal running

$\leadsto$ reaction meanwhile!

Outline

AgentSpeak

The foundational language for *Jason*

- Originally proposed by Rao [Rao, 1996]
- Programming language for BDI agents
- Elegant notation, based on logic programming
- Inspired by PRS [Georgeff and Lansky, 1987], dMARS [d'Inverno et al., 1997], and BDI Logics [Rao et al., 1995]
- Abstract programming language aimed at theoretical results

Jason

A practical implementation of a variant of AgentSpeak

- *Jason* implements the operational semantics of a variant of AgentSpeak
- Has various extensions aimed at a more practical programming language (e.g. definition of the MAS, communication, ...)
- Highly customised to simplify extension and experimentation
- Developed by Jomi F. Hübner, Rafael H. Bordini, and others

Main Language Constructs

Beliefs: represent the information available to an agent (e.g. about the environment or other agents)

Goals: represent states of affairs the agent wants to bring about

Plans: are recipes for action, representing the agent's know-how

Events: happen as consequence to changes in the agent's beliefs or goals

Intentions: plans instantiated to achieve some goal

Main Language Constructs and Runtime Structures

Beliefs: represent the information available to an agent (e.g. about the environment or other agents)

Goals: represent states of affairs the agent wants to bring about

Plans: are recipes for action, representing the agent's know-how

Events: happen as consequence to changes in the agent's beliefs or goals

Intentions: plans instantiated to achieve some goal

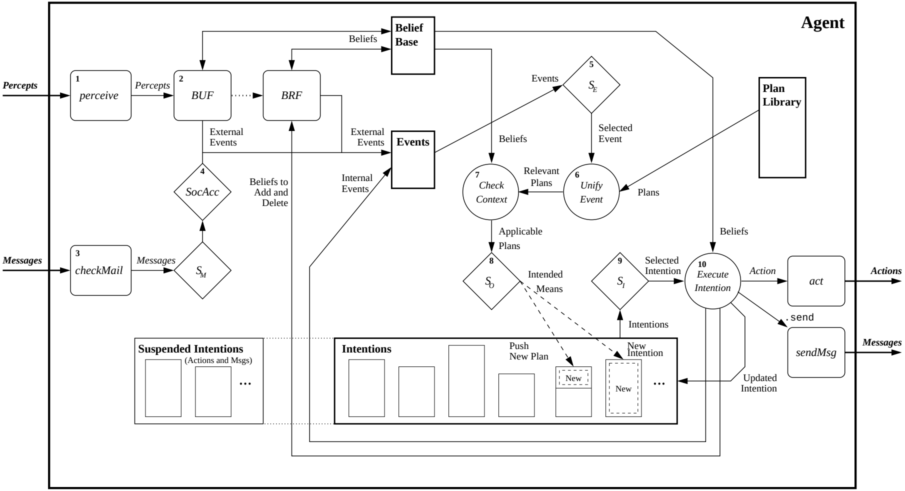
Outline

Basic Reasoning cycle

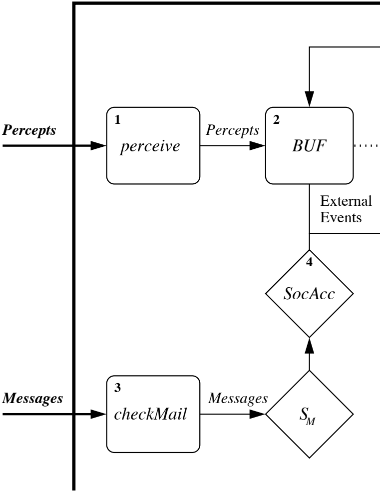
runtime interpreter

- perceive the environment and update belief base
- process new messages
- select event
- select relevant plans
- select applicable plans
- create/update intention
- select intention to execute
- execute one step of the selected intention

Jason Reasoning Cycle

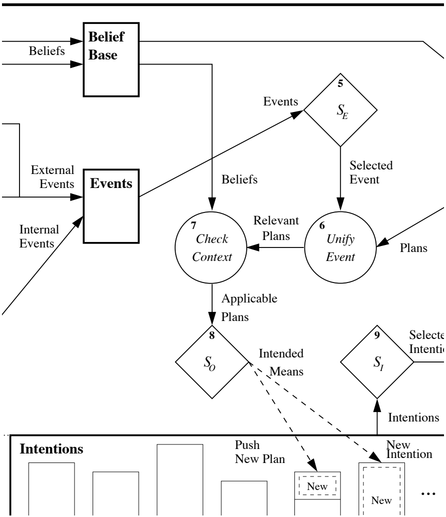


Jason Reasoning Cycle



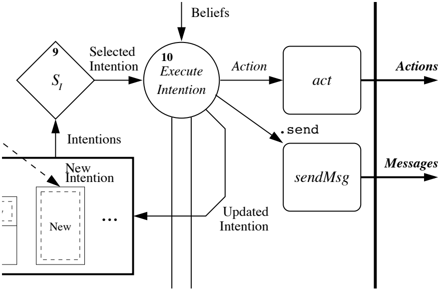
- machine perception
- belief revison
- knowledge representation
- communication, argumentation
- trust
- social power

Jason Reasoning Cycle



- planning
- reasoning
- decision theoretic techniques
- learning (reinforcement)

Jason Reasoning Cycle



- intention reconsideration
- scheduling
- action theories

Outline

Beliefs — Representation

Syntax

Beliefs are represented by annotated literals of first order logic

functor($term_1$, ..., $term_n$)[$annot_1$, ..., $annot_m$]

Example (belief base of agent Tom)

```
red(box1)[source(percept)].
friend(bob,alice)[source(bob)].
lier(alice)[source(self),source(bob)].
~lier(bob)[source(self)].
```

Beliefs — Dynamics I

by perception

beliefs annotated with source(percept) are automatically updated accordingly to the perception of the agent

by intention

the plan operators + and - can be used to add and remove beliefs annotated with source(self) (mental notes)

```
+lier(alice); // adds lier(alice)[source(self)]
-lier(john); // removes lier(john)[source(self)]
```

Beliefs — Dynamics II

by communication

when an agent receives a tell message, the content is a new belief annotated with the sender of the message

```
.send(tom,tell,lier(alice)); // sent by bob
// adds lier(alice)[source(bob)] in Tom's BB
...
.send(tom,untell,lier(alice)); // sent by bob
// removes lier(alice)[source(bob)] from Tom's BB
```

Goals — Representation

Types of goals

- Achievement goal: goal to do
- Test goal: goal to know

Syntax

Goals have the same syntax as beliefs, but are prefixed by
! (achievement goal) or
? (test goal)

Example (Initial goal of agent Tom)

```
!write(book).
!~read(book).
```

Goals — Dynamics I

by intention

the plan operators **!** and **?** can be used to add a new goal annotated with source(self)

```
...
// adds new achievement goal !write(book)[source(self)]
!write(book);
...
!~read(book);

// adds new test goal ?publisher(P)[source(self)]
?publisher(P);
...
?~bought(P);
```

Goals — Dynamics II

by communication – achievement goal

when an agent receives an achieve message, the content is a new achievement goal annotated with the sender of the message

```
.send(tom,achieve,write(book)); // sent by Bob
// adds new goal write(book)[source(bob)] for Tom
...
.send(tom,unachieve,write(book)); // sent by Bob
// removes goal write(book)[source(bob)] for Tom
```

Goals — Dynamics III

by communication – test goal

when an agent receives an askOne or askAll message, the content is a new test goal annotated with the sender of the message

```
.send(tom,askOne,published(P),Answer); // sent by Bob
// adds new goal ?publisher(P)[source(bob)] for Tom
// the response of Tom will unify with Answer
```

Triggering Events — Representation

- Events happen as consequence to changes in the agent's beliefs or goals
- An agent reacts to events by executing plans
- Types of plan triggering events

+b	(belief addition)
-b	(belief deletion)
+!g	(achievement-goal addition)
-!g	(achievement-goal deletion)
+?g	(test-goal addition)
-?g	(test-goal deletion)

Plans — Representation

An AgentSpeak plan has the following general structure:

triggering_event : context <- body.

where:

- the triggering event denotes the events that the plan is meant to handle
- the context represent the circumstances in which the plan can be used
- the body is the course of action to be used to handle the event if the context is believed true at the time a plan is being chosen to handle the event

Plans — Operators for Plan **Context**

Boolean operators

&	(and)
|	(or)
not	(not)
=	(unification)
>, >=	(relational)
<, <=	(relational)
==	(equals)
\ ==	(different)

Arithmetic operators

+	(sum)
-	(subtraction)
*	(multiply)
/	(divide)
div	(divide – integer)
mod	(remainder)
**	(power)

Plans — Operators for Plan **Body**

```
+rain :  time_to_leave(T) & clock.now(H) & H >= T
   <- !g1;           // new sub-goal
      !!g2;          // new goal
      ?b(X);         // new test goal
      +b1(T-H);      // add mental note
      -b2(T-H);      // remove mental note
      -+b3(T*H);     // update mental note
      jia.get(X);    // internal action
      X > 10;        // constraint to carry on
      close(door);// external action
      !g3[hard_deadline(3000)].   // goal with deadline
```

Plans — Example

```
+green_patch(Rock)[source(percept)]
    :  not battery_charge(low)
    <- ?location(Rock,Coordinates);
       !at(Coordinates);
       !examine(Rock).

+!at(Coords)
    :  not at(Coords) & safe_path(Coords)
    <- move_towards(Coords);
       !at(Coords).
+!at(Coords)
    :  not at(Coords) & not safe_path(Coords)
    <- ...
+!at(Coords) :  at(Coords).
```

Plans — Dynamics

The plans that form the plan library of the agent come from

- initial plans defined by the programmer
- plans added dynamically and intentionally by
  - .add_plan
  - .remove_plan
- plans received from
  - tellHow messages
  - untellHow

A note about "Control"

Agents can control (manipulate) their own (and influence the others)

- beliefs
- goals
- plan

By doing so they control their behaviour

The developer provides initial values of these elements and thus also influence the behaviour of the agent

Outline

Failure Handling: Contingency Plans

Example (blind commitment to g)

```
+!g :  g.  // g is a declarative goal

+!g :  ...  <- a1; ?g.
+!g :  ...  <- a2; ?g.
+!g :  ...  <- a3; ?g.

+!g :  true <- !g.  // keep trying
-!g :  true <- !g.  // in case of some failure

+g :  true <- .succeed_goal(g).
```

Failure Handling: Contingency Plans

Example (single minded commitment)

```
+!g :  g.  // g is a declarative goal

+!g :  ...  <- a1; ?g.
+!g :  ...  <- a2; ?g.
+!g :  ...  <- a3; ?g.

+!g :  true <- !g.  // keep trying
-!g :  true <- !g.  // in case of some failure

+g :  true <- .succeed_goal(g).
+f :  true <- .fail_goal(g).  // f is the drop condition for g
```

Failure Handling: Compiler pre-processing – directives

Example (single minded commitment)

```
{ begin smc(g,f)}
   +!g :  ...  <- a1.
   +!g :  ...  <- a2.
   +!g :  ...  <- a3.
{ end }
```

Meta Programming

Example (an agent that asks for plans *on demand*)

```
-!G[error(no_relevant)] :  teacher(T)
   <- .send(T, askHow, { +!G }, Plans);
      .add_plan(Plans);
      !G.
```

in the event of a failure to achieve **any** *goal G due to no relevant plan, asks a teacher for plans to achieve G and then try G again*

- The failure event is annotated with the error type, line, source, ... error(no_relevant) means no plan in the agent's plan library to achieve G
- { +!G } is the syntax to enclose triggers/plans as terms

Other Language Features

Strong Negation

```
+!leave(home)
   :  ~raining
   <- open(curtains); ...

+!leave(home)
   :  not raining & not ~raining
   <- .send(mum,askOne,raining,Answer,3000); ...
```

Prolog-like Rules in the Belief Base

```
tall(X) :-
   woman(X) & height(X, H) & H > 1.70
   |
   man(X) & height(X, H) & H > 1.80.

likely_color(Obj,C) :-
   colour(Obj,C)[degOfCert(D1)] &
   not (colour(Obj,_)[degOfCert(D2)] & D2 > D1) &
   not ~colour(C,B).
```

Plan Annotations

- Like beliefs, plans can also have annotations, which go in the plan label
- Annotations contain meta-level information for the plan, which selection functions can take into consideration
- The annotations in an intended plan instance can be changed dynamically (e.g. to change intention priorities)
- There are some pre-defined plan annotations, e.g. to force a breakpoint at that plan or to make the whole plan execute atomically

Example (an annotated plan)

```
@myPlan[chance_of_success(0.3), usual_payoff(0.9),
        any_other_property]
+!g(X) : c(t) <- a(X).
```

Internal Actions

- Unlike actions, internal actions do not change the environment
- Code to be executed as part of the agent reasoning cycle
- AgentSpeak is meant as a high-level language for the agent's practical reasoning and internal actions can be used for invoking legacy code elegantly

- Internal actions can be defined by the user in Java

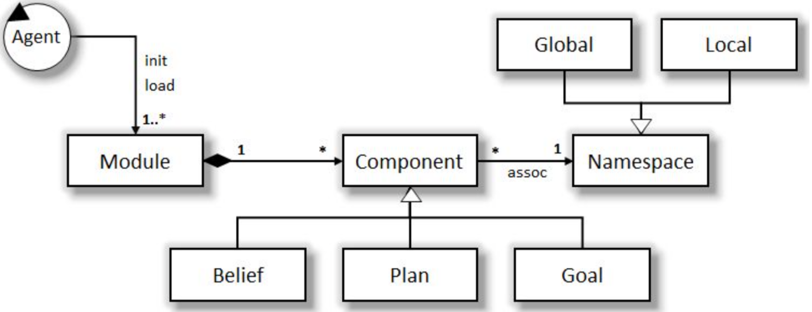
```
libname.action_name(...)
```

Standard Internal Actions

- Standard (pre-defined) internal actions have an empty library name
  - `.print(`$term_1$`,`$term_2$`,...)`
  - `.union(`$list_1$`, `$list_2$`, `$list_3$`)`
  - `.my_name(`*var*`)`
  - `.send(`*ag*`,`*perf*`,`*literal*`)`
  - `.intend(`*literal*`)`
  - `.drop_intention(`*literal*`)`

- Many others available for: printing, sorting, list/string operations, manipulating the beliefs/annotations/plan library, creating agents, waiting/generating events, etc.

Namespaces & Modularity



Namespaces & Modularity

```
{include("initiator.asl", pc)}
{include("initiator.asl", tv)}

!pc::startCNP(fix(pc)).
!tv::startCNP(fix(tv)).

+pc::winner(X)
   <- .print(X).
```

Inspection of agent **alice**

- Beliefs

tv::
introduction(participant)[source(compar
propose(*11.075337225252543*)[sourc
propose(*12.043311087442898*)[sourc
propose(*12.81277904935436*)[source
winner(company_A1)[source(self)].

#8priv::
state(finished)[source(self)].

pc::
introduction(participant)[source(compar
propose(*11.389500048463455*)[sourc
propose(*11.392553683771682*)[sourc
propose(*12.348901000262853*)[sourc
winner(company_A2)[source(self)].

Concurrent Plans

```
+!ga <- ...; !gb; ....
+!gb <- ...; (!g1 |&| !g2); a1; ...  // fork-join-and
// a1 will be executed when !g2 and !g1 will be achieved

+!ga <- ...; !gb; ....
+!gb <- ...; (!g1 ||| !g2); a1; ...  // fork-join-xor
// a1 will be executed after !g2 or !g1 are achieved
// when one of !g2 or !g1 is achieved the other is dropped
-!g :  true <- !g.  // in case of some failure

+g :  true <- .succeed_goal(g).
+f :  true <- .fail_goal(g).  // f is the drop condition for g
```

Jason Customisations

- Agent class customisation:
  selectMessage, selectEvent, selectOption, selectIntention, buf, brf, ...
- Agent architecture customisation:
  perceive, act, sendMsg, checkMail, ...
- Belief base customisation:
  add, remove, contains, ...
  - Example available with *Jason*: persistent belief base (in text files, in data bases, ...)

Outline

Jason × Java

Consider a very simple robot with two goals:

- when a piece of gold is seen, go to it
- when battery is low, go charge it

Java code – go to gold

```
public class Robot extends Thread {
   boolean seeGold, lowBattery;
   public void run() {
      while (true) {
          while (! seeGold) {
              a = randomDirection();
              doAction(go(a));

          }
          while (seeGold) {
              a = selectDirection();

              doAction(go(a));

}  }  }   }
```

Java code – charge battery

```
public class Robot extends Thread {
   boolean seeGold, lowBattery;
   public void run() {
      while (true) {
          while (!  seeGold) {
              a = randomDirection();
              doAction(go(a));
              if (lowBattery) charge();
          }
          while (seeGold) {
              a = selectDirection ();
              if (lowBattery) charge();
              doAction(go(a));
              if (lowBattery) charge();
} } }   }
```

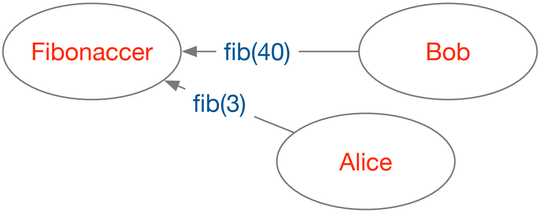
Jason code

```
direction(gold)   :- see(gold).
direction(random) :- not see(gold).

+!find(gold)                        // long term goal
   <- ?direction(A);
      go(A);
      !find(gold).
+battery(low)                       // reactivity
   <- !charge.

^!charge[state(started)]            // goal meta-events
   <- .suspend(find(gold)).
^!charge[state(finished)]
   <- .resume(find(gold)).
```

Fibonacci calculator server – “java” version

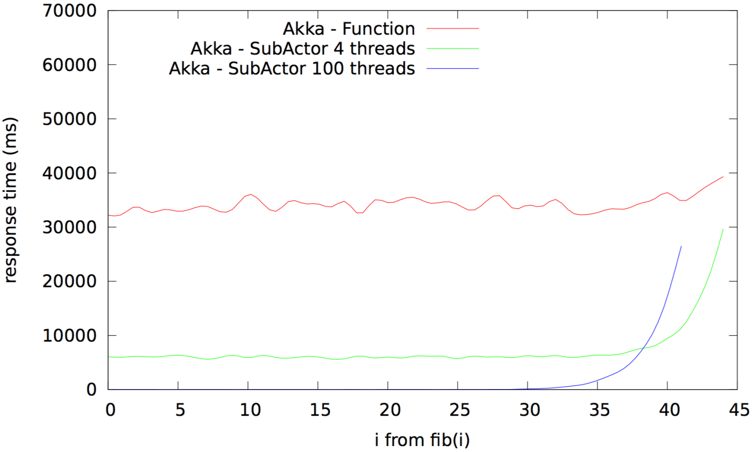



```
while true
  m = receiveMsg()
  if m == fib(N)
     m.answer(fib(m.getArg(0)))
  ...
```

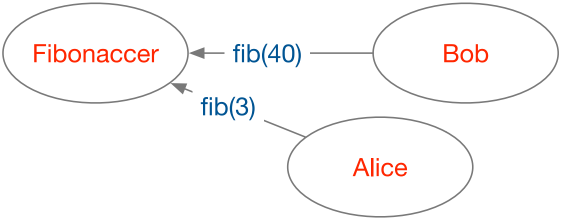
```
int fib(int n)
   if n <= 2
     return 1
   else
     return fib(n-1)+fib(n-2)
```

How long will Alice wait?

Fibonacci calculator server – Akka



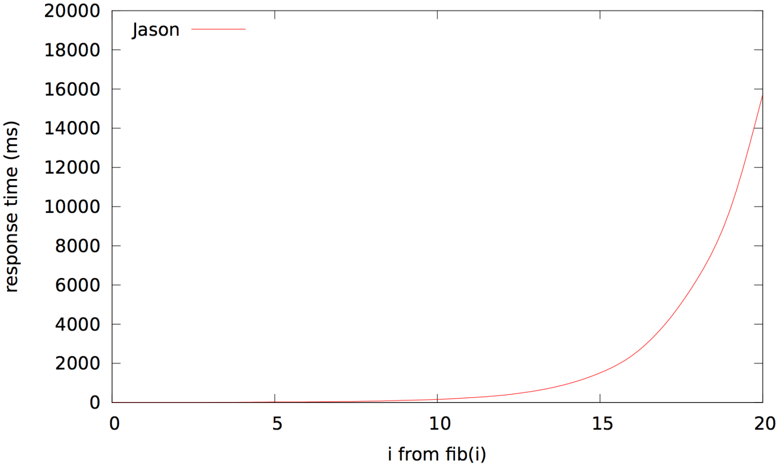
Fibonacci calculator agent – Jason version




```
+?fib(1,1).
+?fib(2,1).
+?fib(N,F) <- ?fib(N-1,A); ?fib(N-2,B); F = A+B.
```

How long will Alice wait?

Fibonacci calculator agent – Jason version



Jason × Prolog

- With the *Jason* extensions, nice separation of theoretical and practical reasoning
- BDI architecture allows
  - long-term goals (goal-based behaviour)
  - reacting to changes in a dynamic environment
  - handling multiple foci of attention (concurrency)
- Acting on an environment and a higher-level conception of a distributed system

Outline

Some Shortfalls

- IDEs and programming tools are still not anywhere near the level of OO languages
- Debugging is a serious issue — much more than “mind tracing” is needed
- Combination with organisational models is very recent — much work still needed
- Principles for using declarative goals in practical programming problems still not “textbook”
- Large applications and real-world experience much needed!

Some Trends

- Modularity and encapsulation
- Debugging MAS is hard: problems of concurrency, simulated environments, emergent behaviour, mental attitudes
- Logics for Agent Programming languages
- Further work on combining with interaction, environments, and organisations
- We need to put everything together: rational agents, environments, organisations, normative systems, reputation systems, economically inspired techniques, etc.

$\leadsto$ Multi-Agent Programming

Some Related Projects I

- Speech-act based communication
  Joint work with Renata Vieira, Álvaro Moreira, and Mike Wooldridge
- Cooperative plan exchange
  Joint work with Viviana Mascardi, Davide Ancona
- Plan Patterns for Declarative Goals
  Joint work with M.Wooldridge
- Planning (Felipe Meneguzzi and Colleagues)
- Web and Mobile Applications (Alessandro Ricci and Colleagues)
- Belief Revision
  Joint work with Natasha Alechina, Brian Logan, Mark Jago

Some Related Projects II

- Ontological Reasoning
  - Joint work with Renata Vieira, Álvaro Moreira
  - JASDL: joint work with Tom Klapiscak
- Goal-Plan Tree Problem (Thangarajah et al.)
  Joint work with Tricia Shaw
- Trust reasoning (ForTrust project)
- Agent verification and model checking
  Joint project with M.Fisher, M.Wooldridge, W.Visser, L.Dennis, B.Farwer

Some Related Projects III

- Environments, Organisation and Norms
  - Normative environments
    Join work with A.C.Rocha Costa and F.Okuyama
  - MADeM integration (Francisco Grimaldo Moreno)
  - Normative integration (Felipe Meneguzzi)
- More on `jason.sourceforge.net`, related projects

Summary

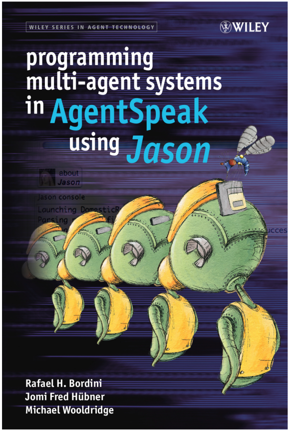
- AgentSpeak
  - Logic + BDI
  - Agent programming language
- *Jason*
  - AgentSpeak interpreter
  - Implements the operational semantics of AgentSpeak
  - Speech-act based communicaiton
  - Highly customisable
  - Useful tools
  - Open source
  - Open issues

Acknowledgements

- Many thanks to the
  - Various colleagues acknowledged/referenced throughout these slides
  - *Jason* users for helpful feedback
  - CNPq for supporting some of our current researh

Further Resources

- `http://jason.sourceforge.net`
- R.H. Bordini, J.F. Hübner, and M. Wooldrige
  Programming Multi-Agent Systems in AgentSpeak using *Jason*
  John Wiley & Sons, 2007.



Multi-Agent Oriented Programming

The JaCaMo Platform

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