
# Multi-Agent Coordination

## Interaction-Centric Coordination

# Outline

- **Introduction**
  - Definitions, Principles
- **Speech Act Theory**
- **Agent Communication Language**
  - KQML, FIPA-ACL
- **Ontologies**
- **Interaction Protocol**
  - Formalism
  - Contract Net

## Definition

- **General [Morin 77]**
  - **Interactions** are **reciprocal actions** modifying the behavior or nature of elements, bodies, objects, phenomena in **presence** or **influence**.

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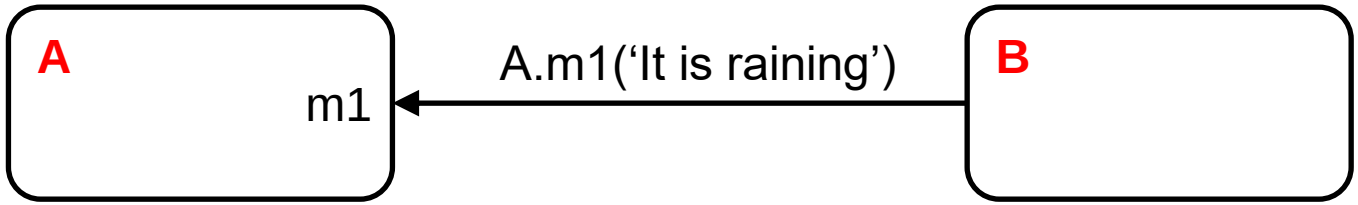
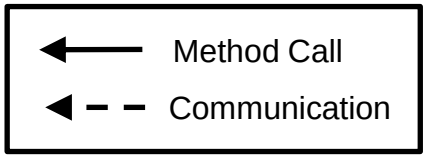
**Object-Oriented Paradigm**



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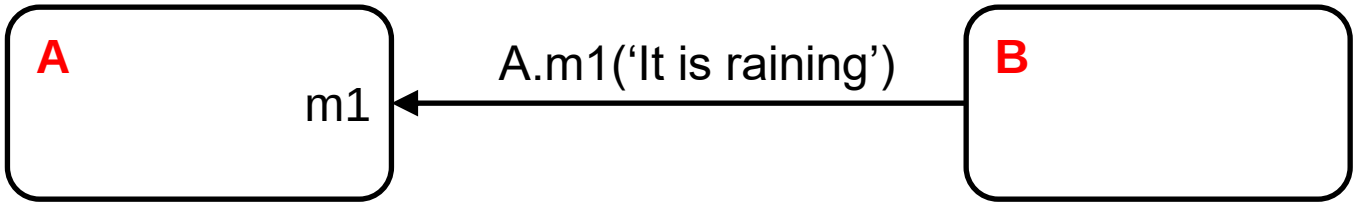
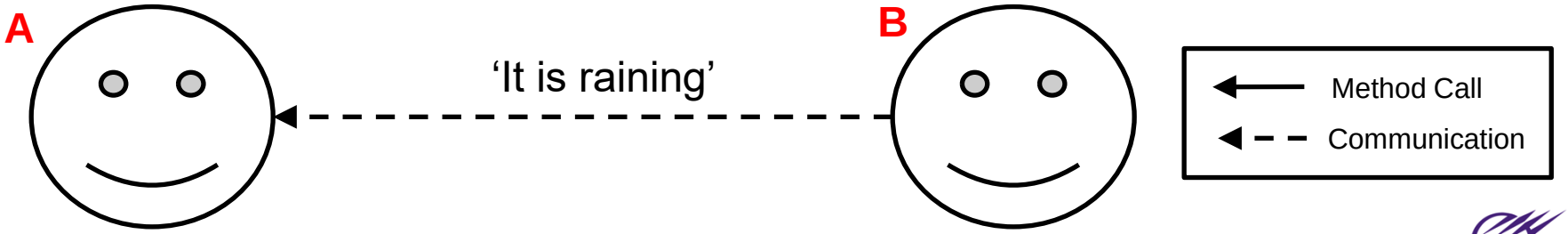



**Multi-Agent Systems Paradigm**



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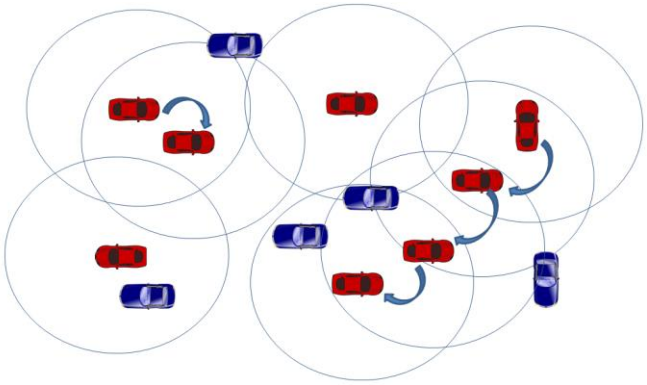

Autonomous Vehicles interact through
1. their **perceptions** of others
2. their **communications**

## Definition

- **Four ways of interacting between agents [Werner 89]**
  - **No communication**: agents do not communicate, they either interact by perceiving the environment or achieve their goal without any external help.
  - **Sending signals**: agents synchronize by sending coded messages.
  - **Sending plans**: agents transfer information concerns their tasks and beliefs.
  - **Sending messages**: the most used in the MAS community, enable agents to exchange their intentions and needs via message passing.

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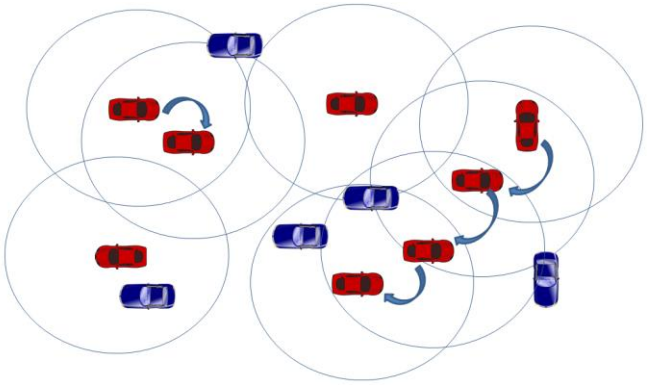

**No communication**: positions, movements, turn signal

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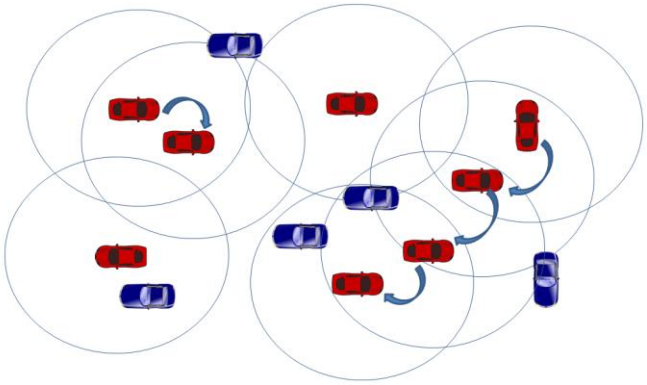

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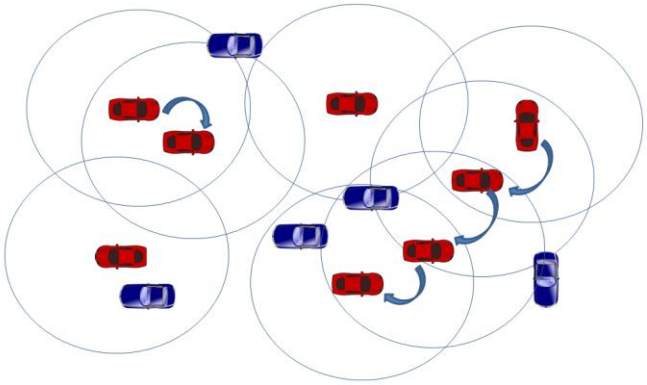

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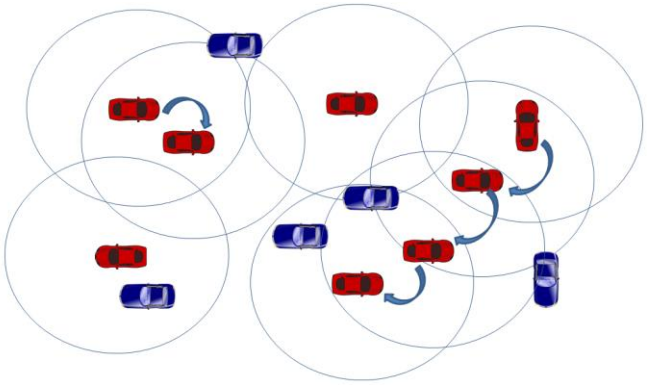


**No communication**: positions, movements, turn signal

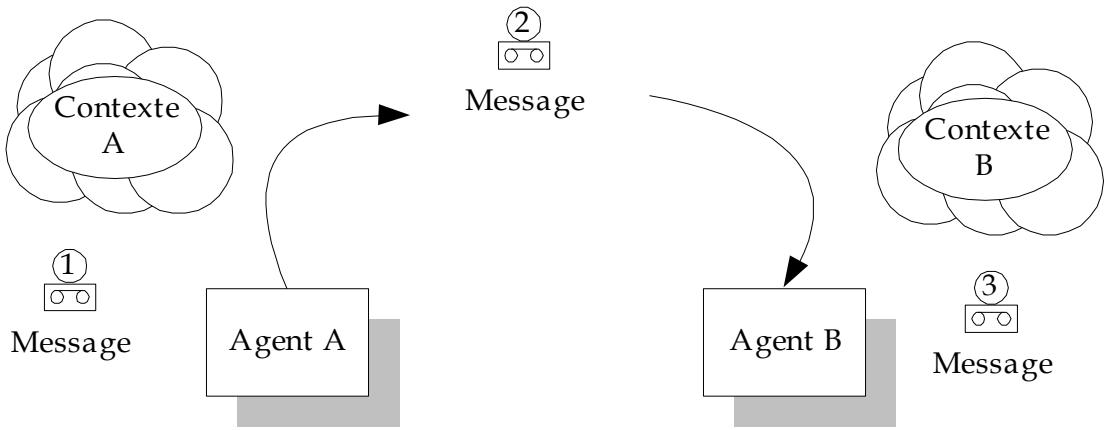
**Sending signals**: honk the horn

**Sending plans**: send its direction at a junction

**Sending messages**: share its intention to overtake

## Communication

- **Problematic [Shannon 48]**




- **Definition:** Communication is the **intentional exchange of information** brought about by the **production and perception of signs** drawn from a **shared system of conventional signs** [Russel & Norvig 10].

## Summary

- **When does an agent decide to communicate with another?**
  - Theory of Speech Act [Austin 62, Searle 69]
- **What language does the agent use to communicate?**
  - Agent communication languages like KQML [Finin et al. 93], FIPA-ACL [FIPA 01]
- **What does an agent communicate about?**
  - Ontologies
- **How is the communication structured?**
  - Interaction protocols

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# Speech Act Theory

## Introduction

- **Initial hypothesis:** A common language constitutes an interface between agents.
  - **Syntax**: The way symbols are structured,
  - **Semantics**: meaning of the symbols used,
  - **Conversation**: Management of message sequences.

# Speech Act Theory

## Introduction

- Most treatments of communication in (multi-) agent systems borrow their inspiration from **speech act theory**
- Speech act theories are **pragmatic** theories of language, i.e., theories of language use: they attempt to account for how language is used by people every day to achieve their goals and intentions
- The origin of speech act theories are usually traced to Austin's 1962 book, *How to Do Things with Words*
- Sources of the Theory of Speech Acts [Austin 62, Searle 69, Vanderveken 88]

Expanded from Rosenschein's slides on Wooldridge's book
http://www.cs.ox.ac.uk/people/michael.wooldridge/pubs/imas/distrib/powerpoint-slides/

# Speech Act Theory

## Introduction

- Austin noticed that some utterances are rather like ‘physical actions’ that appear to **change the state of the world**
- Paradigm examples would be:
  - declaring war
  - christening
  - ‘I now pronounce you man and wife’ :-)
- But more generally, **everything** we utter is uttered with the intention of satisfying some goal or intention

Based on Rosenschein’s slides on Wooldridge’s book
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# Speech Act Theory

## Introduction

- A theory of how utterances are used to achieve intentions is a **speech act theory**
- In speech act theory, verbal actions are called **performative verbs**
- Performative verbs constitute the building blocks of natural language

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# Speech Act Theory

## Performative Taxonomy

- **Taxonomy [Searle 69]**
  - **Assertives/Representatives** are used to give information about the world by asserting something. Paradigm case is *informing*.
    - I inform you that I'm married
  - **Directives** are used to give instructions to the recipient. Paradigm case *requesting*.
    - I request you to come to my wedding
  - **Commissives** commit speakers to perform certain acts. Paradigm case *promising*.
    - I promise to be faithful
  - **Expressives** are used to give the addressee information about the speaker's mental state. Paradigm case *thanking*.
    - I apologize to miss your wedding
  - **Declarations** perform an act by the very fact of pronouncing the utterance. Paradigm case *declaring war*.
    - I marry you

# Speech Act Theory

## Performatives

- The same content may have different interpretations according to the used speech act

- A says to B "*go to the position p1*"

| | |
|---|---|
| **Assertion** | B knows that A goes to the position p1 |
| **Directive** | A asks B to go to position p1 |
| **Commissive** | Not sure that A will go to p1 |
| **Expressive** | A thinks to go to p1 |
| **Declaration** | ??? |

# Speech Act Theory

## Performative Components

- Performative verb are composed by
  - **Locutionary component**: production of a sentence using a given grammar and lexicon.
  - **Illocutionary component**: effect that the sender of the message wants to produce on the recipient.
  - **Perlocutionary component**: effect of the message on the recipient.

# Speech Act Theory

## Performative Components

- From "*A Dictionary of Philosophical Terms and Names*":
- "**Locutionary act**: the simple speech act of generating sounds that are linked together by grammatical conventions so as to say something meaningful. Among speakers of English, for example, 'It is raining' performs the locutionary act of saying that it is raining, as 'Grablistrod zetagflx dapu' would not."
- Act of making an utterance
  - e.g., 'Please make some tea'

Based on Rosenschein's slides on Wooldridge's book
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# Speech Act Theory

## Performative Components

- "**Illocutionary act**: the speech act of doing something else – offering advice or taking a vow, for example – in the process of uttering meaningful language. Thus, for example, in saying 'I will repay you this money next week,' one typically performs the illocutionary act of making a promise."
- Action performed in saying something
  - e.g., 'He requested me to make some tea'

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# Speech Act Theory

## Performative Components

- "**Perlocutionary act**: the speech act of having an effect on those who hear a meaningful utterance. By telling a ghost story late at night, for example, one may accomplish the cruel perlocutionary act of frightening a child."
- Effect of the act
  - e.g., 'He got me to make the tea'

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# Speech Act Theory

## Performative Components

- **Agent A sends the message «please, close the window, I'm cold» to the agent B**

# Speech Act Theory

## Performative Components

- **Agent A sends the message «please, close the window, I'm cold» to the agent B**
  - **Locutionary component**: Production of a sentence using a given grammar and lexicon.
    - A writes the message
  - **Illocutionary component**: effect that the sender of the message wants to produce on the recipient
    - A wants B to close the window, the strength of the message is enforced by "please"
  - **Perlocutionary component**: effect of the message on the recipient
    - B should close the window or propose an alternative to the justification of the demand "I'm cold" for instance B could give a coat to A

# Speech Act Theory

## General Perspective

- In general, a speech act can be seen to have two components:
- a **performative verb**:
  (e.g., request, inform, promise, … )
- a **propositional content**:
  (e.g., “the door is closed”)

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# Speech Act Theory

## General Perspective

- **Consider**
  - performative = request
    content = “the door is closed”
    speech act = “please close the door”
  - performative = inform
    content = “the door is closed”
    speech act = “the door is closed!”
  - performative = inquire
    content = “the door is closed”
    speech act = “is the door closed?”

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# Agent Communication Language

## Introduction

- Message is the most used form of interaction among agents
- Messages are performatives combined with a data structure
- Agent Communication Languages (ACLs) are standard formats for the exchange of messages
- An ACL is defined by
  - the definition of a **set of performatives**
  - the **data structure of the message**

# Agent Communication Language

## Introduction

- ACL uses at least a data structure composed of the following fields
  - Sender
  - Receiver
  - Language of the content
  - Ontology
  - Message content
- The most well known ACL are
  - KQML
  - FIPA-ACL

# Agent Communication Language

## KQML – Introduction

- **Knowledge Query and Manipulation Language**
- Define a common format for messages
- The principle is to **separate**
  - the **semantics** of the **communication protocol** (independent of the application domain)
  - from the **semantics** of the **message content** (application-dependent).
- **Historic**
  - Result of the 1993 DARPA Knowledge Sharing Initiative
  - Designed to exchange information among agents
  - Goal was to develop generic tools to promote the interoperability of heterogeneous agents

# Agent Communication Language

## KQML – Introduction

- KQML is an ‘outer’ language, that defines various acceptable ‘communicative verbs’, or **performatives**
- Example performatives:
  - ask-if (‘is it true that. . . ’)
  - perform (‘please perform the action. . . ’)
  - tell (‘it is true that. . . ’)
  - reply (‘the answer is . . . ’)
- KIF is a language for expressing message **content**

# Agent Communication Language

## KQML – Syntax

**Message Layer**

**Communication Layer**

**Content Layer**

```
(KQML-performative
    :language      <text>
    :ontology      <text>
    :reply-with    <text>
    :sender        <text>
    :receiver      <text>
    :content       <expression>
)
```

**Example:**

```
(ask-one
   :language LPROLOG
   :ontology NYSE-TICKS
   :reply-with ibm-stock
   :sender joe
   :receiver stock-server
   :content (PRICE IBM ?price)
)
```

# Agent Communication Language

## KQML – Performatives

| Category | Name |
|---|---|
| Simple request | evaluate, ask-if, ask-about, ask-one, ask-all |
| Request with several answer | stream-about, stream-all, eos |
| Response | reply, sorry |
| Generic Information | tell, achieve, cancel, untell, unachieve |
| Generator | standby, ready, next, rest, discard, generator |
| Skills definition | advertise, subscribe, monitor, import, export |
| Network management | register, unregister, forward, broadcast, route |

See https://jmvidal.cse.sc.edu/talks/agentcommunication/kqmlperformatives.html for the complete list of performatives and their meanings.

# Agent Communication Language

## KQML – Semantic

- **A performative is defined with**
  - **Preconditions** (Pre) define the required **states of the agents** for the creation of the message
  - **Postconditions** (Post) define the **states of the agents** after the message processing
  - **Completion** describes the expected result of the message
- **Representation of the knowledge of the agent**
  - Bel(A,X): A believes X
  - Know(A,X): A knows X
  - Intend(A,X) A intends to do X
  - Want(A,X) A wants X

## KQML – Example

Tell(A,B,X)

- Pre(A): bel(A,X) ∧
  know(A,want(B,know(B,bel(A,X))∨know(B,¬bel(A,X))))
- Pre(B): intend(B,
  know(B,bel(A,X))∨know(B,¬bel(A,X)))
- Post(A): know(A,know(B,bel(A,X)))
- Post(B): know(B,bel(A,X))
- Completion: know(B,bel(A,X))

# KQML – Discussion

- **Advantages**
  - **First** agent communication «standard»
  - **Several applications support** KQML
  - **Extensible Language**
    - New performatives
    - New parameters
- **Limitations**
  - Ambiguity and imprecision
  - Does not take into account conversation
  - Absence of performatives like Commissive performatives

# Agent Communication Language

## FIPA – Introduction

- Fondation for Intelligent Physical Agents (FIPA)
- Benefited from the research results of KQML
- Basic structure is quite similar to KQML
  - **performative**
    - 20 performatives in FIPA
  - **housekeeping**
    - e.g., sender, etc.
  - **content**
    - the actual content of the message
- Explicit protocols for message exchange

# Agent Communication Language

## FIPA – 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 | | | |

# Agent Communication Language

## FIPA – Message

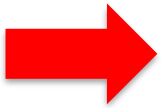
| Parameter | Category of Parameters |
|---|---|
| performative | Type of communicative acts |
| sender | Participant in communication |
| receiver | Participant in communication |
| reply-to | Participant in communication |
| content | Content of message |
| language | Description of Content |
| encoding | Description of Content |
| ontology | Description of Content |
| protocol | Control of conversation |
| conversation-id | Control of conversation |
| reply-with | Control of conversation |
| in-reply-to | Control of conversation |
| reply-by | Control of conversation |

(*inform*
:**sender** A
:**receiver** B
:**content** (price (bid goood02) 150)
:**in-reply-to** round-4
:**reply-with** bid04
:**envelope** 1000
:**language** s1
:**ontology** hpl-auction
:**reply-by** 10
:**protocol** offer
:**conversation-id** conv02
)

# Agent Communication Language

## FIPA – Semantic Language

- Based on **mental attitudes** (beliefs, desires, etc…)
- For **each act**
  - **Feasibility Condition (FR)**: Condition(s) that must be satisfied before planning to perform an speech act
  - **Rational Effect (RE)**: Effect that the agent expects, i.e., attempts to achieve, with the processing of the speech act



Receiver mental state is not taken into account as an initial condition

# Agent Communication Language

## FIPA – Semantic Language

- **Examples**
  - **<i, inform(k, p)>**
    - FP: $B_i p \wedge \neg B_i( Bif_k p \vee Uif_k p )$
    - RE: $B_k p$
  - **<i, request(j, a)>**
    - FP: $B_i Agent(a, j) \wedge \neg B_i I_j Done(a)$
    - RE: Done(a)

# Agent Communication Language

## FIPA – Semantic Language

- **Each performative is related to a protocol**
  - Sender agent knows it has to wait an answer
  - Receiver knows how to react
- **Example**
  - Request
  - Auction
  - ContractNet

# Agent Communication Language

## Comparison of KQML & FIPA ACL

- **Similarities**
  - Both are identical in concepts and principles
  - Both support different content languages
  - Both are syntactically identical
  - Both are capable of parsing messages, compose and channel them using low-level network protocol
  - Both are based on the speech act theory

# Agent Communication Language

## Comparison of KQML & FIPA ACL

| KQML | FIPA ACL |
|---|---|
| Semantic description includes preconditions, postconditions and completion conditions | Semantic description includes feasibility preconditions and rational effect |
| KQML has facilities for agent management and communication agent | FIPA ACL considers these as services offered by basic agents rather than message layer |
| KQML has facilities for multiple solutions like ask-all, stream-all, etc and goal definition like achieve and unachieve | FIPA ACL does not express these concepts in ACL, but in the context of ACL messages |
| KQML has facility for direct belief manipulation | FIPA ACL does not have this facility |
| KQML uses 'sorry' for both failure and refusal | FIPA ACL has facilities like 'failure' and 'refuse'. |

https://people.ucalgary.ca/~far/Lectures/SENG697/PDF/tutorials/2002/Agent_Communication_Languages_and_Protocols.pdf

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# Ontologies

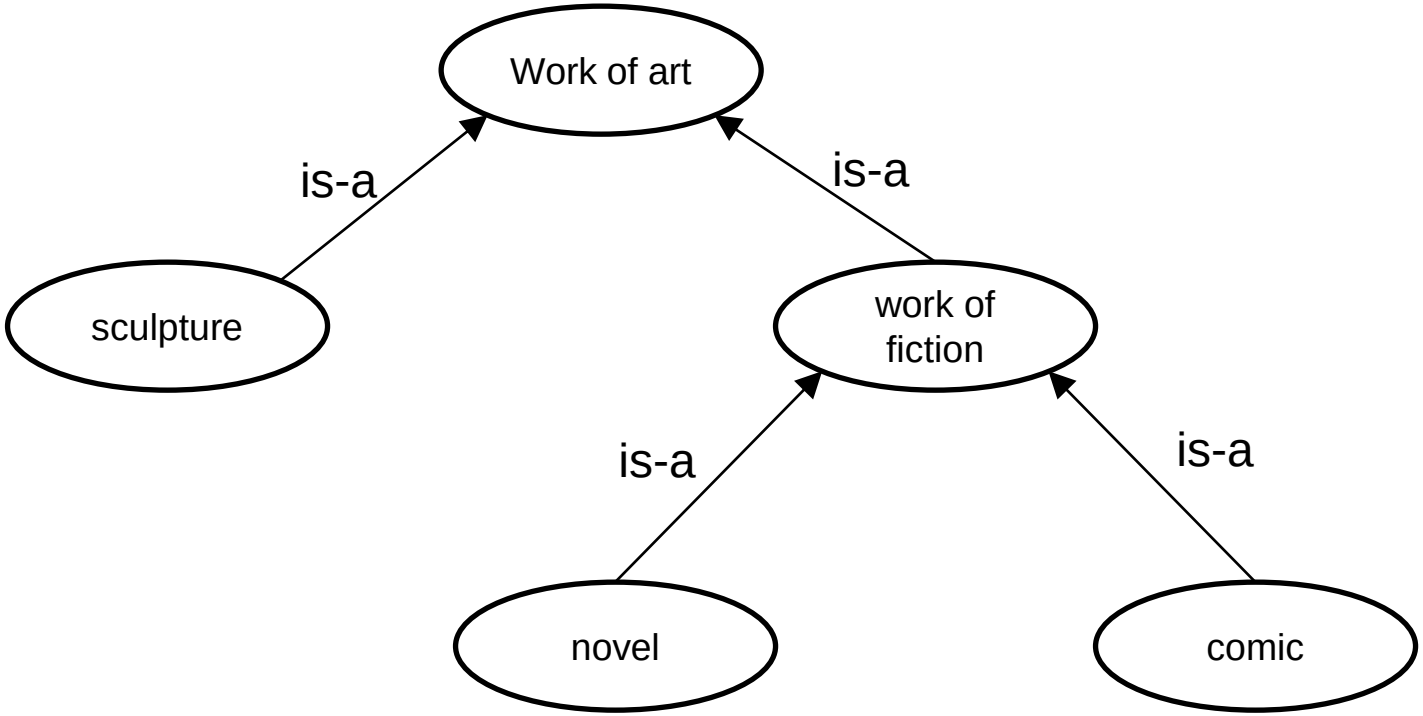
## Introduction

- In order to be able to communicate, agents must have agreed on a common set of terms
- A **formal specification** of a **set of terms** is known as an **ontology**
- An ontology is intended to provide a common basis of understanding about some domain

> *An ontology is a **formal definition** of a **body of knowledge**. The most typical type of ontology used in building agents involves a **structural component**. Essentially a taxonomy of **class** and **subclass relations** coupled with **definitions of the relationships** between these things. (Jim Hendler)* [Woodridge 09]

# Ontologies

## Illustration



## Languages

- **Traditional Ontology Languages**
  - First-order predicate logic
    - KIF, CycL
  - Frame-based languages
    - Ontolingua, F-logic, and OCML
  - Description Logic (DL) based languages
    - Loom
- **Web-based Ontology Languages**
  - RDF + Description Logic
    - OWL DL

[Kalibatiene & Vasilecas 11]

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# Interaction Protocol

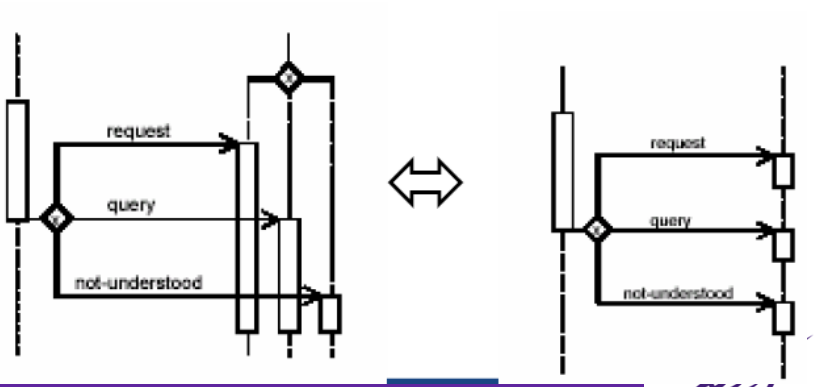
## Introduction

- **Definition**
  - A protocol specifies who can say what to whom and possible reactions to the message it receives
- **Objective**
  - Structure conversations
  - Allow agents to know how to use speech acts
- **Consequences**
  - Restriction on the use of the speech acts
  - Protocol engineering
    - Predefined protocols
    - Protocol definition formalism
    - Methodology for defining protocols

# Interaction Protocol

## Interaction Formalism – AUML

- **A protocol define a set of ordered messages exchanged between roles**
- **Notation**
  - A vertical dimension that represents time
  - A horizontal dimension that represents the different roles
  - Logical operator : and / or
    - Temporal sequence
    - Message: alternative




[Odell et al. 03]

# Interaction Protocol

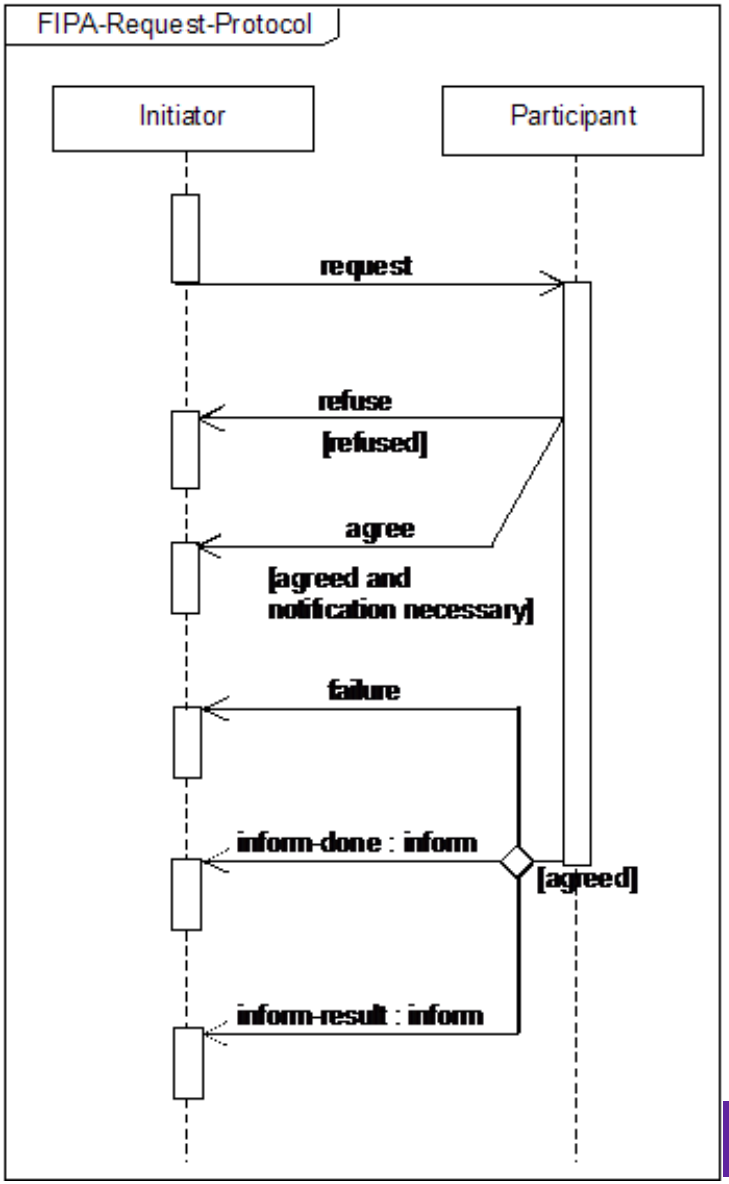
## FIPA

- **Notation**: AUML [http://www.fipa.org/specs/fipa00025/XC00025E.html]
- **Existing protocols** [http://www.fipa.org/repository/ips.php3]

| Identifier | Title |
|---|---|
| SC00026 | FIPA Request Interaction Protocol Specification |
| SC00027 | FIPA Query Interaction Protocol Specification |
| SC00028 | FIPA Request When Interaction Protocol Specification |
| SC00029 | FIPA Contract Net Interaction Protocol Specification |
| SC00030 | FIPA Iterated Contract Net Interaction Protocol Specification |
| XC00031 | FIPA English Auction Interaction Protocol Specification |
| XC00032 | FIPA Dutch Auction Interaction Protocol Specification |
| SC00033 | FIPA Brokering Interaction Protocol Specification |
| SC00034 | FIPA Recruiting Interaction Protocol Specification |
| SC00035 | FIPA Subscribe Interaction Protocol Specification |
| SC00036 | FIPA Propose Interaction Protocol Specification |

# Interaction Protocol

## FIPA – Request Protocol




http://www.fipa.org/specs/fipa00026/SC00026H.html



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# Interaction Protocol

## FIPA – Contract Net Protocol

- How does a group of agents work together to solve a problem?
- There are two main modes of cooperative problem solving:
  - **Task Sharing**: components of a task are distributed to component agents
  - **Result Sharing**: information (partial results, etc.) is distributed
- The Contract Net Protocol is a well-known task sharing protocol for task allocation

# Interaction Protocol

## FIPA – Contract Net Protocol

- The Contract Net Protocol is a high-level protocol for achieving efficient cooperation through task sharing [Wooldridge 09]
- Task distribution viewed as a kind of contract negotiation
- “Protocol” specifies content of communication, not just form
- Two-way transfer of information is natural extension of transfer of control mechanisms

Based on Rosenschein’s slides on Wooldridge’s book
http://www.cs.ox.ac.uk/people/michael.wooldridge/pubs/imas/distrib/powerpoint-slides/

# Interaction Protocol

## FIPA – Contract Net Protocol

- The Contract Net Protocol is carried out in 5 stages
  1. Recognize
  2. Announce
  3. Bid
  4. Award
  5. Expect

Quote from Rosenschein's slides on Wooldridge's book
http://www.cs.ox.ac.uk/people/michael.wooldridge/pubs/imas/distrib/powerpoint-slides/

# Interaction Protocol

## Contract Net Protocol – Recognize

- In this stage, an agent recognizes it has a problem it wants help with.
- Agent has a goal, and either…
  - realizes it cannot achieve the goal in isolation — does not have capability
  - realizes it would prefer not to achieve the goal in isolation (typically because of solution quality, deadline, etc.)

Quote from Rosenschein's slides on Wooldridge's book
http://www.cs.ox.ac.uk/people/michael.wooldridge/pubs/imas/distrib/powerpoint-slides/

# Interaction Protocol

## Contract Net Protocol – Announce

- In this stage, the agent with the task sends out an **announcement** of the task which includes a **specification** of the task to be achieved
- Specification must encode:
  - description of task itself (maybe executable)
  - any constraints (e.g., deadlines, quality constraints)
  - meta-task information (e.g., “bids must be submitted by…”)
- The announcement is then **broadcast**

Quote from Rosenschein’s slides on Wooldridge’s book
http://www.cs.ox.ac.uk/people/michael.wooldridge/pubs/imas/distrib/powerpoint-slides/

# Interaction Protocol

## Contract Net Protocol – Bid

- Agents that receive the announcement decide for themselves whether they wish to **bid** for the task
- Factors:
  - agent must decide whether it is capable of expediting task
  - agent must determine quality constraints & price information (if relevant)
- If they do choose to bid, then they submit a **tender**

Quote from Rosenschein's slides on Wooldridge's book
http://www.cs.ox.ac.uk/people/michael.wooldridge/pubs/imas/distrib/powerpoint-slides/

# Interaction Protocol

## Contract Net Protocol – Award & Expect

- Agent that sent task announcement must choose between bids & decide who to “award the contract” to
- The result of this process is communicated to agents that submitted a bid
- The successful **contractor** then expedites the task
- May involve generating further manager-contractor relationships: **sub-contracting**

Quote from Rosenschein’s slides on Wooldridge’s book
http://www.cs.ox.ac.uk/people/michael.wooldridge/pubs/imas/distrib/powerpoint-slides/

# Interaction Protocol

## FIPA – Contract Net Protocol – Illustration

We need to arrive as soon as possible to the company but we do not have a car?

# Interaction Protocol

## FIPA – Contract Net Protocol – Illustration

I want a Taxi !

Taxi 1

I want a Taxi !

I want a Taxi !

Taxi 3

Taxi 2

# Interaction Protocol

## FIPA – Contract Net Protocol – Illustration

I can be there in 12m

Taxi 1

I can be there at 7m

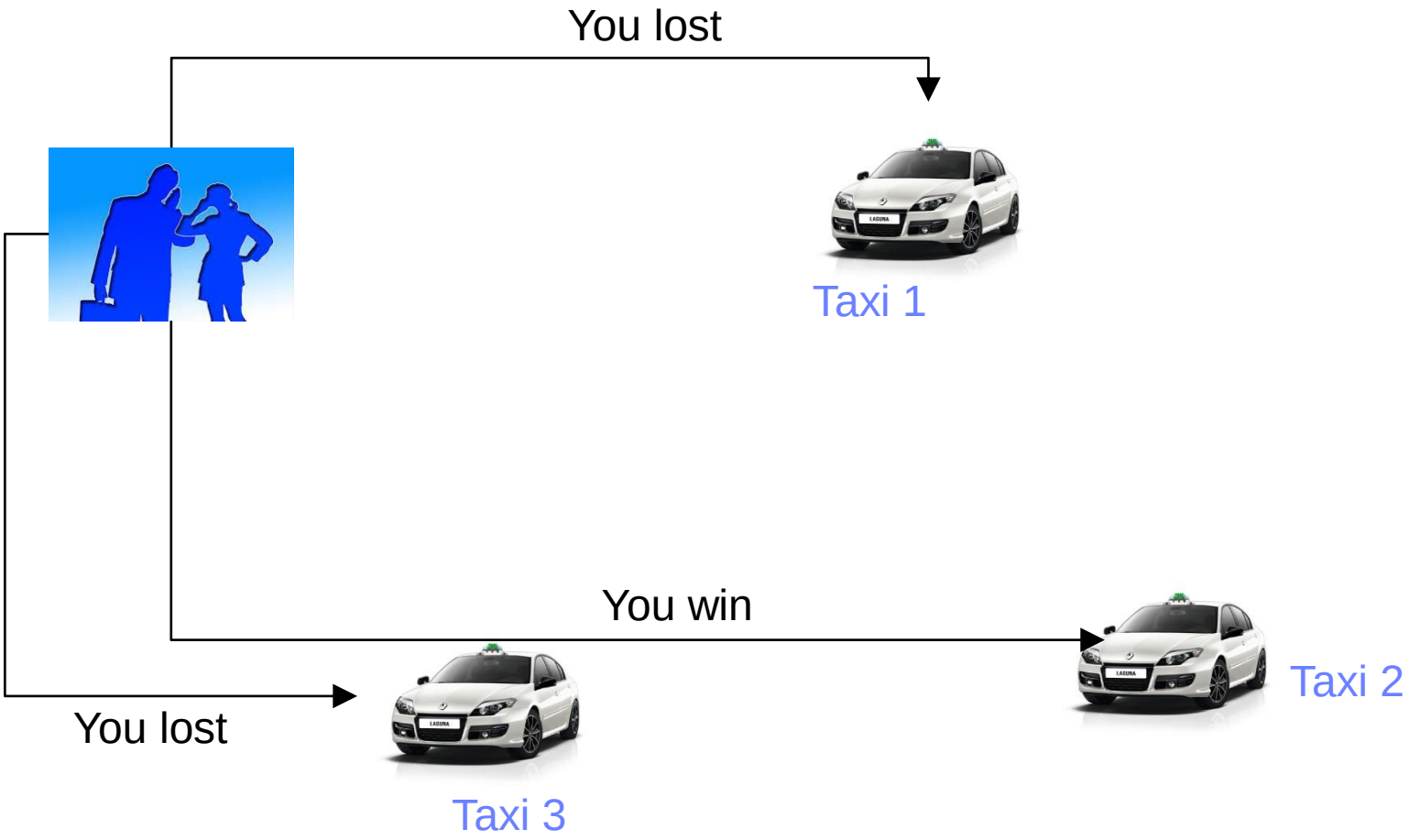
Taxi 3

I can be there at 5m

Taxi 2

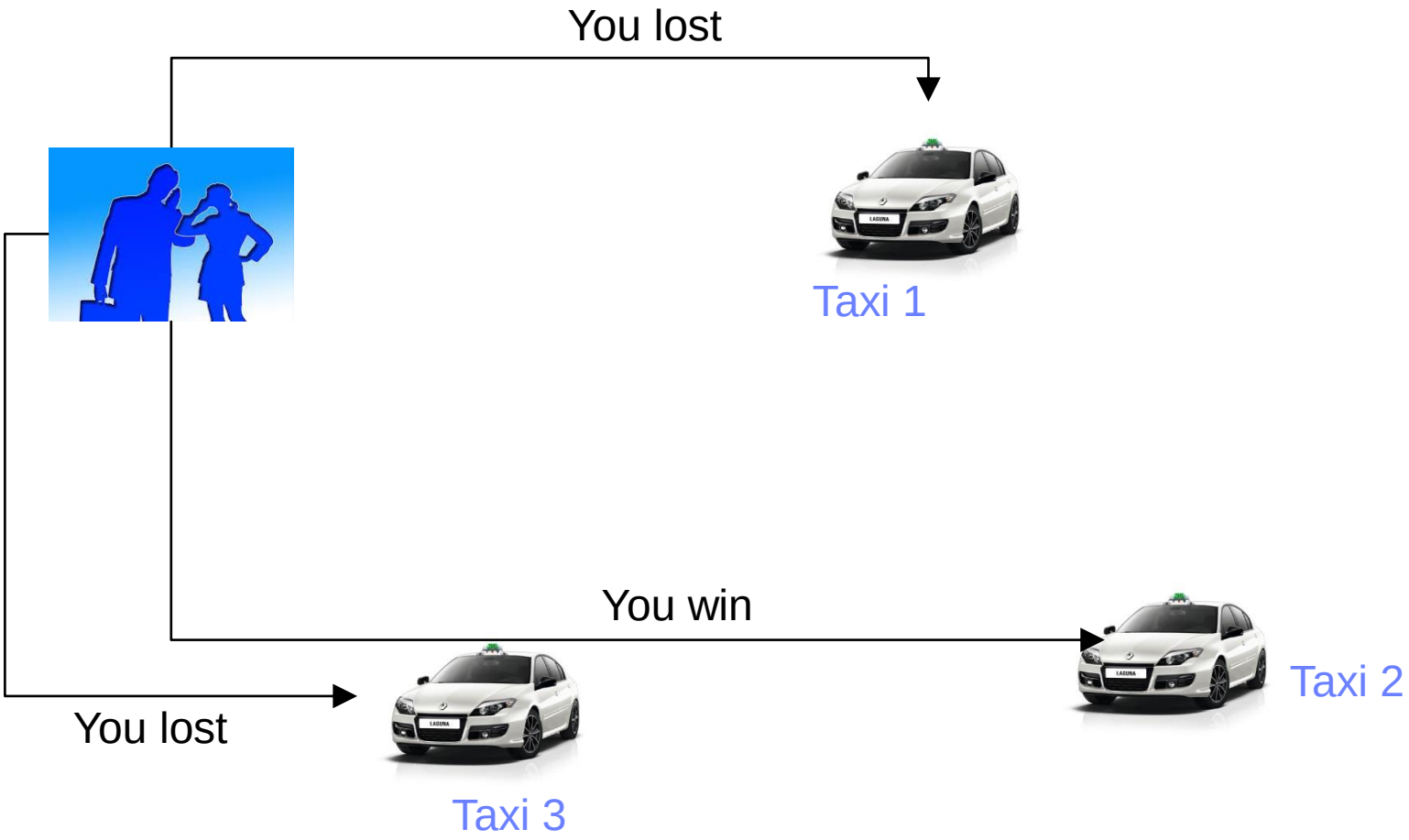
# Interaction Protocol

## FIPA – Contract Net Protocol – Illustration



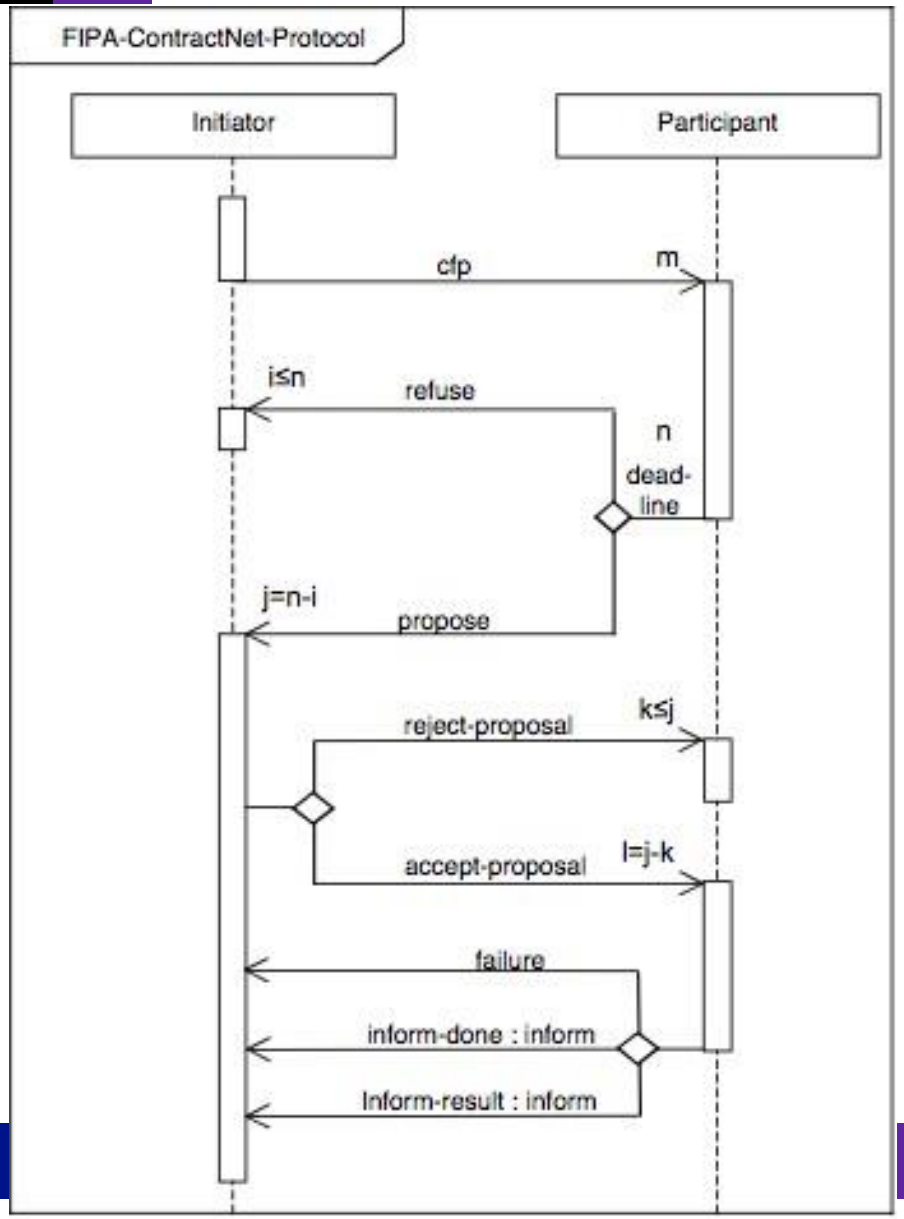
# Interaction Protocol

## FIPA – Contract Net Protocol – Illustration



# Interaction Protocol

## FIPA – Contract Net Protocol




https://www.fipa.org/specs/fipa00029/SC00029H.html



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