Introduzione ai sistemi multi-agente basati su logica computazionale

Paolo Torroni
DEIS, Università di Bologna

Outline

1. Introduction to multi-agent systems and their applications
2. Logic (programming)-based agent languages, architectures, and frameworks

Part One

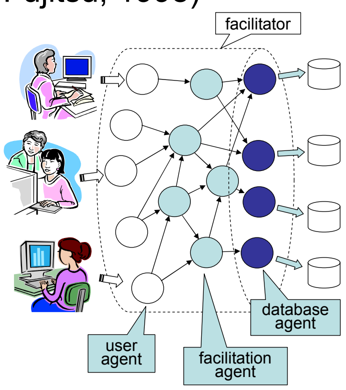
Introduction to multi-agent systems and their applications

Overview

- Agent research: theory and practice
  - difficult even to *define* the overloaded concept of ‘agent’
  - many industrial/commercial applications already exist which directly or indirectly refer to the agent paradigm
- Part One: application perspective
  - to motivate the use of agents in concrete scenarios,
  - to single out a set of characteristics that distinguish agents from other computational paradigms
- Discuss about the use and importance of logics in the development of agent applications

Virtually integrated Distributed DBs (Format-X, Fujitsu, 1998)

- Environments where databases are necessarily distributed:
  - security
  - management
  - sharing maintenance
- E.g.: *Steel Plant* : a steel making company can quickly find parts to repair equipment
  - from within the company
  - from equipment manufacturers
  - from plants of other steel-making companies



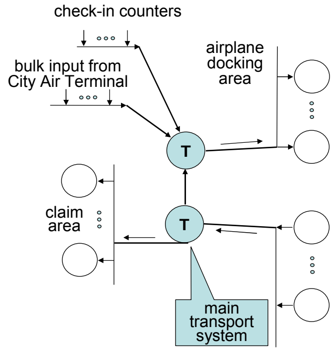
- Each agent has a set of rules {condition} → {agent}, e.g.: [*Bay area*] and [*motors*] → `bay.area@tcals.or.jp`
- When a user sends a request to the user agent, a database navigation phase is started, based on the *conditions* of requests
- If the conditions are consistent with the conditions of a rule (no contradiction): *fwd*
- *Advantages:*
  - load balance
  - agent-local maintenance
  - distribution of maintenance and management
  - agent-based security
  - scalability
  - robustness

Scenario #1: *knowledge integration*

- Fujitsu's Format-X is an example of knowledge integration based on agents
- Some other experiences:
  - Information and Knowledge intergration (SAGE and FIND Future), Fujitsu (2000)
  - Web-linked Integration of Network-based Knowledge (WINK), GFormula (2001)
  - Distributed Information Systems and Intelligent Information Integration, ITC-IRST (Trento)
  - Oracle Intelligent Agents (2000)
  - Business Process Management, Agentis Software
- Advantages of an agent-based architecture

Baggage Handling System (Flavors Technology Inc.,)

- Denver Int'l Airport
  - *4000* telecarts that carry bags at *28 kmph*, servicing *20* airlines along *32 km* of track
  - control handled by *64* PCs, hooked to *5,800* electric eyes, *315* radio receivers, *182* switches, and at least *60* bar code scanners
  - it didn't work!! *1 year delay*, *$500K per day*



Problems with a centralized control

- Dimension of the problem
- Complexity of the solution (controller programs and mainframe)
- Chaos (performance or several components depending on many factors)
- Maintenance
- Difficulty in tracking problems
- Real-time scheduling

Scenario #2: *distributed scheduling*

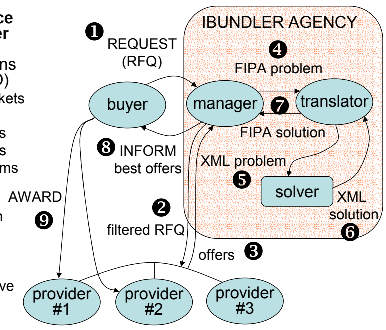
- Motivation:
  - **uncertainty** in the availability of resources
  - **multi-objective optimization** problem
  - **accuracy of data** (better if optimization is solved at the source)
  - **sub-optimal solutions** are often enough
  - **information persistence, self-configurability, inter-operability of software** call for the need of distribution of information processing and integration of planning and execution
- Advantages:
  - scalability (time taken to get to a sub-optimal solution)
  - modelling (agents can model resources and their constraints)
- Other experiences:
  - ANTS (Agent Network for Task Scheduling and Execution), Deneb robotics, SRI Int.
  - IntelliDiary, Distributed Schedule Management System, Fujitsu

Similar problems: *supply chain management and manufacturing*

- GM Paint System, Flavors Technology Inc.
- Distributed control, Rockwell Automation
- Manufacturing Agility Server, Flavors Technology Inc.
- Holonic Manufacturing Systems (HMS), consortium including: Hitachi, Toshiba, Softing GmbH, Aitec, Anca, Broken Hill, Mandrelli SpA, Nestlé, Yaskawa, Rockwell/Allen Bradley
- Supply chain planning, Lost wax

Market based resource allocation

- IBundler: **negotiation service** for buying agents and **winner determination service** for reverse combinatorial auctions with side constraints (iSOCO)
  - negotiate over multiple markets
  - offer aggregation
  - business sharing constraints
  - constraints over single items
  - constraints over multiple items
  - specification of providers' capacities
  - multiple bids over each item
  - combinatorial offers
  - multi-unit offering
  - packing constraints
  - complementary and exclusive offers

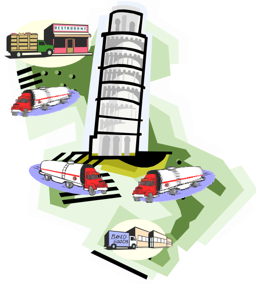


Scenario #3: *e-procurement*

- Advantages for the buyer:
  - reduced time and cost of the whole sourcing process
  - simplified decision-making and supplier selection process
  - process automation
  - quality improvement and time to market reduction
- Advantages for the seller:
  - companies can access new markets
  - selling process cost reduced
  - competitive advantage for the buyer
- Which parts can be automated, and how?

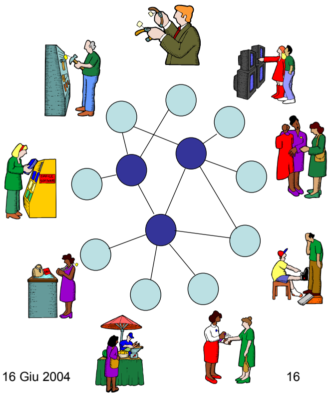
Scenario #4: Distribution and logistics

- Highly dynamic domain:
  - weather
  - work stoppages due to funds/material shortages
  - congested traffic
  - …
- What can be done?
  - trucks ↔ agents
  - automatic negotiation (e.g., Contract Net Protocol)
  - find similar orders
  - transportation management and just-in-time vehicle re-routing,



Scenario #5: *customer-oriented services*

- High diversity of customers:
  - needs
  - knowledge
  - constraints
  - priority
- E.g. U.S. State Public Housing Authority (Agentis)
  - tear down and rebuild public housing for 160,000 families
  - off-the-shelf solutions are no good: highly customized management required
  - traditional approach 1 year



More scenarios

- **Agents for armed forces**, Cambridge Consultants W.P.,
- **Health care** (information selection and filtering, proactive monitoring), Cambridge Consultants W.P.
- **Crawling agents**, iSOCO, GruSMA
- **Games and film industry** (The Lord of The Rings)
- **Mission critical** unmanned vehicle piloting, agent-software
- **PDA-oriented services**: virtual secretaries and recommender systems, travel planners, …, see Siemens MOTIV and AgentCities projects
- **Human-Machine Interfaces**: humanoid cartoon characters, Fujitsu (1999) and Animation systems for interface agents, Fraunhofer IGD
- **Network management**, Fujitsu (2001)
- **Simulation**: Central JR Shinkhansen, Flavors Technology Inc., (1998), Air traffic management, Intelligent Automation Inc., Multi-modal transportation, Ketensimulator, TNO

Why agents?

1. ***Agents don't get tired*** *or frustrated with negotiation*

2. Agent ***negotiation can happen more often***

3. In complex negotiation settings, automated agents will be more successful at obtaining better deals because they ***can keep track of more options*** (K. Woghiren, LostWax)

- …this allows for:
  - Market searching, sorting, monitoring, and negotiation
  - Dynamic solutions
  - Customer-oriented solutions
- Other experiences:
  - Living markets, living systems AG (2001; now Whitestain Technologies)
  - Lost wax
  - Adaptive Deal Flow Optimization, living systems AG (2002)

What challenges

- buyers/market owners need to **trust** agents
- users need be able to **specify** the behaviour of agents
- infrastructures / **interoperability** !!
  - ***CUSTOMERS*** *do not have the financial or technical clout to force the development of interoperable solutions, or to test products to ensure that they really are interoperable*
  - ***USERS*** *and IT staff in large business may want interoperability, but will have a difficult time justifying the possible long-term savings vs. the short-term costs* (O. Omidvar, ATP PM)
- agents must be **intelligent** in order to be able to negotiate effectively
- agents need to be able to **adapt** to new scenaria

→ *role of logic?*

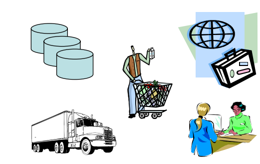
Summary: you should consider looking at agent architectures…

- When the **metaphor is appropriate** (*customer modelling, recommender systems, interfaces*)
- When there is a decision to take based on **multiple sources**, on **large amounts of data**, and in a **dynamic environment** (*e-markets, logistics*)
- For **complex control tasks**, when it is not possible to use a centralized controller and **decentralized problem solving is needed** (*supply chain management, manufacturing*)
- For **simulation of populations of proactive individuals**, when a mathematical model is not available (*traffic, games, cinema*)
- When it is necessary to **integrate and share knowledge from multiple sources** (*databases, business support*)
- Where **autonomous problem solving is needed** (*electronic trading, space crafts*)
- With **high run-time uncertainty**, or **incomplete or complex information** (*telecom services across multiple providers*)

…what is an agent…?

- Basic components:
  - Data structures (mental state)
  - Control structure (life cycle)
  - I/O (communication language & protocols)
- Design choices
  - Pro-active (goal-oriented) vs. reactive (swarm intelligence)
  - Standard (inter-platform) vs. proprietary (intra-platform)
  - Cooperation vs. competition
  - Adaptive vs. static
  - …

Domain-dependent categories

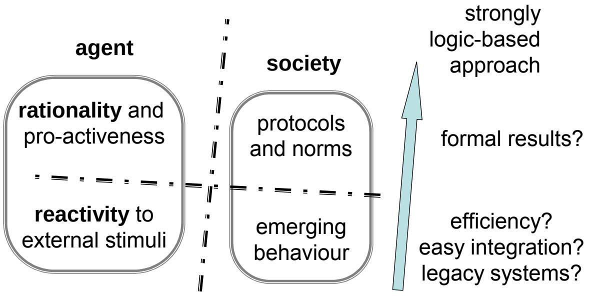


	Pro-activeness	Standards	Robustness	Properties	Cooperation	Adaptability
Knowledge integration	?	✓	?	✓	✓	?
Distributed scheduling	✓	✗	✓	✓	✓	✓
E-procurement	✓	✓	✓	✓	✗	✓
Distribution & logistics	✓	?	✓	✓	✓	✓
Service composition	?	?	✗	✓	✓	✓

Is agent technology mature enough?

- A number of applications for "closed" domains
- *Open domains*: importance of fundings by State
- Some problems to sort out:
  - trust, security (monitoring, mobile agents)
  - user-interface
  - extensive testing
  - availability of standards and general-purpose development framework
- New challenges
- Logics?
  - For prototyping (AOSE)
  - For intelligence (reasoning, goals, consistency)
  - For verification (individuals, interactions)

Where do we use logics?



Part Two

Logic (programming)-based agent languages, architectures, and frameworks

Developing agent-based applications

- Basic elements
  - Agents:
    - Knowledge representation
    - Control structure
  - Agent systems:
    - Agent Communication Languages
    - Ontologies
    - Protocols
    - Institutions and norms

OOP vs. AOP [Sho93]

OOP	AOP
Basic unit: – object	*Basic unit:* – agent
Parameters defining state of basic unit: – unconstrained	*Parameters defining state of basic unit:* – beliefs, commitments, capabilities, choices, …
Process of computation: – message passing and response methods	*Process of computation:* – message passing and response methods
Types of message: – unconstrained	*Types of message:* – inform, request, offer, promise, decline, …
Constraints on methods: – none	*Constraints on methods:* – honesty, consistency, …

BDI logics

- Software Agent: a system that enjoy the properties of
  - **Autonomy**: make decisions based on an internal state
  - **Reactivity**: perceive the environment and respond in a timely fashion to changes that occur in it
  - **Pro-activeness**: take the initiative to achieve goals
  - **Social ability**: interact with other agents via an ACL
- **Beliefs**: information about the state of the environment (*informative state*)
- **Desires**: objectives to be accomplished (*motivational state*). Adopted desires are often called Goals
- **Intentions**: currently chosen course of action (*deliberative component*)

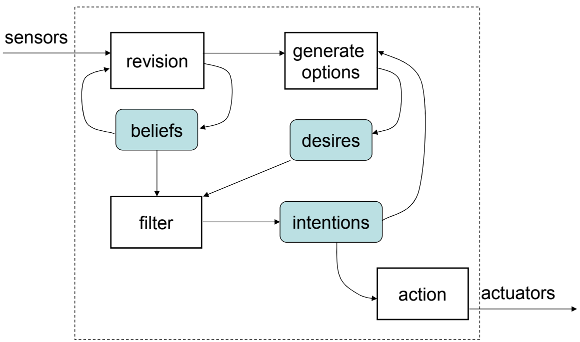
BDI architecture

- BDI formalization has 2 main objectives:
  - To build practical systems
  - To build formally verifiable systems
- Building blocks:
  - Interpreter and cycle theory
  - Logics
  - Semantics

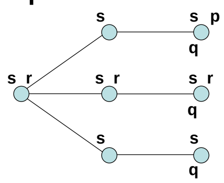
BDI interpreter (cycle)

Initialize-state();
repeat
  options := option-generator (event-queue);
  selected-options := deliberate (options);
  update-intentions (selected-options);
  execute();
  get-new-external-events();
  drop-successful-attitudes();
  drop-impossible-attitudes();
end repeat

BDI architecture



Temporal reasoning: Time trees



- *Inevitably always* **s**
- *Inevitably eventually* **q**
- *Optionally always* **r**
- *Optionally eventually* **p**

- Time tree: temporal structure with
  – Branching time future
  – Single past
- A particular time point is called *situation*
- Standard temporal operators operate over state and path formulas

Example [RG92]

- John acquires a goal to quench its thirst. He believes that he can satisfy it in one of two ways:
  – (a1) open the tap, (a2) fill the glass, (a3) drink water from the glass
  – (b1) get to a state where he has soda, (b2) fill the glass, (b3) drink soda from the glass
- (b1) is a sub-goal, the remaining parts of its plans are atomic actions
- To get to the state where he has soda, John has to (c1) open the fridge, and (c2) remove the soda bottle
- John's beliefs:
  – about the effects of atomic actions
  – about the possibility of carrying them out successfully
  – about the possible failure of his plan to obtain soda

BEL (inevitable □(have-soda; fill-glass; drink) ⊃quenched-thirst)
BEL (inevitable □(open-tap; fill-glass; drink) ⊃quenched-thirst)
BEL (inevitable □(open-fridge; remove-soda) ⊃have-soda)
BEL (optional ◊(have-soda; fill-glass; drink))
BEL (optional ◊(open-tap; fill-glass; drink))
BEL (optional ◊(open-fridge; remove-soda))
BEL (inevitable □(¬ (soda-in-fridge) ⊃inevitable ¬ ◊(remove-soda))
GOAL (inevitable ◊(quenched-thirst))

BEL	GOAL	INTEND	*done*	*succeeded*
B	**◊(quenched-thirst)**	-	-	-
¬◊(remove-soda)	*idem*	-	**open-fridge**	**open-fridge**
idem	*idem*	**fill-glass; drink**	**open-tap**	**open-tap**
idem	*idem*	**drink**	**fill-glass**	**fill-glass**
quenched-thirst	-	-	**drink**	**drink**

*John is **not** blindly committed ⇒ he can choose an alternative plan*

Is BDI logic implemented in practical systems?

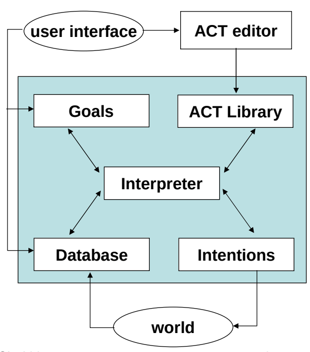
- Many implemented systems are *inspired* to BDI concepts…
- Problem: the time taken by agents to reason is potentially unbounded !!
- The abstract architecture is an *idealization* that faithfully captures the theory, **not** a *practical* system for rational reasoning
- Solution: some important 'choices of representation' (simplifications) must be made…

BDI operationalized (PRS, dMARS)

- Only beliefs about the *current state* of the world are explicitly represented
- Only *ground* sets of literals with *no disjunctions or implications*
- The information about the means of achieving certain future world state is coded in a *plan library* (special beliefs)
- *Intentions* are represented *implicitly* using a *conventional run-time stack* of hierarchically related plans
- Each *plan* consists of:
  – a trigger (invocation condition)
  – a context (precondition)
  – a maintenance condition (to hold true during the execution)
  – a body (course of *goals* / primitive actions)

PRS components [PRS01]

1. A database containing current *Beliefs*
2. A set of current *Goals* to be realized
3. A set of plans (*Acts*)
   - goal achievement
   - reaction to situations
4. *Intentions* containing chosen plans
5. An *Interpreter*



An Agent Oriented Programming computational framework: **AGENT-0**

- More or less contemporary to BDI
- Builds on work by Cohen and Levesque
- A different set of modalities
  - Beliefs
  - Capabilities
  - Choices
  - Commitments
- Stress on the *social aspect* (Commitments)

Components of an AOP system

1. A restricted ***formal language*** with clear syntax and semantics for describing ***mental state***;
2. An ***interpreted programming language*** in which to ***define and program agents***, with primitive commands such as **`REQUEST`** and **`INFORM`**;
   - the semantics of the programming language will be required to be ***faithful*** to the semantics of the mental state;
3. An ***"agentifier",*** converting neutral devices into programmable languages

Agent programs

- A program is constituted by:
  - a definition of *capabilities* and *initial beliefs* + fixing of *time grain*, and
  - a sequence of **conditions under which the agent will enter into new commitments** *(commitment rules)*
- Example (commitment rule):

```
(COMMIT (?a REQUEST ?action)
   (B (now (myfriend ?a)))
   (?a ?action)).
```

- Syntax:

```
(COMMIT msgcond mntlcond (agent action)*)
```


Communicative acts

- 3 types of communicative actions:
  - **`INFORM`**
  - **`REQUEST`**
  - **`UNREQUEST`** (to cancel a request)
- Example:

```
(REQUEST 1 a
   (REQUEST 5 b
      (INFORM 10 c fact ))).
```


Agent Communication Languages

- Two major proposals
  - KQML (1993 - ~1998)
  - FIPA ACL (1996 - now)
- Define a number of *communicative actions / performatives*
- Semantics based on *mental states* (KQML):
  1. An *intuition* given in natural language
  2. An expression describing the illocutionary act
  3. Pre-conditions for sender and receiver
  4. Post-conditions in case of successful receipt
  5. Completion condition (final state of a conversation)
  6. Any comments

KQML: semantics for *tell* [LF98]

1. A states to B that A believes the content to be true.
2. BEL(A,X)
3. **Pre(A)**: BEL(A,X) $\wedge$KNOW(A,WANT(B,KNOW(B,S)))
   Pre(B): INT(B,KNOW(B,S)),
   where S may be any of BEL(B,X), or $\neg$(BEL(B,X)).
4. **Post(A)**: KNOW(A,KNOW(B,BEL(A,X)))
   Post(B): KNOW(B,BEL(A,X))
5. **Completion**: KNOW(B,BEL(A,X))
6. The completion condition holds, unless a *sorry* or *error* suggests B's inability to acknowledge the *tell* properly, as is the case with any other performative.

FIPA ACL semantics for *inform* *[FIP01]*

- Semantic Language
- Feasibility Preconditions (FP) for a CA:
  - Ability preconditions
  - Context-relevant preconditions
- Rational Effect (RE)

`<i, inform (j, ϕ)>`

FP : $\mathbf{B}_i \phi \wedge \neg \mathbf{B}_i (\mathtt{Bif}_j \phi \vee \mathtt{Uif}_j \phi)$

RE : $\mathbf{B}_j \phi$

Where $\mathtt{Bif}_j \equiv \mathbf{B}_j \phi \vee \mathbf{B}_j \neg \phi$; **U** means uncertainty

Social semantics of ACL

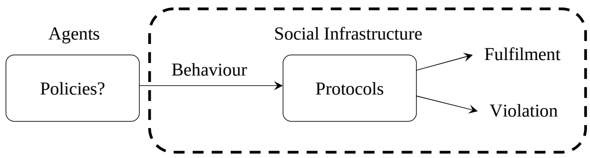
- Some questions…
  - Why constrain agents' social acts?
  - Why refer to a particular agent architecture?
  - How to *verify* communication?
  - How to approach *openness* and heterogeneity?
- Other approaches!
- Semantics based on social *commitments*
  - Singh & Yolum [Sin98,YS02]
  - Colombetti, Fornara & Verdicchio [CFV02,FC02,…]
- Semantics based on *expectations* [SOCS]

The SOCS social model [AGM^{+*}]

- Perspective: openness = no information about internals of agents
- Focus: different aspects of interaction (ACL, interaction protocols, properties of interaction)
- Aim: Declarative representation + operational model
  - Possibility to verify interactions and prove properties
  - ACL semantics, interaction protocols, and *properties* specified using the same formalism!

Protocols

- Agents behave according to their own policies
- Social expectations can be used:
  - to check the correct functioning of the society
  - to suggest to the agents a course of actions
- Protocols are defined through Social Integrity Constraints:
- The society generates expectations out of protocols & events



Social Integrity Constraints (SICs)

- SICs ::= $[\chi \rightarrow \varphi]^*$

  χ ::= $(\neg)$**H**(*Event* [,*Time*])

  φ ::= $\vee$ { $\wedge$ $(\neg)$**E**/**NE**(*Event* [,*Time*]) / *constraints* }
- Examples
  1. $\neg$**H**(*tell*(*A*,*B*,*propose*),*T*),*T*<*T1* → **NE**(*tell*(*B*,*A*,*accept*),*T1*)
  2. **H**(*tell*(*X*,*Y*,*ask*,*D*),*T*) →
     E(*tell*(*Y*,*X*,*yes*,*D*),*T'*), T'>T ∨ **E**(*tell*(*Y*,*X*,*no*,*D*),*T'*)
  3. **H**(*tell*(*X*,*Y*,*yes*,*D*),*T*) → **NE**(*tell*(*Y*,*X*,*no*,*D*),*T'*)
  4. **H**(*tell*(*X*,*Y*,*no*,*D*),*T*) → **NE**(*tell*(*Y*,*X*,*yes*,*D*),*T'*)
  5. **H**(*tell*(*X*,*Y*,*S*,*D*),*T*) → **NE**(*tell*(*Y*,*X*,*S*,*D*),*T'*), *T* > *T'*

SIC-based ACL semantics and Interaction Protocol specification

- The semantics of communicative acts can be recovered into the SIC formalism:
- E.g.: semantics of **`promise`**

H(**`promise`**(*Sender*,*Receiver*,*P*,*Context*),T_p)
→ E(do(*Sender*,*Receiver*,*P*,*Context*),T_d):
$T_d \leq T_p + \tau$

- Similar to the idea of commitment
- Verifiable!

Declarative Semantics

Given a society and a set **HAP** of events…

1. a set of expectations **EXP** is *admissible* iff
   SOKB ∪ **HAP** ∪ **EXP** ⊨ SICs
2. a set of expectations **EXP** is *coherent* iff
   { **E**(p), **NE**(p) } ⊈ **EXP**
3. a set of expectations **EXP** is *consistent* iff
   { **E**(p), ¬**E**(p) } ⊈ **EXP**
   { **NE**(p), ¬**NE**(p) } ⊈ **EXP**
4. a coherent, consistent, and admissible **EXP** is *fulfilled* iff
   HAP ∪ **EXP** ⊨ {**E**(p) → **H**(p)} ∪ {**NE**(p) → ¬**H**(p)}
5. if each coherent and consistent admissible set of expectations is not fulfilled, HAP produces a violation in the society

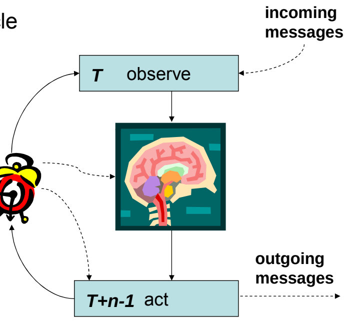
Agents in logic

- Agent architectures
  - ✓ BDI
  - ✓ Agent-0
  - KS-agents, STT, …
  - ALIAS
  - Speculative Computation
  - MINERVA
  - Kakas et al., KGP, …
  - 3APL
  - IMPACT
  - Linear Logics
  - MetateM
  - ConGolog
  - Dylog
  - …
- Agent interaction
  - ✓ KQML, FIPA
  - ✓ Yolum & Singh / Fornara, Colombetti & Verdicchio
  - ✓ SOCS social infrastructure
  - norms / institutions (deontic logic-based approaches)

KS-agents [KS99]

The *observe-think-act* cycle

- ***To cycle** at time T*
- ***observe** any inputs at time T*
- ***think***
- ***select** one or more actions to perform*
- ***act***
- ***cycle** at time T+n*



Thinking component

- *Backward reasoning* (ALP) combined with *forward reasoning* (ICs): ***IFF proof-procedure** [FK97]*
- The set of predicates is partitioned into:
  - closed predicates (iff definitions)
  - open representing actions of the agent
  - open representing events in the environment
  - “constraint” predicates
- Internal state:
  - Beliefs which are iff-definitions
  - Beliefs which are observations
  - Goals in if-then form

Goals

- Queries to database:
  - for-all E [**if** employee (E) **then** exists M manager (M,E)]
- Obligations:
  - **if** *true* **then** co-operate
- Prohibitions:
  - for-all Time [**if** do (steal, Time) **then** *false*]
- Reaction:
  - for-all Agent, Act, T1, T2
    if happens (ask (Agent, do (Act, T2)), T1)
    then exists T, T’
    [confirm (can-do (Act, T2), [T, T’])] &
    do (Act, T2) & T1 < T < T’ < T2

Observations

- Positive observations:
  - simple, variable-free atomic predicates

  e.g.: employee (mary)
- Negative observations:
  - variable-free implications with conclusion *false*

  e.g.: **if** employee (bob) **then** *false*

The unified agent cycle

To **cycle** at time *T*,

- **record** any observations at time *T*,
- **resume** the proof procedure, giving priority to forward reasoning with the new observations,
- **evaluate** to *false* any disjuncts containing subgoals that are not marked as observations but are atomic actions to be performed at an earlier time,
- **select** subgoals, that are not marked as observations, from among those that are atomic actions to be performed at times consistent with the current time,
- **attempt to perform** the selected actions,
- **record the success or failure** of the performed actions and mark them as observations,
- **cycle** at time *T + n.*

Example

<u>*happens*</u> (become-thirsty, T)
$\rightarrow$ <u>*holds*</u> (quench-thirst, [T1, T2]) **&** $T \leq T1 \leq T2 \leq T+10$

<u>*holds*</u> (quench-thirst, [T1, T2]) $\leftrightarrow$ <u>*holds*</u> (drink-soda, [T1, T2]) **or**
<u>*holds*</u> (drink-water, [T1, T2])

<u>*holds*</u> (drink-soda, [T1, T2]) $\leftrightarrow$ <u>*holds*</u> (have-glass, [T1, T']) **&**
<u>*holds*</u> (have-soda, [T'',T2]) **&**
<u>*do*</u> (drink, T2) **&**
$T1 < T'' < T2 \leq T'$

<u>*holds*</u> (have-soda, [T1, T2]) $\leftrightarrow$ <u>*do*</u> (open-fridge, T1) **&**
<u>*do*</u> (get-soda, T2) **&**
$T1 \leq T2$

<u>*holds*</u> (drink-water, [T1, T2]) $\leftrightarrow$ <u>*holds*</u> (have-glass, [T1, T']) **&**
<u>*do*</u> (open-tap, T'') **&**
<u>*do*</u> (drink, T2) **&**
$T1 < T'' < T2 \leq T'$

KS-agents vs. BDI

- *Similarities:*
  - cycle
  - both distinguish goals and beliefs as separate components of an agent's internal state
  - both have two kinds of beliefs: facts and plans
- *Differences:*
  - **BDI**: distinguishes **intentions as a separate component**, **KS**: **intentions are treated as goals** that represent the actions to be performed in the future
  - **BDI**: **goals are conjunctions of literals**; **KS**: **goals are more general implications**
  - **BDI**: uses **two languages** (modal logic specifications / procedural implementation); **KS**: uses the **same language** for specification and implementation
  - **BDI**: **implicit representation of time** in the implementation (modal operators in the specifications); **KS**: **explicit representation of time** (which allows for historical record of past observations)

Extensions

- Communication & Updates:
  - Dell'Acqua, Sadri & Toni [DST98 & 99]
  - Dell'Acqua, Nilsson & Pereira [DNP02]
- KS agents for resource sharing (Sadri, Toni and Torroni) [STT*]
  - social interactions; protocols & policies
  - results on termination, "completeness"

Argumentation-based negotiation (Sadri, Toni and Torroni)

- A model of agent which puts together
  - declarative specification
  - an operational counterpart
- Tools:
  - abductive logic programming
  - agent cycle inspired by KS-agent
  - social interaction by way of dialogues
- Scenario: negotiation for resource sharing
- Results:
  - general properties and
  - application-specific properties

Negotiation Policies

- Policies are part of the agent *B*eliefs. They are *dialogue constraints*
- Policies can be used used to decide how to reply to requests
- Example of dialogue constraint:

tell(Y, x, request(give(R, (Ts,Te))), D, T)
$\wedge$ *have(R, (Ts,Te), T)* $\wedge$ *not need(R, (Ts, Te), T)*
$\Rightarrow$ $\exists$ *T' | (tell(x, Y, accept(request(give(R, (Ts, Te)))), D, T'), T' > T)*

Mapping onto ALP

Abductive Logic Program =
Logic Program (*P*)
\+ Integrity Constraints (*IC*)
\+ Set of abductible predicates (*A*)

⟨ *P*, *IC* , *A* ⟩

beliefs + past dialogues (*K*)

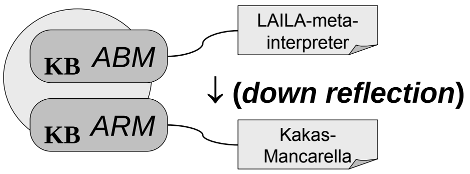
negotiation language

negotiation policies (in *B*)

Coordination of agent reasoning: the ALIAS architecture [CLMT*]

- Problem solving in *open worlds*:
  - Incomplete knowledge
  - Multiple knowledge
- Definition and implementation of an architecture based on *multiple intelligent* agents:
  - Reasoning capabilities
  - **Coordination of reasoning** among agents
- Agent social behaviour
  - Collaborative vs. competitive

The Architecture of an agent



- Agent Behaviour Module + KB (LAILA, Language for AbductIve Logic Agents)
- Abductive Reasoning Module + KB (abductive program)

An Example: Distributed Diagnosis

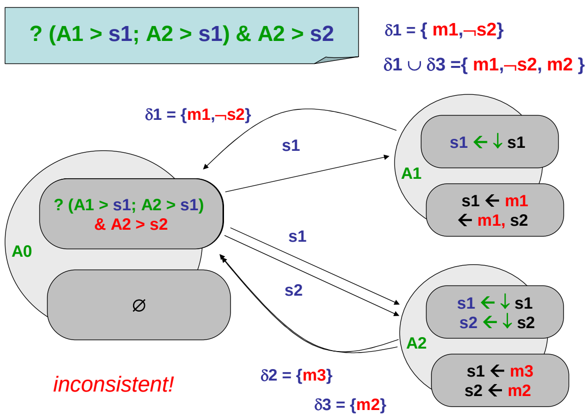
- distributed diagnosis is a popular application domain of agents
- in ALIAS, we can have diverse specialised agents with local domain knowledge (e.g. different kinds of vehicles, or parts of vehicles)
  - problem: observed symptoms s1, s2, … (→ query)
  - agents: diagnosis (abducibles d1, d2, ...)
- **collaboration**: when there is a problem, agents of different areas produce explanations of the symptoms, they must be coherent with each other
- **competition**: several agents specialized in different areas (with different KBs) produce different alternative explanations of the same symptoms
- *Advantage:* maintenance of local knowledge, specialization of tasks

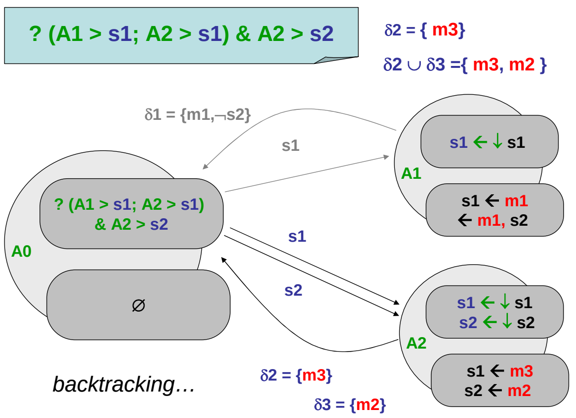
An Example

- **A0** :

  ? (A1 > s1; A2 > s1) & A2 > s2

- **A1** and **A2** represent two diagnostic agents
- **A1** and **A2** are asked to solve **s1** competitively; a δ_1 is selected
- **A2** is asked to solve **s2**; a δ_2 is obtained;
- δ_1 and δ_2 must be consistent (possible backtracking)





Logics for Kiga-kiku computing: Speculative Computation [SIIS00]

- Another approach to coordination of reasoning
- Idea of "*Kiga-kiku*": computers *understand a situation* and *take an appropriate action* for the situation *without being told explicitly what to do*
- What do we need:
  - situation-awareness
  - understanding user intention without much interaction
  - learning user's preference
  - handling incompleteness and a mechanism of back-up in the "kiga-kiku" action is not appropriate

→ **Speculative computation by abduction**

Meeting room reservation

- *A*, *B*, and *C* to attend the meeting.
- If a person is available, then he will attend the meeting.
- We ask a person whether he is free or not.
- If all the persons are available, we reserve a big room.
- If only two persons are available, we reserve a small room.

Suppose we have answers from *A* and *B* that they are free but we do not have an answer from *C*.

Then, non-"kiga-kiku" computer (or person) cannot decide a room reservation since the answers from *C* are not obtained.

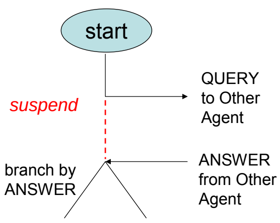
Solution

- We can decide a room reservation based on a *plausible answer* whether *C* is usually busy or not.
  ("kiga-kiku" reservation)
- If the answers *C* is an *exception*, then we cancel the room and make a new reservation.
  (backing-up for failure of "kiga-kiku" action)

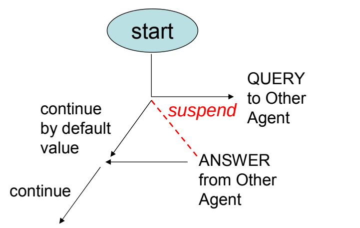
This process is called **speculative computation**.

- need to have a set of *default answers*
- *operational semantics* given in terms of process activation/suspension
- a set of *assumptions* of the form **(not) Q@S** is maintained

Ordinary computation

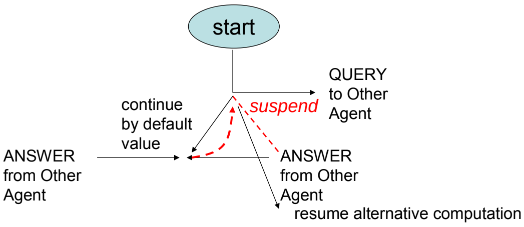


Speculative computation



…when the returned answer is consistent with a default, we just continue the computation…

Speculative computation



…when the returned answer contradicts a default…

…we resume the other alternative computation.

MINERVA - A Dynamic Logic Programming based Agent Architecture [Lei03, LAP02a]

- An architecture to represent the epistemic states of agents and its evolution.
- It employs:
  - Multi-dimensional Dynamic Logic Programming (MDLP) [ALP++, LAP01a, Lei03];
  - Knowledge And Behaviour Update Language (KABUL) [Lei03]

Multi-Dimensional Dynamic Logic Programming (MLDP)

- Knowledge is given by a set of Generalized Logic Programs related according to a Directed Acyclic Graph (DAG)
- The DAG can encode several aspects e.g., temporal relations, hierarchy relations, etc. [LAP01b]
- MDLP assigns semantics to such knowledge representations
- The semantics of MDLP is *a generalization of the answer-sets semantics*

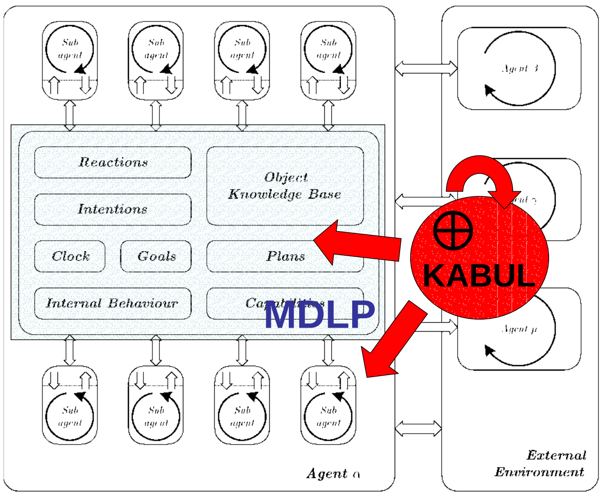
KABUL

- MDLP: the declarative representation of knowledge states,
- KABUL: declarative representation of state transitions i.e. behaviours.
- A program in KABUL is a set of *statements*
- *Statements* allow the **specification of updates** (e.g., assertions, retractions, …), both
  - to the MDLP (knowledge)
  - and to the KABUL program itself (behaviour),

  thus allowing for *its own evolution*.

MINERVA – modular agent architecture

- Every agent is composed of *specialized sub-agents* that execute special tasks, e.g., reactivity, planning, scheduling, belief revision, action execution
- A *common internal KB (one or more MDLP)*, concurrently manipulated by its specialized sub-agents
- The MDLPs may encode
  - object level knowledge,
  - knowledge about goals, plans, intentions, etc…
- KABUL used to encode specification and evolution of the *epistemic state of each sub-agent*



Argumentation & decision making [KM02,KM03a]

- Uniform method of Decision Making via argumentation-based decision policies for:
  - "Professional" policies, related to the different agent's capabilities (i.e. problem solving, cooperation, communication, etc.)
  - "Personality" policies, on needs and motivations
- Deliberation to be sensitive to Roles & Context

Argumentation with Roles and Context

- **Default Context**↔definition of roles
  - Market: normal, regular customer
- **Specific Context**
  - High season, sales season
- **Example Agent theory: T=($\mathcal{T}$, P_R, P_C)**

R1: h-p(r1(Prd, Ag), r3(Prd, Ag))
R2: h-p(r3(Prd, Ag), r1(Prd, Ag)) ← regular (Ag), buy-2 (Ag, Prd)
R3: h-p(r3(Prd, Ag), r1(Prd, Ag)) ← regular (Ag), late-del (Ag, Prd)
C1: h-p(R1(Prd, Ag), R2(Prd, Ag)) ← high-season
C2: h-p(R1(Prd, Ag), R3(Prd, Ag)) ← high-season
C3: h-p(R2(Prd, Ag), R3(Prd, Ag))

Capabilities and Personality

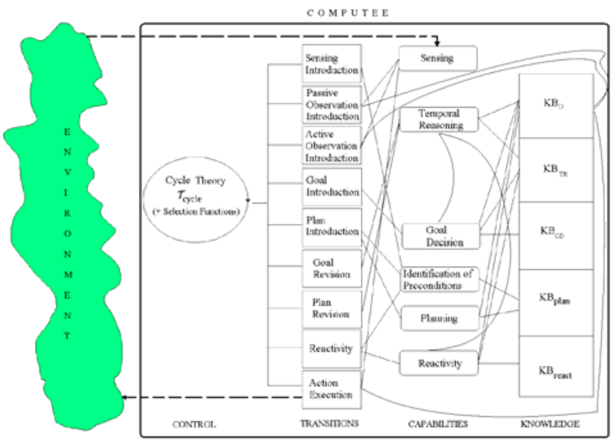
- The Personality can influence the decision making of the agent associated to his different capabilities
- Example: Decide within the problem solving module which requested task to perform according to his "professional" policy and his personality

➢ Professional Policy
r1(A, T1, A1): perform (A, T1, A1) ← ask (A1, T1, A)
r2 (A, T1, T2, A1): ¬perform(A, T1, A1) ← perform (A, T2, self)
R1: h-p (r1(A, T1, A1), r2(A, T1, T2, A1)) ←higher-rank (A1, A)
R2: h-p (r2(A, T1, T2, A1), r1(A, T1, A1)) ← competitor (A1, A)
C1: h-p (R1(A, T1, T2, A1), R2(A, T1, T2, A1)) ← common-project (A, T1, A1)
C2: h-p (R2(A, T1, T2, A1), R1(A, T1, T2, A1)) ← urgent (A, T2)

➢ Personality Policy: The case of a selfish agent (3 = social needs; 4 = ego)
R^2_{43}: h-p (G_4, G_3) ← ¬S_4, ¬N_3
R^2_{34}: h-p (G_3, G_4) ← ¬S_3, ¬N_4
H^2_{43}: h-p (R^2_{43}, R^2_{34}) ← true (basic hierarchy)
E^2_{34}: h-p (R^2_{34}, R^2_{43}) ← dangerous-for-company (G_4) (exception policy)
C^2_{34}: h-p (E^2_{34}, H^2_{43}) ← true

The *KGP model of agency* [KMS⁺*]

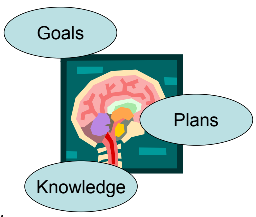
- An *internal* (*mental*) *state*;
- A set of *reasoning* capabilities for performing
  - planning,
  - temporal reasoning,
  - identification of preconditions of actions,
  - reactivity, and
  - goal decision;
- A *sensing* capability;
- A set of formal *state transition rules*;
- A set of *selection functions*;
- A *cycle theory*.



Mental state of a computee

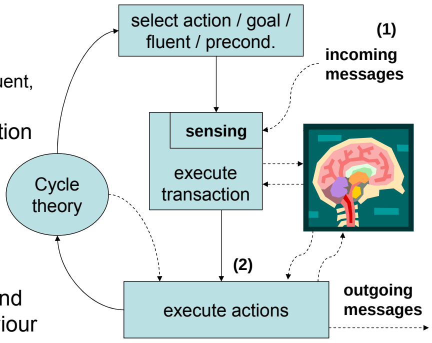
< KB, Goals, Plans >

- **KB** consists of different modules (KB_{plan} , KB_{react} , …), supporting different capabilities
- KB_0 contains the *state* of the environment
- **Goals** can be mental / sensing
- **Plan** is a concrete set of (physical / communicative / sensing) actions



Selection functions & cycle

- 4 core selection functions
  - Action, Goal, Fluent, Precondition
- 4 heuristic selection functions
- Cycle theory determines the *sequences of transitions*
- Cycle patterns and profiles of behaviour



Goal Decision based on LPwNF

- Taken from work by Kakas and Moraïtis
- KB_{GD} is composed of two main parts:
  - lower-level: rules that generate goals

    $L \leftarrow L_1, \ldots, L_n \; (0 \leq n)$

    where $L_1, \ldots, L_n$ are either time-dependent conditions of the form *holds-at* (l,t), or time-independent conditions or temporal constraints
  - higher-level: rules that specify prioritites between other rules of the theory

    $h\text{-}p\,(rule1,rule2) \leftarrow L_1, \ldots, L_n, Tc$
- *rule1*, *rule2* are names of other rules in KB_{GD}
- $KB_{GD} \cup KB_{TR}$ is used to evaluate the conditions

Cycle theories

- A cycle theory is a logic program T_{cycle} with priorities reasoning on the whole state of the computee (meta-program)
- 4 components:
  - $T_{initial}$ (initialization), containing rules of the form:

    $r_{0\,|\,k}(S_0,X) : T_k\,(S_0,X) \leftarrow T_{ik}(S_0,\ \tau,\ X))$
  - a *basic* part T_{basic} (basic steps of iteration), of rules:

    $r_{i\,|\,k}(S',X') : T_k(S',X') \leftarrow T_i(S,X,S'),\ C_{i\,|\,k}(S',\ \tau,\ X'))$
  - an *interrupt* part $T_{interrupt}$ (cycle steps that can follow a POI):

    $r_{POI\,|\,k}(S',X) : T_k(S',X) \leftarrow T_{POI}(S,S'),\ C_{POI\,|\,k}(S',\ \tau,\ X))$
  - a *behaviour* part $T_{behaviour}$ (computee's characteristics):

    $R^i_{k\,|\,l} : h\text{-}p(r_{i\,|\,k}(S,X_k),\ r_{i\,|\,k}(S,X_l)) \leftarrow BC^i_{k\,|\,l}(S,X_k,X_l,\ \tau))$

Cycle theories

- Example:

  $R^{POI}_{AE|*} : h\text{-}p(r_{POI|AE}(S,As'),\ r_{POI|*}(S)) \leftarrow$
  $h^{u}_{AS}(S,\tau) = As',\ As' \neq \emptyset,$
  very-urgent $(As',\ \tau)$

  meaning that : we do not want to carry out any of the interrupt cycle-steps at the expense of delaying the execution of very urgent actions

Cycle theory as control

- The cycle theory of an agent provides a form of *declarative* and *flexible* control
- Cycle theories with special features (namely inducing a total ordering on the transitions) give a more conventional *fixed* control, namely whose operational trace is given by

  $T_1, \ldots, T_n, T_1, \ldots, T_n, T_1, \ldots, T_n, \ldots$

  (e.g. Plan, Execute, Observe, React, Plan…)
- Control via cycle theories can in principle be adopted via any agent architecture

Agents in logic

- Agent architectures
  - ✓ BDI
  - ✓ Agent-0
  - ✓ KS-agents, STT, …
  - ✓ ALIAS
  - ✓ Speculative Computation
  - ✓ MINERVA
  - ✓ Kakas et al., KGP, …
  - 3APL
  - IMPACT
  - Linear Logics
  - MetateM
  - ConGolog
  - Dylog
  - …
- Agent interaction
  - ✓ KQML, FIPA
  - ✓ Yolum & Singh / Fornara, Colombetti & Verdicchio
  - ✓ SOCS social infrastructure
  - norms / institutions (deontic logic-based approaches)

3APL: a combination of declarative and imperative programming

- Agent programming language, primarily concerned with the dynamics of an agent's mental life [HBHM99a]
  - representation of beliefs
  - belief updating
  - goal updating, to facilitate practical reasoning
  - no communication/social aspects involved
- Beliefs: entailment relation for 1st ord. logic, $\models$, and CWA
- Goals: *procedural* notion (goals-to-do). Basic actions affect the *mental state* of the agent
- Basic goals: basic actions, achievement goals, test goals
- (static) *practical reasoning rules*:
  - to *build* a plan library
  - to revise and monitor goals of the agent

Practical reasoning rules

- The set Rule of p.r.r. is defined by:
  - $\pi_h \leftarrow \varphi \mid \pi_b \in$ Rule *s.t.* any goal variable X occurring in π_b also occurs in π_h (φ = *guard*)
  - $\leftarrow \varphi \mid \pi_b \in$ Rule *s.t.* no goal variables occur in π_b , i.e., $\pi_b \in$ Goal
  - $\pi_h \leftarrow \varphi \in$ Rule

$\pi_h \leftarrow \varphi \mid \pi_b$ states that if the agent has adopted some goal or plan π_h and believes that φ is the case, then it may consider adopting π_b as a new goal.

→ (sub-)goals in the head are replaced by those body, when the guard is believed true.

Programming agents in 3APL

- Agent defined as a tuple: < Π, σ, Γ > (goals, beliefs, p.r.r)
- Classification of rules (*ordering*)
  - Failure rules (highest proprity)
  - Reactive rules
  - Plan rules
  - Optimization rules (lowest priority)
- Selection mechanisms (to reduce the non-determinism of the language): a *meta-language* for programming control structures.
- Basic actions:
  - rule selection, **`selap`** (r,g,R,G)
  - application of a number of rules, **`apply`** (R,G,G')
  - goal selection, **`selex`** (g,G)
  - execution of a set of goals, **`ex`** (G,G')

Update-Act cycle

1. Select a rule R to fire
2. Update goal base by firing R
3. Select a goal G
4. Execute (part of) G
5. Goto 1

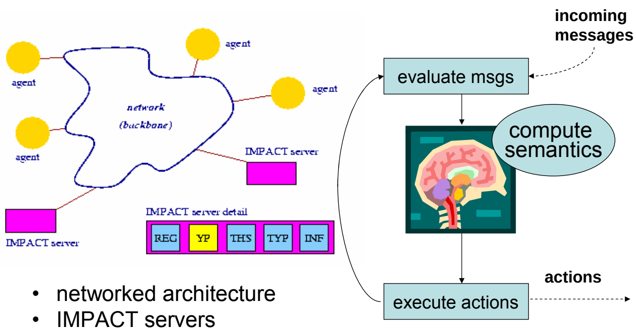
F, R, P, and O are the 4 sets of rules

<u>*while*</u> Π ≠∅ <u>*do*</u>
<u>*begin*</u>
`selap` (*R* ∪ *P* ∪ *O*, Π,R,G)
`apply` (R,G,_)
planning
<u>*repeat*</u>
`selex` (Π, G)
`selap` (*F*, G, R, _)
`apply` (R, G, _)
filtering
<u>*until*</u> R = ∅
`ex` (G, _)
execution
<u>*end*</u>

IMPACT: the Interactive Maryland Platform for Agents Collaborating Together [SBD$^+$00]

- Motivations:
  - Agentize arbitrary Legacy Code (à la Shoham)
  - Code-calls to access distributed and heterogeneous knowledge
  - Clear semantics to agent activity
- Data access
- Architecture
- Programs
- Semantics based on *deontic operators*

IMPACT Architecture & Cycle



- networked architecture
- IMPACT servers

Agent Program

- *A program P is a Set of rules* of the form
  Op **a(**arg1,…,argn**)<---** **<code call condition>** &
  Op_1 $\mathbf{a_1}$(<args>) & … & Op $\mathbf{a_n}$(<args>)

- Op is a "deontic modality" and is either
  - → P - permitted
  - → F - forbidden
  - → O - obligatory
  - → W - waived
  - → Do - execute
- If **code call condition** is true and the deontic modalities in the rule body are true, then Op **a(**arg1,…,argn**)** is true.

Example: select driving lane

O(*go-rightmost*) ←

O(*drive*(r-lane)) ← **Do**(*go-rightmost*), **in**(r-lane, *status*:*free-lanes*())

F(*drive*(L)) ← **not-in**(L, *status*:*free-lanes*())

Do(*drive*(l-lane)) ← **F**(*drive*(r-lane)), **in**(l-lane,*status*:*free-lanes*())

Semantics: *Status Set*

- A *status set* is a collection of ground action status atoms Op α. Status set *S* is ***feasible*** on an agent state, if
  1. *S* is closed under rules of *P*,
  2. *S* satisfies deontic and action consistency,
  3. *S* is deontically and action closed,
  4. executing Do(*S*) = { α | Do(α) ∈ *S* } leads to a consistent new state.
- Example (both lanes free):
  S = {**O**(*go-rightmost*), **Do**(*go-rightmost*),
  P(*go-rightmost*), **Do**(*drive*(r-lane),
  P(*drive*(r-lane)))}

Deontic Logic for Agents and for Societies

- IMPACT uses deontic concepts to define feasible status sets: stress on the behaviour *of the individual* agent
- Deontic logic used to represent and reason about rules and norms in a society
- **ALFEBIITE** project
  – Legal Aspects of Inter-Agent Communication
  – Open societies
  – Formal approach to trust

Linear Logics

- Logic of *occurrences:* two copies of a formula are not equivalent to one copy of it !!
- Suitable for agents because resources are usually *bounded*
- Two forms of conjunction:
  – cumulative: p ⊗ p *not equivalent to* p
  – not cumulative: p & p ≡ p
- Potentially infinite amount of a resource: *!p*
  – *classical reasoning: formulae beginning by !*
- Classical disjunction: p ⊕ q
- Negation: $F^{\perp}$
- Derivation (and consumption): p —o q
  – once the formula is used, p is no longer available, but q is

Agents in Linear Logic

- Harland & Winikoff [HW02,THH03]
- Küngas & Matskin [KM03b,KM04]
- Mascardi *et al.* [MMZI], using Delzanno's $\mathbf{E}_{hhf}$
  – linear logic language that can be used to specify
    - concrete agent architectures,
    - agent program and
    - state.
  – Specifications in $\mathbf{E}_{hhf}$ [Del97] are executable, so it is possible to directly interpret the given specification.
  – $\mathbf{E}_{hhf}$ can be used to characterize an agent architecture under a semantic point of view.

Designing Agent Programming Systems using Linear Logics (Harland & Winikoff)

- An agent can be represented by the sequent:

  $E, A, B, !P \vdash G$

  where
- *B* are the *beliefs* of the agent (which are linear since they change)
- *P* are the *program clauses* (i.e. goal-plan decompositions)
- *G* are the agent's *goals* (intentions)
- *E* are *events*
- *A* are *actions*

Agent programs in LL

P can include *action descriptions:*

"**to** achieve (have-lemonade)
try do (open-fridge) then do (get-lemonade)"

!(do (get-lemonade) ⊗ fridge (open) —o
fridge (open) ⊗ *have-lemonade*)
!(do (open-fridge) ⊗ fridge (closed) —o
fridge (open))
…and in case of *failure*:
!(do (get-lemonade) ⊗ fridge (closed) —o
fridge (closed) ⊗ fails (get-lemonade))

Linear Logic for rapid prototyping (Mascardi et al.)

- CaseLP (Complex Application Specification Environment based on Logic Programming) is:
  - a set of tools for the *specification* of MAS,
  - a set of tools for describing the *behaviour of agents*,
  - a set of tools for the *integration of legacy systems/data*
  - a set of simulation tools for *animation* of MAS
- E_{hhf} is the language used for high-level specification of MAS

Other approaches using other logics

- Many other approaches in literature!!
  - Temporal Logic – Concurrent MetateM (Fisher)
  - Situation Calculus – ConGolog (De Giacomo, Lespérance, Levesque)
  - Dynamic Logic – DyLOG (Patti)
  - BOID (Dastani et al.)
  - …

Wrap-up

- Given insights on (pointers to)
  - application domains of multi-agent systems
  - basic categories of agent programming
  - logic based construct to model
    - internals (state + thinking)
    - interactions
- Identified links and similarities in the literature
- Logic useful for
  - modelling & specification
  - operational model ⇒ implementation/prototyping
  - identification and verification of properties

What properties

- Properties are important!
- "Classical" properties of computational systems (e.g., termination, absence of inconsistency, …)
- "Classical" properties of distributed systems (e.g., robustness, modularity, scalability, openness, …)
- Properties related to interaction
  - conformance to protocols / social norms
  - competent use of protocols
  - properties of interaction mechanisms
- Properties of "agency"
  - social attitudes (altruistic, selfish, malicious, rational..)
  - profiles of individual behaviour (impatient, focussed, risk-averse, …)

Final remarks

- Computational logic used to tackle several different aspects of agent-based programming
- Important link from specification to implementation (including verification): Theory and practice can work together
- Need to make tools understood and accessible by industry (connection with standards, mapping onto existing formalisms)

- Watch the SOCS website
- Submit your work to CLIMA-V by June 22nd
- attend DALT2004

Pointers

- Web sites:
  - AgentLink II: http://www.agentlink.org
  - UMBC Agent WEB: http://agents.umbc.edu/
  - Agent Based Systems: http://www.agentbase.com/survey.html
  - Agent Construction Tools: http://www.agentbuilder.com/AgentTools/
- Journals
  - Journal of Autonomous Agents and Multi-Agent Systems
- Conferences and Workshops
  - International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS) – next in New York, deadline: 16 January 2004
  - Past events: ATAL, ICMAS, AA and related WS (LNAI, IEEE, and ACM Press)

Pointers

- Journals
  - Artificial Intelligence
  - Journal of Logic and Computation
  - Annals of Mathematics and Artificial Intelligence
  - The Knowledge Engineering Review
  - Journal of Group Decision and Negotiation
  - Theory and Practice of Logic Programming
  - Journal of Cooperative Information Systems
- Conferences and Workshops
  - Workshop on **Computational Logics in Multi-Agent Systems** (**CLIMA**) – next in Lisbon, Sep. 29-30, 2004
    deadline: next week!!
  - **Declarative Agent Languages and Technologies** (**DALT**) – *New York, July 19th, 2004, together with AAMAS'04*

Research groups & projects

- **SOCS**, EU Project, http://lia.deis.unibo.it/research/socs
- **MASSiVE**, MIUR Project, http://www.di.unito.it/massive
- **DyLOG**: DI, Università di Torino, http://www.di.unito.it/~alice/
- **CaseLP**: DISI, Università di Genova, http://www.disi.unige.it/index.php?research/ai-mas
- **ALIAS**: DEIS, Università di Bologna, http://lia.deis.unibo.it/research/ALIAS/
- **ALFEBIITE**, EU Project, http://www.iis.ee.ic.ac.uk/~alfebiite/
- **3APL**: Intelligent Systems Group, University of Utrecht, http://www.cs.uu.nl/groups/IS/agents/agents.html
- **xGOLOG**: Cognitive Robotics Group, University of Toronto, http://www.cs.toronto.edu/cogrobo/
- **IMPACT**: University of Maryland, http://www.cs.umd.edu/projects/impact/
- **MetateM**: Logic and Computation Group, University of Liverpool, http://www.csc.liv.ac.uk/~michael/
- **DESIRE**: http://www.cs.vu.nl/vakgroepen/ai/projects/desire/
- **JACK**: The Agent Oriented Software Group, http://www.agent-software.com/
- **BOID**: http://boid.info/
- **RMIT**: http://www.cs.rmit.edu.au/agents/
- **Dagstuhl** seminar 02481 on logic based MAS: http://www.cs.man.ac.uk/~zhangy/dagstuhl/

Pointers

- Surveys on multi-agent systems

[JSW98] N. Jennings, K. Sycara, and M. Wooldridge, *A Roadmap of Agent Research and Development*. AAMASJ 1998.

[WC00] M. Wooldridge and P. Ciancarini, *Agent-Oriented Software Engineering: The State of the Art.* In Proc. First Int. Workshop on Agent-Oriented Software Engineering, LNCS, 2000

[LMP03] M. Luck, P. McBurney, C. Preist, *Agent Technology Roadmap. 2003*. Available electronically http://www.agentlink.org/roadmap/

- Books

[Wei99] G. Weiss (ed.), *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*. MIT Press, 1999

[Woo02] M. Wooldridge, *Introduction to Multi-Agent Systems*. John Wiley & Sons, 2002.

Pointers

- Some surveys on logic-based multi-agent systems

[ST99] F. Sadri and F. Toni, *Computational Logic and Multi-Agent Systems: a roadmap*. COMPULOG (1999), electronic version available at http://www2.ags.uni-sb.de/net/Forum/CL_and_MAS.ps

[Hoe01] W. van der Hoek, *Logical Foundations of Agent-Based Computing*. In Multi-Agent Systems and Applications, LNAI 2086, pp. 50-73 (2001)

[MMS] M. Martelli, V. Mascardi, and L. Sterling, *Logic-Based Specification Languages for Intelligent Software Agents*. To appear in TPLP. Electronic version available via ftp://ftp.disi.unige.it/pub/person/MascardiV/Papers/ (TPLP03.ps.gz)

Pointers

- SOCS home page:
  [SOC] http://lia.deis.unibo.it/research/socs/
- Publications:
  - **SOCS deliverables** (contact me)
  - Conferences: ECAI'03, AAMAS'04, IJCAI'03, AI*IA'03, CEEMAS'03, AAMAS'03, JELIA'02, UKMAS'02, …
  - Workshops: DALT'04, TAPOCS'04, AT2AI-4, ACM SAC2004, CLIMA-IV, DALT'03, CLIMA'02, ESAW'03, LCMAS'03, FAMAS'03, MFI'03, PSE'03, …