Multi-Agent Systems

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Typology of agent interaction

- Non-/Quasi-communicative interaction:
  - Shared environment (interaction via resource/capability sharing)
  - "Pheromone" communication (e.g., ant algorithms, remember slime mold)
- Knowledge-level Communication:
  - Information exchange: sharing knowledge, exchanging views and plans
  - Collaboration, distributed planning: optimising use of resources and distribution of tasks, coordinating execution
  - Negotiation: reaching agreement in the presence of conflict
  - Human-machine dialogue, reporting errors, etc.

OOP vs. AOP

- Objects vs. Agents:
  - “Objects do it for free; agents do it for money."(Jennings, Sycara, Wooldridge, 1998)
  - “Objects do it because they have to; agents because they want to."(Joseph, Kawamura, 2001)
- Communication
  - OOP: Object o_2 can communicate with o_1 by invoking o_1's method $m1$ (i.e., $o_1.m1(arg)$). I a way, object o_2 makes the decision to make o_1 to perform some action while o_1 has no control about it.
  - AOP: There is no such thing as method invocation. Agent *i* can try to act in a way to bring about that agent *j* intends what *i* intends, viz., by speech acts.

Speech act theory

- Most multiagent approaches to communication based on speech act theory (started with Austin's book, *How to Do Things with Words*, 1962)
- Basic idea: treat communication in a similar way as non-communicative action
- Austin (1962): Utterances are produced, and may have effects, like "physical" actions: utterances may change the state of the world:
  - *I hereby name this ship H.M.S titanic!*
  - *Bring me some beer!*

    ⇒Not true or false but appropriate or inappropriate
- In MAS speech act theory is used to specify how utterances are can be used to achieve intentions

Speech act theory: Austin

- A speech act can be conceptualised to consist of:
  1. Locutionary act (physical utterance)
  2. Illocutionary act (intended meaning)
  3. Perlocution (effect of the act)

- Two parts of a speech act:
  1. Performative: communicative verb used to distinguish between different "illocutionary forces"
     Examples: promise, request, purport, insist, demand, etc.
  2. Propositional content: what the speech act is about

- Example:
  - Propositional content: "the window is open"
  - Performative: can be a request/inform/enquire

Speech act theory: Searle

- Searle (1972) identified the following categories of performatives, each corresponding to a different type of speech acts:
  - assertives/representatives (informing, making a claim)
  - directives (requesting, commanding)
  - commissives (promising, refusing)
  - declaratives (effecting change to state of the world)
  - expressives (expressing mental states)

- Ambiguity problems: “The window is open.”
- Detection of performative for natural language understanding:
  - A: “Open the door!” (Directive: Request)
  - B: “Sure!” (Commissive: Promise)

$\Rightarrow$Different types of speech acts require different conditions to hold to be meaningful.

Speech act theory

Specification of speech acts in terms of the conditions under which they can be successfully completed.

Austin's felicity conditions for *declarations*:

1. Conventionality of procedure: There must be an accepted conventional procedure for the performative
2. Complete execution: The procedure must be executed correctly and completely
3. Complete execution: the speaker completes the speech act without errors or interruptions

Searle's properties for success of a *request*:

1. I/O conditions: ability to hear request
2. Preparatory conditions: requested action can be performed, speaker must believe this, hearer will not perform action anyway
3. Sincerity conditions: speaker wants action to be performed

Speech acts: Plan-based semantics

- Communication as action: Preconditions and effects. Thus, we can ask for a plan of speech acts to achieve some goal.
- Cohen and Perrault (1979) proposed applying planning techniques to speech acts (STRIPS-style)
- Preconditions and effects describe beliefs, abilities and wants of participants
- Distinction between `can-do` and `want` preconditions
- Identified necessity of mediating acts, since speech acts say nothing about perlocutionary effect
- This has been the most influential approach to using communication in multiagent systems!

Cohen & Perrault: Request

Specfications

- Request(s, h, α)
  - Cando.pr: $\text{Bel}_s\,\text{Can}_h\,\alpha \wedge \text{Bel}_s\,\text{Bel}_h\,\text{Can}_h\alpha$
  - Want.pr: $\text{Bel}_s\,\text{Want}_s$ *requestinstance*
  - Effect: $\text{Bel}_h\,\text{Bel}_s\,\text{Want}_s\alpha$
- CauseToWant($a1, a2, \alpha$)
  - Cando.pr: $\text{Bel}_{a1}\,\text{Bel}_{a2}\,\text{Want}_{a2}\alpha$
  - Want.pr: –
  - Effect: $\text{Bel}_{a1}\,\text{Want}_{a1}\,\alpha$

- Guenther wants Jutta to get him some beer. He makes up the following plan:
  1. Request(guenther, jutta, getbeer)
  2. CauseToWant(jutta, guenther, getbeer)

Cohen & Perrault: Inform

Specfications

- Inform(s, h, φ)
  - Cando.pr: $\text{Bel}_s \varphi$
  - Want.pr: Bel_s Want_s *informinstance*
  - Effect: $\text{Bel}_h \text{Bel}_s \varphi$
- Convince($a1, a2, \alpha$)
  - Cando.pr: $\text{Bel}_{a1} \text{Bel}_{a2} \varphi$
  - Want.pr: –
  - Effect: $\text{Bel}_{a1} \varphi$

- Guenther wants Jutta to believe that the Britains have voted for Brexit. He makes up the following plan:
  1. Inform(guenther, jutta, brexitvoting)
  2. Convince(jutta, guenther, brexitvoting)

Agent communication languages

- Agent communication languages (ACLs) define standards for messages exchanged among agents
- Usually based on speech act theory, messages are specified by:
  - Sender/receiver(s) of the message
  - Performative to describe intended actions
  - Propositional content in some content language
- Most commonly used languages:
  - KQML/KIF
  - FIPA-ACL (today the de-facto standard)

FIPA: Foundation for Intelligent Physical Agents
KQML: Knowledge Query and Manipulation Language
KIF: Knowledge Interchange Format

KQML/KIF

- KQML: Knowledge Query and Manipulation Language
- ...is an "outer" language, defines various performatives
- Example performatives:
  - `ask-if` ("is it true that ...")
  - `perform` ("please do the following action ...")
  - `tell` ("it is true that ...")
  - `reply` ("the answer is ...")
- Message format:

```
(performative
     :sender        <word>    :receiver    <word>
     :in-reply-to   <word>    :reply-with  <word>
     :language      <word>    :ontology    <word>
     :content       <expression>
)
```

Example: Advertise a capability

```
(advertise
   :sender        Agent1
   :receiver      Agent2
   :in-reply-to   ID1
   :reply-with    ID2
   :language      KQML
   :ontology      kqml-ontology
   :content       (ask-if
                     :sender   Agent1
                     :receiver Agent3
                     :language Prolog
                     :ontology blocks-world
                     :content  "on(X,Y)"
                     )
    )
```

KQML/KIF

- KQML is not suited as a general content language
- KIF (Knowledge Interchange Format): a logical language to describe knowledge
- . . . essentially first-order logic with some extensions/restrictions
- Examples:
  - `(forall (?x ?n) (=> (and (real-num ?x) (even-num ?n)) (> (expt ?x ?n) 0)))`
  - `(married guenther jutta)`
  - (forall (?x) (=> (human ?x) (exists ?y (and (amountOfWater ?y) (essentialFor ?y ?x)))))
- KIF can also be used to describe the ontology referred to by interacting agents.

Example: Dialog

```
(evaluate
    :sender A            :receiver B
    :language KIF        :ontology motors
    :reply-with q1       :content (val (torque m1))
)
(reply
    :sender B            :receiver A
    :language KIF        :ontology motors
    :in-reply-to q1      :content (= (torque m1)
                                    (scalar 12 kgf.m))
)
```

KQML/KIF

- KQML/KIF were very successful, but also some problems
- List of performatives (up to 41!) not fixed (interoperability problems)
- No formal semantics, only informal descriptions of meaning
- KQML completely lacks commissives, this is a massive restriction!
- Performative set of KQML rather ad hoc, not theoretically clear or very elegant

$\rightsquigarrow$ These lead to the development of FIPA ACL

FIPA ACL

Basic structure is quite similar to KQML:

- performatives: fixed set of 20 performatives in FIPA
- housekeeping: e.g., sender, receiver, message IDs
- content: the actual content of the message

Example:

```
(inform
   :sender   agent1
   :receiver agent3
   :content  (price goodABC 125)
   :language Prolog
   :ontology auction
)
```

FIPA ACL performatives

performative	passing info	requesting info	negotiation	performing actions	error handling
accept-proposal			x		
agree				x	
cancel		x		x	
cfp			x		
confirm	x				
disconfirm	x				
failure					x
inform	x				
inform-if	x				
inform-ref	x				
not-understood					x
propose			x		
query-if		x			
query-ref		x			
refuse				x	
reject-proposal			x		
request				x	
request-when				x	
request-whenever				x	
subscribe		x			

Inform and Request

The meaning of inform and request is defined in two parts:

- feasibility pre-condition: what must be true in order for the speech act to succeed
- rational effect: what the sender of the message hopes to bring about

$\langle i, inform(j, \varphi)\rangle$

- feasibility precondition: $B_i\varphi \wedge \neg B_i(B_j\varphi \vee B_j\neg\varphi \vee U_j\varphi \vee U_j\neg\varphi)$
- rational effect: $B_j\varphi$

$\langle i, request(j, \alpha)\rangle$

- feasibility precondition: $B_i Agent(\alpha, j) \wedge \neg B_i I_j Done(\alpha)$
- rational effect: $Done(\alpha)$

Problems

- Impossible for the speaker to enforce those beliefs on the hearer! No way to verify mental state of agent on the grounds of its (communicative) behavior. This is a fundamental problem of all mentalistic approaches to communication semantics!
- Alternative approaches use the notion of social commitments
  - Idea: "A debtor s is indebted to a creditor h to perform action α or to believe proposition φ"
    - $[inform(s,h,\varphi)]O_{s,h}B_s\varphi$
    - $[promise(s,h,\alpha)]O_{s,h}I_s\alpha$
  - Often public commitment stores are used to track status of generated commitments
  - Benefit: at least (non)fulfilment of commitments can be verified

Communication in GOAL

Moods of messages

- Indicative: **:**
  - “I have run out of milk.”
  - Example: **send:**(amountLeft(milk, 0))
- Declarative: **!**
  - “I want the door to be closed!”
  - Example: **send!**(status(door, closed))
- Interrogative: **?**
  - “What time is it?”
  - Example: **send?**(timeNow(_))

- No inbuilt check of precondition and rational effects.
- Agents may lie, and agents may ignore others’ messages.

Sending and receiving messages

- Fridge runs out of milk and tells the grocery planner.
  - **if bel**(amountLeft(milk, 0)) **then** (groceryplanner).**send:**(amountLeft(milk, 0))
- Grocery planner receives the message and adopts buying milk as a new goal.
  - **if** (fridge).**sent:**(amountLeft(milk, 0)) **then adopt**(buy(milk)).

- Special agent expressions:
  - all: all agents in the MAS
  - allother: all agents except the sending agent
  - some: select some agent randomly
  - someother: random selection among the other agents
  - self: the sender itself

Ontologies

- One aspect we have not discussed so far: how can agents ensure the terminology they use is commonly understood?
- A prerequisite for meaningful communication is to agree on a “formal, explicit specification of a shared conceptualization” $\stackrel{\text{def}}{=}$ Ontology!

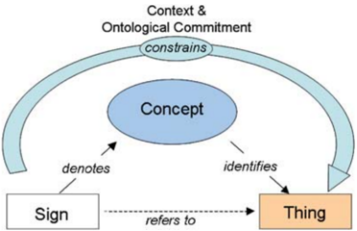
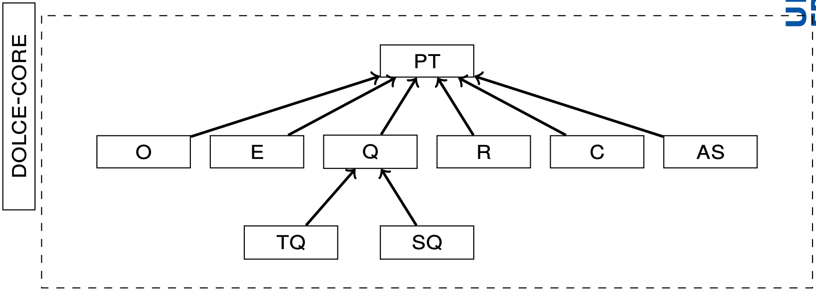


Fig.: Source: [4]

The DOLCE-CORE Upper-Level ontology (cf., [6])



- Axioms constrain the interpretations. Ideally, the possible interpretations match the intended interpretations.
- Example: $\forall x, y\, [E(x) \rightarrow \exists y\, [TQ(y) \wedge I(y, x)]]$ excludes interpretations in which something is an event but not located in time.

Ontology engineering

From a domain modeller's perspective, an ontology is a (terminological) knowledge base given by:

- a vocabulary used to describe some given domain
- a specification of the intended meaning of the vocabulary
- possibly, further constraints specifying additional domain knowledge

The aim is:

- to specify a common understanding of the domain
- to have a formal and machine-readable model of the domain
- Linking domain-level ontologies to upper ontologies can help to increase interoperability

Ontology engineering

An ontology should be:

- meaningful, e.g., all named classes can have instances
- correct, in the sense that domain experts can agree on the meaning of the vocabulary as specified in the ontology
- rich, in the sense that the specified meaning provides a reasonable approximation of the intended meaning of the vocabulary

Existing tools and reasoners (Protege, Fact++, Racer, etc.) can help to build such ontologies, but also to solve several reasoning tasks.
There exists a family of well-defined ontology languages (e.g., OWL-languages) with a solid logical basis (Description Logics).

Reasoning services

- Concept satisfiability: Is there a model of the ontology such that the concept's interpretation is nonempty?
- Concept subsumption: Does concept *A* subsume concept *B*, i.e., must each (possible) instance of concept *B* be an instance of concept *A*?
- Subsumption hierarchy: Compute the subsumption relations between all pairs of named concepts mentioned in the ontology
- Instance queries: Given a knowledge base of the individuals of the domain, retrieve all instances that match a given query
- Ontology mapping/alignment: Given two ontologies of the same domain, map/align the concepts specified in both

Summary

- Speech act theory: Communicating as acting
- Formalizations of speech acts in terms of preconditions and effects on agents' mental states ...
- ...provide semantics for Agent Communication Languages
- Communication on the knowledge level requires agents to share an ontology

Literature

- A subset of the slides is based on: Dr. Michael Rovatsos, The University of Edinburgh
  `http://www.inf.ed.ac.uk/teaching/courses/abs/abs-timetable.html`
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