

Distributed Artificial Intelligence
and
Intelligent Agents

Marco Peressutti

April 14, 2022

Contents

1	Introduction	5
1.1	Definition of an Agent	5
1.1.1	Formal definitions	5
1.1.2	Logicale behind autonomous systems	6
1.1.3	Agent definition and properties	6
1.2	Individual and Group Perspective	8
1.3	Distributed AI and MAS	8
1.3.1	Distributed Problem Solving (DPS)	8
1.3.2	Multi-Agent Systems (MAS)	9
1.4	Emergence, Swarm Intelligence and other terms	11
1.4.1	Emergence	11
1.4.2	Swarm Intelligence	11
1.4.3	Self-Organisation	11
1.4.4	Self-Adaptation	11
1.4.5	Characteristics of Emergence, Swarm Intelligence, Self-Adaptation and Self-Organization	11
1.4.6	Application	11
2	Agent Negotiation	12
2.1	Multiagent Interactions	14
2.1.1	Utilities and Preferences	15
2.1.2	Setting the scene	16
2.1.3	Solution Concepts and Solution Properties	17
2.1.4	Competitive and Zero-Sum Interactions	19
2.1.5	The Prisoner's Dilemma	20
2.1.6	Other Symmetric 2×2 Interactions	21
2.2	Voting	22
2.2.1	Social Welfare Functions and Social Choice Functions	22
2.2.2	Voting Protocols	23
2.2.3	Desirable Properties for Voting Procedures	24
2.2.4	Insincere Voters	25
2.3	Auctions	26
2.3.1	Auction parameters for classification	26
2.3.2	English auctions	27
2.3.3	Japanese auctions	27
2.3.4	Dutch auctions	27
2.3.5	First-price sealed-bid auctions	27
2.3.6	Vickrey auctions	28
2.3.7	Interralated auctions	28
2.3.8	Lies and Collusion	29
2.4	Negotiation parameters	29
2.4.1	Task Oriented Domain	30
2.4.2	Worth Oriented Domain	32
2.4.3	Monotonic Concession Protocol (MCP)	33
2.4.4	The Zeuthen strategy	33

2.4.5	Deception	34
2.5	Contract Net Protocol (CNP)	35
3	Agent Communication	37
3.1	Approaches to software interoperation	37
3.1.1	Components of a system for effective interaction and interoperability	38
3.1.2	Three Important Aspects	38
3.2	Speech Acts	39
3.2.1	Austin	39
3.2.2	Searle	39
3.2.3	Plan-based theory	40
3.2.4	Speech acts as rational actions	40
3.3	Agent Communication Languages (ACL)	40
3.3.1	KSE	41
3.3.2	FIPA ACL	45
4	Agent Coordination	46
4.1	General models	46
4.1.1	Motivation	47
4.1.2	Coordination properties and mechanisms	47
4.1.3	Coordination problem	48
4.1.4	DAI and distributed search	48
4.2	Common coordination techniques	50
4.2.1	Comparing common coordination techniques	50
4.2.2	Organizational structures	51
4.2.3	Meta-level information exchange	53
4.2.4	Multi-agent planning	56
4.2.5	Explicit analysis and synchronization	56
4.2.6	Social Norms and Laws	57
4.2.7	Coordination Models based on human teamwork	57
5	MAS Architecture	59
5.1	Low-level architectures	60
5.1.1	Blackboard Architecture	60
5.1.2	ACTORS	62
5.2	Message sending based architecture: Agent Factory	63
5.3	Testbeds	63
5.3.1	DVMT	63
5.3.2	MACE	64
5.4	Infrastructures that use wrappers: ARCHON	64
5.4.1	ARCHON Layer	64
5.5	Infrastructures that use Middle Agents: RETSINA	65
5.6	Market-based architectures	65
5.6.1	MAGNET	66
5.7	Conclusion	67
6	Agent Oriented Software Engineering	68
6.1	When is an Agent-Based Solution Appropriate?	68
6.2	Agent-Oriented Analysis and Design	68
6.2.1	The AAIL methodology	69
6.2.2	The GAIA methodology	70
6.2.3	The Tropos methodology	70
6.2.4	The Prometheus methodology	71
6.2.5	Agent UML	71
6.2.6	Discussion	72
6.3	Pitfalls of Agent Development	72

7	Agent Theory	73
7.1	Agents as intentional systems	73
7.1.1	Attitudes	73
7.1.2	Theories of Attitudes	74
7.1.3	Study of Knowledge	74
7.2	Foundation of formal logic	74
7.2.1	Logical inference	76
7.3	Formalising attitudes	76
7.3.1	Possible worlds	77
7.3.2	Modal Logic	77
7.4	Logic of Knowledge	79
7.5	BDI architecture	80
8	Agent Architecture	82
8.1	Abstract agent architectures	82
8.2	Deliberative Architectures	82
8.2.1	BDI	82
8.2.2	PRS	82
8.2.3	IRMA	82
8.3	Reactive Architectures	82
8.3.1	Brook's subsumption Architecture	82
8.3.2	Steel's Mars Explorer	82
8.4	Hybrid Architectures	82
8.4.1	Touring Machine	82
8.4.2	InteRRaP	82
8.5	Discussion	82
9	Mobile Agents	83
9.1	Remote Procedure Calls vs Mobile Agents	83
9.1.1	Remote Procedure Calls	83
9.1.2	Remote execution	84
9.1.3	Advantages of RE over RPC	84
9.2	Mobile Agent Environment	85
9.3	Issues with Mobile agents	85
9.3.1	Security	86
9.4	Requirements for Mobile Agents	87
	Bibliography	88

Chapter 1

Introduction

1.1 Definition of an Agent	5
1.1.1 Formal definitions	5
1.1.2 Logicale behind autonomous systems	6
1.1.3 Agent definition and properties	6
1.2 Individual and Group Perspective	8
1.3 Distributed AI and MAS	8
1.3.1 Distributed Problem Solving (DPS)	8
1.3.2 Multi-Agent Systems (MAS)	9
1.4 Emergence, Swarm Intelligence and other terms	11
1.4.1 Emergence	11
1.4.2 Swarm Intelligence	11
1.4.3 Self-Organisation	11
1.4.4 Self-Adaptation	11
1.4.5 Characteristics of Emergence, Swarm Intelligence, Self-Adaptation and Self-Organization	11
1.4.6 Application	11

1.1 Definition of an Agent

- an agent has **independent behaviour**: when there is no possibility for direct supervision
- agents **collaborate** and **communicate** with each other
- angets have **proactive behaviour**: they have the reasoning possibility to proactively propose some solutions
- **privacy ensurance**: privacy should be ensured via **personalization**. A person's interest should not be disclouse to some external entity other than the agent itself.

independent
behaviour

collaborate

communicate

proactive
behaviour

privacy
ensurance

personalization

1.1.1 Formal definitions

1. American Heritage Dictionary:

“One that acts or has the power or authority to **act** ... or **represent** another”

Agents are not independent entities that operate by their own view but they always represent some interest of those who create them.

2. Negroponte

“Digital sister in law”

Agents should have specialized expertise and knowledge of preferences of those who create them

3. Russel and Norvig

“An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors.”

4. Pattie Maes

“Autonomous Agents are computational systems that **inhabit** some complex dynamic environment, **sense** and **act** autonomously in this environment, and by doing so **realize** a set of goals or tasks for which they are designed”

Agents live in an environment.

5. IBM

“Intelligent agents are software entities that carry out some set of **operations on behalf of** a user or another program with some degree of **independence** or **autonomy**, and in doing so, employ some **knowledge** or **representations** of the user’s **goals** or **desires**”

6. Coen

“Software agents are programs that engage in dialog [and] **negotiate** and **coordinate** transfer of information”

Agents must have the possibility to communicate and consequently coordinate and negotiate with one another.

1.1.2 Logics behind autonomous systems

- More and more everyday tasks are computer based
- The world is in a midst of an information revolution
- increasingly more users are untrained
- **Lack of programming paradigm** for decentralized program/system construction in dynamic environment.

Lack of programming paradigm

Existing paradigms were constructed for closed world (i.e. completely specified environment). However in AI the environment is not specified completely (hence there is the need for dynamic exploration of the environment).

The solution to this lack of paradigm is to **emulate human behaviour**, therefore agents must be able to:

emulate human behaviour

- perceive the environment
- affect the environment or act in the environment
- have a **model of behaviour**
- have intentions/motivations to be fulfilled by implementing corresponding goals.
- communication

model of behaviour

In fact, goals are not enough, the system needs to generate new goals from its intentions and beliefs.

1.1.3 Agent definition and properties

Wooldridge, Jennings (**weak notion**):

weak notion

“Agent is a hardware or (more usually) software-based computer system that enjoys the following properties:”

- **autonomy.**

autonomy

Agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state.

Hence in order for an agent to be autonomous it must:

- Act independently

- Have control over its internal state.

Contrary to objects, agents need to encapsulate behaviour other than their state in the environment.

They, in fact, differs from objects since they are required to have a:

1. **degree of autonomy**: agents embody a stronger notion of autonomy than objects, in particular, agents decide for themselves whether or not to perform an action. degree of autonomy
 2. **degree of smartness**: capable of flexible (reactive, pro-active, social) behaviour; standard object models do not have such behaviour degree of smartness
 3. **degree of activeness**: a multi-agent system is inherently multi-threaded in that each agent is assumed to have at least one thread of active control. degree of activeness
- **pro-activeness**.
Agents do not simply act in response to their environment, they are able to exhibit goal-directed behavior by taking the initiative. pro-activeness
In short, agent must be able to create goals on their own initiative.
 - **reactivity**. reactivity
Agents perceive their environment and respond in a timely fashion to changes that occur in it.
In short, communication with the environment.
 - **social ability**. social ability
Agents interact with other agents (and possibly humans) via some kind of agent-communication language.
In short, communication with other agents

Wooldridge, Jennings (**strong notion**): strong notion

- **Mentalistic notions**, such as beliefs and intentions are often referred to as properties of strong agents Mentalistic notions
- **Veracity**, agents will not knowingly communicate false information Veracity
- **Benevolence**: agents do not have conflicting goals and always try to do what is asked of it Benevolence
- **Rationality**: an agent will act in order to achieve its goals and will not act in such a way as to prevent its goals being achieved Rationality
- **Mobility**: the ability of an agent to move around a network Mobility

In addition to these basic properties several other alternatives have been proposed over the years:

1. Isaac Asimov's laws of robotics:

Law One

A robot may not injure a human being or, through inaction, allow a human being to come to harm

Law Two

A robot must obey orders given to it by human beings except where such orders would conflict with the First Law

Law Three

A robot must protect its own existence, as long as such protection does not conflict with the First or Second Law

Law Zeroth

A robot may not harm humanity, or, by inaction, allow humanity to come to harm

2. A robot must establish its identity as a robot in all cases
3. A robot must know it is a robot
4. A robot must reproduce. As long as such reproduction does not contradict with Laws 1,2 and 3
5. All robots endowed with comparable human reason and conscience should act towards one another in a spirit of brotherhood

Summary:

- Agents acts on behalf of other entities
- Agents must have weak agent characteristics
- Agents may have strong agent characteristics

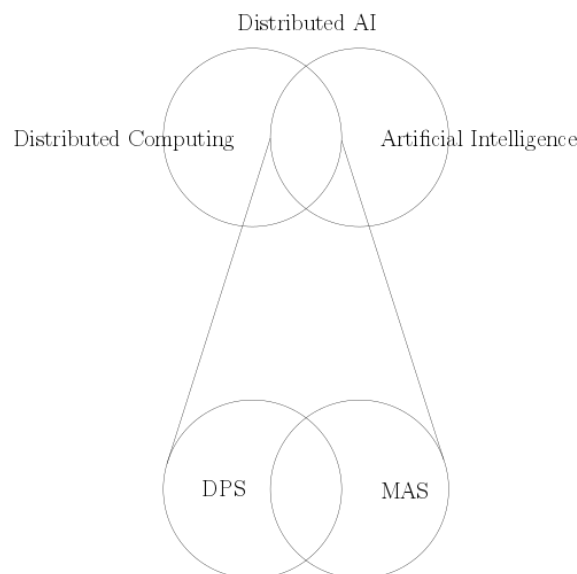
1.2 Individual and Group Perspective

There are two fundamental agents dimensions:

- **Individual agents perspective.** That deals with how to build agents that are capable of independent autonomous actions in order to successfully carry out the tasks that we delegate to them (**Micro aspects**). Individual agents perspective
- **Group agents perspective.** That deals with how to build agents that are capable of interacting (cooperating, coordinating, negotiating) with other agents in order to successfully carry out the tasks we delegate to them (**Macro aspects**). Micro aspects
Group agents perspective
Macro aspects

1.3 Distributed AI and MAS

- Distributed AI is a topic/subject rather than the creation of a brain that is distributed.
- It became part of AI when it was possible to execute on more than one CPU.
- For this reason, it is often considered as the intersection of **Distributed Computing** and **Artificial Intelligence**. Distributed Computing
Artificial Intelligence



- Distributed AI includes two different subfield: **Distributed Problem Solving (DPS)** and **Multi-Agent Systems (MAS)**. Distributed Problem Solving (DPS)
Multi-Agent Systems (MAS)
- DAI deals with several aspects and dimensions such as:
 - Agent granularity
 - Heterogeneity of agents
 - Communication possibilities
 - Methods of distributing control among agents

1.3.1 Distributed Problem Solving (DPS)

DPS considers how the task of solving a particular problem can be divided among a number of modules that cooperate in dividing and sharing knowledge about the problem and its evolving solution(s):

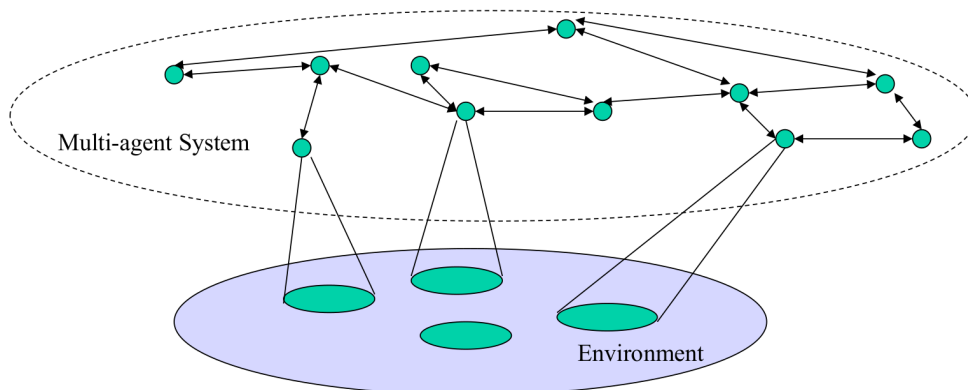
- In pure DPS systems, all interaction strategies are incorporate as an integral part of the system
- DPS has focused on achieving goals under varying environmental conditions, having agents with established properties

In other terms in DPS:

1. a problem is divided into modules
2. each module is allocated to a different agent
3. the agents will solve the problem by means of communicating the solution to their allocated module

1.3.2 Multi-Agent Systems (MAS)

- MAS are designed in a decentralized way with great part of independency and autonomy
- Agents with individual preferences will interact in particular environments such that each will consent to act in a way that leads to desired global goal
- MAS asks how, for a particular environment, can certain collective goal be realized if the properties of agents can vary uncontrollably:
 - loosely-coupled networks of problem solvers (agents) that work together to solve problems that are beyond their capabilities
 - no necessary guarantees about other agent
- MAS contain a number of agents which interact with one another through communication. The agents are able to act in an environment; where each agent will act upon or influence different parts of the environment. If two field of influence overlap, the conflict is (hopefully) resolved via negotiation and communication



- An important concept in MAS is that there is no central control (because the control is distributed to the various agents) and knowledge or information sources may also be distributed

In other terms, contrary to DPS, MAS do not deal with task to be solved but rather rules to be followed, and these rules are for example, their beliefs, desire and intentions or protocols for negotiation and communication.

The motives behind the use of MAS are:

- To solve problems that are too large for a centralized agent
- To allow interconnection and interoperation of multiple legacy systems
- To provide a solution to inherently distributed problems
- To provide solutions which draw from distributed information sources
- To provide solutions where expertise is distributed
- To offer conceptual clarity and simplicity of design

There are two subclasses of MAS:

- **Cooperative.**

Cooperative

Agents are designed by interdependent designers.

Agents act for increased good of the system.

Agents are concerned with increasing the performance of the system.

Hence if we imagine that the goodness of the system is represented by a global function.

Agents in a cooperative MAS will try to maximize such function.

- **Self-interested**

Self-interested

Agents designed by independent designers.

Agents have their own agenda and motivation.

Agents are concerned with the benefit and performance of the individual agent.

Hence, if we imagine that the goodness of each agent is represented by a local function (one for each agent). They will try to maximize their own function.

Among the benefits of using MAS over DPS we find that, MAS:

- Faster problem solving
- Decrease in communication
- Flexibility
- Increased reliability

However, its main drawback is the **lack of predictability**.

lack of
predictability

Summary of definitions:

- Distributed Computing: focus on low level parallelization and synchronization
- Distributed AI: Intelligent control as well as data may be distributed. Focus on problem solving, communication and coordination
- DPS: Task decomposition (task sharing) and/or solution synthesis (result sharing): information management
- MAS: Behavior coordination and management

1.4 Emergence, Swarm Intelligence and other terms

1.4.1 Emergence

With the term **Emergence**, we refer to those global (macro level) behaviour, patterns and properties that arise from the interactions between local parts of the system (micro level).

Systems that exhibit emergence can be characterized as simple, robust and adaptive.

Emergence

1.4.2 Swarm Intelligence

The term **Swarm Intelligence** refers to any attempt to design algorithms or distributed problem-solving devices inspired by the collective behaviour of social insect colonies and other animal societies. Multi-robot systems, which implement or adapt the concept of emergent behaviour, are commonly referred to as **swarm robotic systems**.

Swarm Intelligence

swarm robotic systems

1.4.3 Self-Organisation

Self-Organization is a dynamical and adaptive process where systems acquire and maintain structure themselves, without external control.// The term self-organization is also used as the process that leads to the state of emergence.

Self-organization and emergent systems are distinct concepts, they still have one thing in common, that is: there is no explicit external control whatsoever.

The main difference between self-organization and emergence is that in the case of self-organization, individual entities can be aware of the system's intended global behaviour. In consequence, self-organization can be seen as a weak form of emergence.

The intuitive and regularly used approach to realize self-organization is applying the concept of feedback loops.

Self-Organization

1.4.4 Self-Adaptation

When the approach with feedback loop is applicable to single entity system it is usually referred as **self-adaptation**.

Self-adaptive software modifies its own behaviour in response to changes in its operating environment. If a decentralized system containing several entities exhibits adaptive behaviour to external changes this is as well considered self-adaptation.

self-adaptation

1.4.5 Characteristics of Emergence, Swarm Intelligence, Self-Adaptation and Self-Organization

having ensembles of robust (multi-)agent systems that maintain their structure and feature a high level of adaptation.

It would no longer be necessary to exactly specify the low level system behaviour in all possible situations that might occur, but rather leaving the system with a certain degree of freedom to allow for autonomous reaction and adaptation to new situations in an intelligent way.

1.4.6 Application

Self-organization algorithms have been applied in many multi-agent domains, like combinatorial optimization, communication networks and robotics.

The algorithms, respectively mechanism, are used for various purposes, like motion control, information sharing and decision making.

Chapter 2

Agent Negotiation

2.1	Multiagent Interactions	14
2.1.1	Utilities and Preferences	15
2.1.2	Setting the scene	16
2.1.3	Solution Concepts and Solution Properties	17
	Dominant strategies - Dominance	17
	Nash Equilibria	17
	Pareto efficiency	18
	Maximizing social welfare	19
	Other minor properties	19
2.1.4	Competitive and Zero-Sum Interactions	19
2.1.5	The Prisoner's Dilemma	20
2.1.6	Other Symmetric 2×2 Interactions	21
2.2	Voting	22
2.2.1	Social Welfare Functions and Social Choice Functions	22
2.2.2	Voting Protocols	23
	Simple majority voting	23
	Binary protocol	23
	Borda protocol	24
	Majority Graph: Condorcet's Winner and Slater ranking	24
2.2.3	Desirable Properties for Voting Procedures	24
2.2.4	Insincere Voters	25
2.3	Auctions	26
2.3.1	Auction parameters for classification	26
2.3.2	English auctions	27
2.3.3	Japanese auctions	27
2.3.4	Dutch auctions	27
2.3.5	First-price sealed-bid auctions	27
2.3.6	Vickrey auctions	28
2.3.7	Interralated auctions	28
2.3.8	Lies and Collusion	29
2.4	Negotiation parameters	29
2.4.1	Task Oriented Domain	30
2.4.2	Worth Oriented Domain	32
2.4.3	Monotonic Concession Protocol (MCP)	33
2.4.4	The Zeuthen strategy	33
2.4.5	Deception	34
2.5	Contract Net Protocol (CNP)	35

- Davis and Smith
“Negotiation is a process of improving agreement (reducing inconsistency and uncertainty) on common viewpoints or plans through the exchange of relevant information”.

Negotiation is a two way exchange of information (more than one agent must be involved for negotiation to happen).

Each party evaluates the information from its own perspective.

final agreement is achieved by **mutual selection**.

mutual selection

- Pruitt
“Negotiation is a process by which a joint decision is made by two or more parties. The parties first verbalize contradictory demands and then move towards agreement by a process of concession or search for new alternatives”

Mutual conflict

Mutual conflict is the necessary condition to start negotiation.

Negotiation involves three main elements: **communication**, **decision making** (decision about next concession to make in order to continue negotiation) and a **procedural model** (protocol inside which we communicate and make decision).

communication

decision making

Implicit negotiation where one or more parties does not know that there is conflict can happen but it will not be treated in the course.

procedural model

From the definitions provided we can conclude that there are three basic negotiation categories:

Implicit negotiation

- **Negotiation language category** (Communication)

We will consider the language category more in depth in chapter 3: Agent Communication.

The language category deals with the concepts of:

Negotiation language category

- **Language primitives**

Low level communications (message sending) and conversational aspects (relative to speech acts and performatives)

Language primitives

- **Object structure**

What is the object of negotiation (price, schedule, tasks, ...) and what is the context of the message/information.

Object structure

- **Internal protocol**

Specify the possibilities of initiating a negotiation cycle and responding to a message

Internal protocol

- **Semantics**

Strictly related to language primitives (pre-conditions, post-conditions, modal logic).

Semantics

- **Negotiation decision category** (Decision making)

The decision category deals with which strategy and consequently which language primitive to choose inside of a protocol.

Negotiation decision category

It deals with the concepts of:

- preferences
what are preferable outcomes
- utility functions
numerical/functional representation of preferences
- comparing and matching functions
- negotiation strategies

- **Negotiation process category** (Protocols/procedural model)

Negotiation process category

It deals with the concepts of:

- **Procedural negotiation model**

what is the protocol of negotiation and their properties

Procedural negotiation model

- **System behaviour and analysis**

analysis of the interaction between different parts of the system in order to recognize what are protocols and preferences (it will not be considered in the course)

System behaviour and analysis

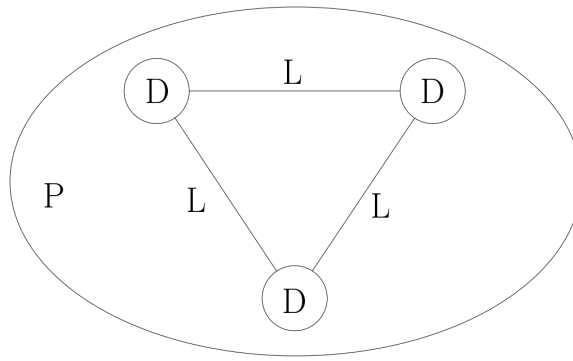


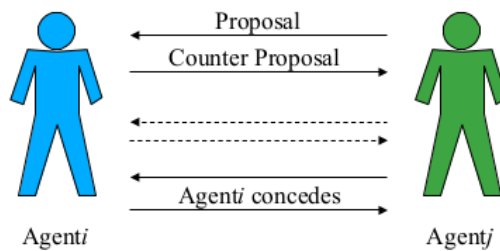
Figure 2.1: trivial form of how the categories are interrelated in the negotiation context

Furthermore, since negotiation happens when mutual conflict occurs, we can say that negotiation is a **conflict resolution** approach/method/area.

In general terms, negotiation usually proceeds in **series of rounds** with every agent making a proposal at every round. For this reason, the negotiation process can be seen as a mutual exchange of information.

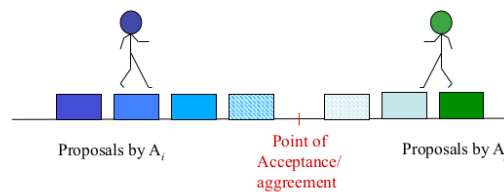
conflict resolution

series of rounds



Another way of looking at the negotiation process is as an iterative concession process: each agent starts at its most preferred outcome and makes a proposal, it will then proceed to concede to a less preferred outcome until a **Point of acceptance or agreement** is reached. (Be aware of the fact that not all negotiation end with agreement).

Point of acceptance or agreement



Hence the Negotiation process can be seen as moving towards a point of agreement.

2.1 Multiagent Interactions

In the typical structure of a multiagent systems, one can notice the presence of some common elements:

- the system contains a number of agents
- each agent has the ability to communicate with another agent
- each agent has the ability to act in an environment
- different agents have different **spheres of influence**, i.e. they are able to influence or have control over the environment, or a part of it.

spheres of influence

- these spheres of interest may coincide or overlap giving rise to dependencies between agents.

Thus:

“When faced with what appears to be a multiagent domain, it is critically important to understand the type of interaction that takes place between agents in order to be able to make the best decision possible about what action to perform.”

2.1.1 Utilities and Preferences

In order to simplify the analysis of multiagent interactions, throughout this chapter we will consider the following assumption, unless stated differently:

- Two agents act and interact in an environment. We will refer to these two agents as agent i and agent j
- The two agents are **self-interest**, i.e. each agent has its own preferences and desires about how the world should be self-interest
- There exists a **set of outcomes** that the two agents have preferences over. We will refer to this set with the notation: set of outcomes

$$\Omega = \{\omega_1, \omega_2, \dots\}$$

The preferences of the two agents are formally captured by means of **utility functions**, which maps each outcome in the set Ω to a real number describing how “good” an outcome is. utility functions
Since the agents are self-interest each agent will have its own utility function, hence:

$$u_i : \Omega \rightarrow \mathbb{R} \quad ; \quad u_j : \Omega \rightarrow \mathbb{R}$$

The introduction of an utility function eventually leads to a **preference ordering** over the outcomes of the set for each agent. This means that, if ω and ω' are both possible outcomes contained in Ω and $u_i(\omega) \geq u_i(\omega')$, then agent i prefers outcome ω at least as much as outcome ω' . preference ordering

Since we will make extensive use of the concept of preference ordering throughout the next sections, it is worth introduce a much more compact notation. We will write:

$$\begin{array}{lll} \omega \succeq_i \omega' & \text{as an abbreviation for} & u_i(\omega) \geq u_i(\omega') \\ \omega \succ_i \omega' & \text{as an abbreviation for} & u_i(\omega) > u_i(\omega') \end{array}$$

where the second expression represents the case in which outcome ω is **strictly preferred** by agent i over ω' . strictly preferred

In other words, the notation can be summarized as follows:

$$\boxed{\omega \succ_i \omega' \iff u_i(\omega) \geq u_i(\omega') \text{ and not } u_i(\omega) = u_i(\omega')}$$

Moreover we can notice that the ordering relation expressed by the operator \succeq , has the following properties:

1. **Reflexivity** Reflexivity
$$\forall \omega \in \Omega \rightarrow \omega \succeq_i \omega$$
2. **Transitivity** Transitivity
$$\text{If } \omega \succeq_i \omega' \text{ \&\& } \omega' \succeq_i \omega'' \rightarrow \omega \succeq_i \omega''$$
3. **Comparability** Comparability
$$\forall \omega \in \Omega, \forall \omega' \in \Omega \rightarrow \omega \succeq_i \omega' \parallel \omega' \succeq_i \omega$$

The strict preference relationship still has the second and third property, however it is not reflexive

2.1.2 Setting the scene

So far, we have talked introduced a model to represent the agents preferences, but we still need to formalize a model of the environment in which agents act and interact. In particular, we will assume that:

- Two agents will simultaneously choose an action to perform in the environment
- as a result of the actions they select, an outcome in Ω will result
- the **actual outcome** that will result will depend on the particular **combination of actions** performed. actual outcome
- In other terms: both agents can influence the actual outcome combination of actions
- The two agents must perform an action
- The two agents cannot see the action performed by the other agent

We will restrict our analysis to two possible actions that the agent can choose from: cooperate C and defect D . Hence, we will refer to the **set of actions** with the notation set of actions

$$Ac = \{C, D\}$$

Given all the above, the environment formally described by a **state transformer function**: state transformer function

$$\tau : \underbrace{Ac}_{\text{agent } i\text{'s action}} \times \underbrace{Ac}_{\text{agent } j\text{'s action}} \rightarrow \Omega$$

Hence, several scenarios can happen:

1. The environment maps each combination of actions to a different outcome, and thus is sensitive to the actions of both agents

$$\tau(D, D) = \omega_1 \quad \tau(D, C) = \omega_2 \quad \tau(C, D) = \omega_3 \quad \tau(C, C) = \omega_4$$

2. The environment maps each combination of actions to the same outcome and thus neither of the agents have influence in the environment

$$\tau(D, D) = \omega_1 \quad \tau(D, C) = \omega_1 \quad \tau(C, D) = \omega_1 \quad \tau(C, C) = \omega_1$$

3. The environment maps each combination of actions to an outcome that is correlated to the choice of only one agent and thus the outcome depends solely on the action performed by one agent

$$\tau(D, D) = \omega_1 \quad \tau(D, C) = \omega_2 \quad \tau(C, D) = \omega_1 \quad \tau(C, C) = \omega_2$$

Since the latter two cases are of no interest for our analysis we will focus on the scenario in which both agents exert some kind of influence on the actual outcome. We, therefore, will consider the agent preferences (in the form of utility function) as follows

$$\left. \begin{array}{llll} u_i(\omega_1) = 1 & u_i(\omega_2) = 1 & u_i(\omega_3) = 4 & u_i(\omega_4) = 4 \\ u_j(\omega_1) = 1 & u_j(\omega_2) = 4 & u_j(\omega_3) = 1 & u_j(\omega_4) = 4 \end{array} \right\}$$

Given the state transformer function, we can abuse notation and write

$$\left. \begin{array}{llll} u_i(D, D) = 1 & u_i(D, C) = 1 & u_i(C, D) = 4 & u_i(C, C) = 4 \\ u_j(D, D) = 1 & u_j(D, C) = 4 & u_j(C, D) = 1 & u_j(C, C) = 4 \end{array} \right\}$$

Hence, with respect to agent i 's preferences (first row) over the possible outcomes, we can characterize the preference ordering as follows:

$$(C, C) \succeq_i (C, D) \succeq_i (D, C) \succeq_i (D, D)$$

Similarly for agent j , the resulting preference ordering can be characterize as follows:

$$(C, C) \succeq_i (D, C) \succeq_i (C, D) \succeq_i (D, D)$$

	i defects	i cooperates
j defects	1 1	4 1
j cooperates	1 4	4 4

It is straightforward to see that if both agents **act rationally**, i.e. “they both choose to perform the action that will lead to their preferred outcomes”[1], they will both choose to cooperate. This is because, both agents prefer all the outcomes in which they cooperate, regardless of what the other agent action is. act rationally

A common way to represent the previously described interaction scenario is via **pay-off matrix** (standard game-theoretic notation): The pay-off matrix uniquely defines a **game in strategic form**. The way to interpret it is as follows: pay-off matrix
game in strategic form

- each cell in the matrix correspond to one of the possible outcomes
- The top-right value in each cell corresponds to the payoff received by the column player
- The bottom-left value in each cell corresponds to the payoff received by the row player

2.1.3 Solution Concepts and Solution Properties

A question still remains unanswered: What should an agent do? What action should he chooses?

We briefly touched on the topic on the previous section, but we have provided neither the concepts that make up the solution nor the desirable properties that a solution should have.

In this section, we will tackle the problem to its core.

Dominant strategies - Dominance

One of the main concept that we will introduce is that of **dominance**.

“A strategy s_i is [said to be] **dominant** for player i if, no matter what strategy s_j agent j chooses, i will do at least as well playing s_i as it would doing anything else”[1]. The notion of **dominant strategy** is strictly related to the concept of **best response**, in the sense that “a strategy s_i for agent i is dominant if it is the best response to **all** of agent strategies”[1]. dominance
dominant strategy
best response

Thus, a dominant strategy, if it exists, simplify the decision about what action to perform: “the agent guarantees its best outcome by performing the dominant strategy”[1].

Nash Equilibria

The notion of **equilibrium**, or more precisely **Nash equilibrium**, is hard to formalize in the context of strategic decision making. equilibrium

We can, however, provide a basic definition by saying that two strategies s_1 and s_2 are in Nash equilibrium if: Nash equilibrium

1. under the assumption that agent i plays s_1 , agent j can do no better than play s_2 , and
2. under the assumption that agent j plays s_2 , agent i can do no better than play s_1

From this conditions, one can clearly notice that **two strategies are in Nash equilibrium if they are the best response to each other**.

The mutual nature of the concept makes it so that *neither agent has any incentive to deviate from a Nash equilibrium*: even if an agent chooses a different strategy, the other agent can do no better than to choose the strategy in Nash equilibrium.

Technically, this type of Nash equilibrium is known as **pure strategy Nash equilibrium**, and as much as it is appealing from its theoretical stand point, it is extremely expensive from a computational stand point. pure strategy Nash equilibrium

In fact, finding one or more Nash equilibria requires to consider each combination of strategy and check if they are in Nash equilibrium.

Thus, if there are n agents, each with m possible strategies to choose from, the number of possible combinations of actions (and hence possible outcomes) will be m^n .

Nonetheless, the presence of Nash equilibrium provides a definite answer to what action an agent should choose. However, two common issues might emerge:

1. Not every interaction scenario has a pure strategy Nash equilibrium
2. Some interaction scenarios have more than one pure strategy Nash equilibrium

With regard to the first issue, we need to modify our notion of what a strategy is. So far, we have implicitly considered a strategy as a deterministic choice of an action. This is inline with the fact that the subroutines that an agent can execute should not be subject to uncertainties or randomness (in general, we would like a subroutine to yield the same correct result on different execution).

However, “it can be useful to introduce randomness or uncertainty into our actions”[1]. The reason why that is can be best explained considering the game of rock-paper-scissors, of which the pay-off matrix is provided below: From the provided payoff matrix, one can clearly notice

	i plays rock	i plays paper	i plays scissors
j plays rock	0	1	-1
j plays paper	-1	0	1
j plays scissors	1	-1	0

that the game has no pure strategy Nash equilibrium as well as no dominant strategy. Yet, this is not completely true: a **mixed strategy** allows the agent to choose between possible choices by introducing randomness into the selection. mixed strategy

If the agent chooses one of the actions at random, with each choice having equal probability of being selected, the strategy turns out to be in **Nash equilibrium with itself**. This is because if an agent decides to choose an action at random, the other agent can do no better than adopting the same strategy and vice versa.

In general, if a player has k possible choices, s_1, s_2, \dots, s_k , then a mixed strategy over these choices takes the form:

- play s_1 with probability p_1
- play s_2 with probability p_2
- ...
- play s_k with probability p_k

In other terms, a mixed strategy over s_1, s_2, \dots, s_k is a probability distribution over s_1, s_2, \dots, s_k .

The result formalized by John Forbes Nash, Jr. best summarize the discussion that we have made so far:

“Every game in which every player has a finite set of possible strategies has a Nash equilibrium in mixed strategies”

Pareto efficiency

The notion of **Pareto efficiency** or **Pareto optimality**, contrary to the notion of Nash equilibrium and dominant strategy, is more of a (desirable) property of solutions rather than a solution concept.

Formally:

“an outcome is Pareto efficient if there is no other outcome that improves one player’s utility without making somebody else worse off”.[1]

On the other hand: “An outcome is said to be Pareto inefficient if there is another outcome that makes at least one player better off without making anybody else worse off”[1].

To put it in simpler terms we can consider an example: a brother and a sister have to divide a cake. Among the solutions of this problem, those who are Pareto efficient are:

Pareto efficiency

Pareto optimality

- The brother eats the whole cake
- The sister eats the whole cake
- Any other distribution of the cake, which leaves no cake left

Hence, a solution is Pareto efficient if it consumes/uses the total utility.

Maximizing social welfare

Similarly to Pareto efficiency, **social welfare** is an important property of outcomes, but is not generally a way of directly selecting them. social welfare

The core principle of **Maximizing social welfare** involves the measurement of how much utility is created by an outcome in total. Maximizing social welfare

Formally, let $sw(\omega)$ denote the sum of utilities of each agent for outcome ω

$$sw(\omega) = \sum_{i \in Ag} u_i(\omega)$$

the outcome that maximized social welfare is the one that maximizes this value.

From an individual agent's point of view, the problem with maximizing social welfare is that it does not look at the pay-offs of individual agents, only to the total welfare created. (maximizing social welfare does not care about how the utility of an outcome is divided among the players).

Other minor properties

- **Convergence/ guaranteed success**
If it ensures that eventually agreement is certain to be reached. Convergence/
guaranteed
success
- **Computational efficiency**
As little computations is needed as possible. Trade off between the cost of the process and the solution quality Computational
efficiency
- **Distribution**
All else being equal, distributed protocols should be preferred to avoid a single point of failure and a performance bottleneck. This may conflict with minimizing the amount of communication that is required. Distribution
- **Stability**
Among self interested agents, mechanism should be designed to be stable (non-manipulable), it should motivate each agent to behave in the desired manner. Stability
- **Individual rationality**
Participation in a negotiation is individually rational to an agent if the agent's payoff in the negotiated solution is no less than payoff that the agent would get by not participating in the negotiation. Individual
rationality
A mechanism is individually rational if participation is individually rational for all agents.
If the negotiated solution is not individually rational for some agent then self-interested agent would not participate in that negotiation.

2.1.4 Competitive and Zero-Sum Interactions

A scenario in which an outcome $\omega \in \Omega$ is preferred by agent i over an outcome ω' , if, and only if, ω' is preferred over ω by agent j , is said to be **strictly competitive**. strictly
competitive

Formally, a competitive scenario takes the form:

$$\omega \succ_i \omega' \iff \omega' \succ_j \omega$$

Under this condition, it is straightforward to see that the preferences of the players are **diametrically opposed** to one another diametrically
opposed

Zero-sum encounters, similarly, are those in which, for any particular outcome, the utilities of the two agents sum to zero. Formally, these scenario is described by the condition: Zero-sum
encounters

$$u_i(\omega) + u_j(\omega) = 0 \quad \forall \omega \in \Omega$$

Once again, any zero-sum scenario is strictly competitive, allowing for no possibility of cooperative behavior: “the best outcome for an agent is the worst outcome for its opponent. If an agent allows the opponent to get a positive utility, then it will get negative utility.”[1]

Popular Zero-sum encounters are the games of chess and checkers as well as rock-paper-scissors.

Interesting enough, zero-sum is debatable that zero-sum games actually exists in real-world scenarios (apart from artificially forms of interaction like the games mentioned before). However, it appears that people interacting in many scenarios have a tendency to treat them as if they were zero sum.

2.1.5 The Prisoner’s Dilemma

The **Prisoner’s Dilemma** is as follows: “Two man are collectively charged with a crime and held in separate cells. They have no way of communicating with each other or making any kind of agreement. The two man are told that:

Prisoner’s
Dilemma

1. If one of them confesses to the crime and the other does not, the confessor will be freed, and the other will be jailed for three years
2. If both confess to the crime, then each will be jailed for two years

Both prisoners know that if neither confesses, then they will each be jailed for one year.”[1] Under this conditions let us associate the act of confessing with defection D and not confessing with cooperating C .

There exists 4 possible outcomes to the prisoner’s dilemma: Where the number displayed are

	i defects	i cooperates
j defects	2 2	0 5
j cooperates	5 0	3 3

NOT the year spent in prison.

From the provided payoff matrix we can come up with the preference ordering of each agent/prisoner:

$$\begin{cases} (D, C) \succ_i (C, C) \succ_i (D, D) \succ_i (C, D) & \text{for agent } i \\ (C, D) \succ_j (C, C) \succ_j (D, D) \succ_j (D, C) & \text{for agent } j \end{cases}$$

Thus, we can analyze the best response of an agent to the choice of action of the other:

- Assuming the other player cooperates. The best response is to defect
- Assuming the other player defect. The best response is to defect

From this we can conclude that defection for i is the best response to all possible strategies of the player j : by definition, defection is thus a dominant strategy for i .

Since the same conclusion can be drawn for agent j , the scenario under consideration is **symmetric**: this will result in both agent choosing to defect.

From an analysis of the problem under the concepts that we have seen previously, we can state that

- the pair (D, D) is the only Nash equilibrium of the scenario, however intuition says that this is not the best the players can do.
- the pair of actions (D, D) is also the only one that is not Pareto efficient.
- The outcome that maximizes social welfare is (C, C)

“The fact that utility seems to be wasted here, and that the agents could both do better by cooperating, even though the rational thing to do is to defect, is why this is referred to as dilemma.” [1]

Moreover, the prisoner’s dilemma also seems to be the game that characterized the **tragedy of the commons**: which is concerned with the use of a shared, depletable resource by a society of

tragedy of the
commons

self-interested individuals (e.g. overfishing in the seas, exploitation of bandwidth capacity on the Internet).

Many people find the conclusion of the analysis deeply upsetting: “the result seems to imply that cooperatoin can only arise as a result of irrational behavior, and that cooperative behavior can be exploited by those who behave rationally.”[1]

Binmore argues that the discomfort we have with the analsys of the prisoner’s dilemma is misplaced: “A whole generation of scholars swallowed the line that the prisoner’s dilemma embodies the essence of the problem of human cooperation. They therefore set themselves the hopeless task of giving reasons why [this analysis] is mistaken... Rational players don’t cooperate in the prisoner’s dilemma because the conditions necessary for rational cooperation are absent”.

2.1.6 Other Symmetric 2×2 Interactions

The prisoner’s dilemma and its variation are not the only type of multiagent interaction that exists.

In fact, if we restrict our attention to interaction in which there are:

- Two agents
- Each agent has two possible actions (C or D)
- The scenario is symmetric

Then $4! = 24$ possible orderings of preferences, and as a consequence, 24 different games, can be constructed.

Scenario	Preferences over outcomes	Comment
1	$(C, C) \succ_i (C, D) \succ_i (D, C) \succ_i (D, D)$	cooperation dominates
2	$(C, C) \succ_i (C, D) \succ_i (D, D) \succ_i (D, C)$	cooperation dominates
3	$(C, C) \succ_i (D, C) \succ_i (C, D) \succ_i (D, D)$	
4	$(C, C) \succ_i (D, C) \succ_i (D, D) \succ_i (C, D)$	stag hunt
5	$(C, C) \succ_i (D, D) \succ_i (C, D) \succ_i (D, C)$	
6	$(C, C) \succ_i (D, D) \succ_i (D, C) \succ_i (C, D)$	
7	$(C, D) \succ_i (C, C) \succ_i (D, C) \succ_i (D, D)$	
8	$(C, D) \succ_i (C, C) \succ_i (D, D) \succ_i (D, C)$	
9	$(C, D) \succ_i (D, C) \succ_i (C, C) \succ_i (D, D)$	
10	$(C, D) \succ_i (D, C) \succ_i (D, D) \succ_i (C, C)$	
11	$(C, D) \succ_i (D, D) \succ_i (C, C) \succ_i (D, C)$	
12	$(C, D) \succ_i (D, D) \succ_i (D, C) \succ_i (C, C)$	
13	$(D, C) \succ_i (C, C) \succ_i (C, D) \succ_i (D, D)$	game of chicken
14	$(D, C) \succ_i (C, C) \succ_i (D, D) \succ_i (C, D)$	prisoner’s dilemma
15	$(D, C) \succ_i (C, D) \succ_i (C, C) \succ_i (D, D)$	
16	$(D, C) \succ_i (C, D) \succ_i (D, D) \succ_i (C, C)$	
17	$(D, C) \succ_i (D, D) \succ_i (C, C) \succ_i (C, D)$	
18	$(D, C) \succ_i (D, D) \succ_i (C, D) \succ_i (C, C)$	
19	$(D, D) \succ_i (C, C) \succ_i (C, D) \succ_i (D, C)$	
20	$(D, D) \succ_i (C, C) \succ_i (D, C) \succ_i (C, D)$	
21	$(D, D) \succ_i (C, D) \succ_i (C, C) \succ_i (D, C)$	
22	$(D, D) \succ_i (C, D) \succ_i (D, C) \succ_i (C, C)$	
23	$(D, D) \succ_i (D, C) \succ_i (C, C) \succ_i (C, D)$	defection dominates
24	$(D, D) \succ_i (D, C) \succ_i (C, D) \succ_i (C, C)$	defection dominates

For the sake of the analysis we will briefly look into two more of these games: stag hunt and the game of chicken.

- The stag hunt

	i defects	i cooperates
j defects	1 1	0 2
j cooperates	2 0	3 3

- The Game of chicken

	i defects	i cooperates
j defects	0 0	1 3
j cooperates	3 1	2 2

2.2 Voting

So far we have looked at the general setting of a multiagent encounter. In this section we will look at a specific class of protocols intended for making group decisions. This is the domain of social choice theory (aka voting theory).

2.2.1 Social Welfare Functions and Social Choice Functions

The general setting of a voting protocol is as follows:

- A set of agents or **voters** voters

$$Ag = \{1, \dots, n\}$$

Ideally, this should be finite and the cardinality should be an odd number to avoid ties.
- A set of possible outcomes or **candidates** candidates

$$\Omega = \{\omega_q, \omega_w, \dots\}$$

over which voters will make group decision. This set is assumed to be finite.

The goal of the agents is to rank or order these candidates or simply to choose one from the set.

The problem that social choice theory tries to solve is,

“given a collection of preference orders, one for each agent, how do we combine these to derive a group decision?”.

The answer is by using a **social welfare function** which maps the voter preferences to a **social preference order** social welfare function

$$f : \Pi(\Omega) \times \dots \times \Pi(\Omega) \rightarrow \Pi(\Omega)$$
social preference order

The social preference ordering will be denoted with the notation \succ^* .

If the agents are required to choose just one candidate over the set Ω , we will use a **social choice function** or **voting procedure**: social choice function

$$f : \Pi(\Omega) \times \dots \times \Pi(\Omega) \rightarrow \Omega$$
voting procedure

2.2.2 Voting Protocols

Simple majority voting

- Every voter submits their preference order
- The winner is the outcome that appears first in the preference orders the largest number of times
- This is generally applied to single choice, but it can be generalized to a social preference ordering.

Simple majority voting works relatively well with only two candidates, since it is straightforward to implement and understand by the voters.

Simple majority voting

However, when more than 2 voters are involved problems start to arise.

Let us consider that three voters submitted the following preferences:

$$\begin{array}{ll} 42\% & \omega_L \succ \omega_D \succ \omega_C \\ 14\% & \omega_D \succ \omega_L \succ \omega_C \\ 44\% & \omega_C \succ \omega_D \succ \omega_L \end{array}$$

Then the winner is selected based on the top preferences (i.e. C), even though the majority of the voters considered C as the least preferable outcome.

This means that in principle the majority of the voters will be unhappy with the result of the voting protocol.

Furthermore, this simple majority protocol is sensible to insincere strategical voting (e.g. the 14% that voted D instead could have voted for L just to make C lose the voting).

Moreover, the simple majority voting is sensible to **Condorcet's paradox**:

Condorcet's paradox

$$\omega_1 \succ_i \omega_2 \succ_i \omega_3 \omega_3 \succ_j \omega_1 \succ_j \omega_2 \omega_2 \succ_k \omega_3 \succ_k \omega_1$$

In this case the winner is dependent on the agenda: which order we start to compute the outcome, but nonetheless $2/3$ of the voters will prefer another candidate.

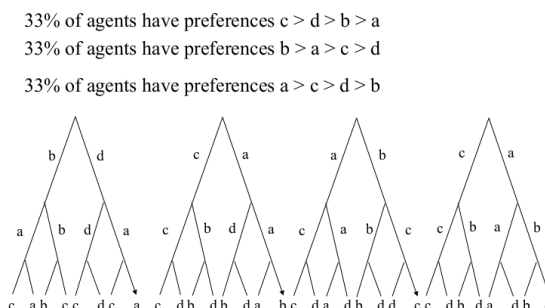
Binary protocol

Among the alternative to simple majority voting there is the **Binary protocol** (aka sequential majority elections).

Binary protocol

- Voters submit their preference ordering
- The element of the set of outcomes are compare pairwise
- the winner of the pairwise “election” is allowed to continue to the next pairwise election
- The order of pairwise elections (i.e. which candidates to compare first), is called **agenda**

agenda



From the picture provided we can clearly notice that the winner of the overall election depends on the agenda, which imply that the protocol can be manipulated if the preference orderings is known a priori.

Borda protocol

One issue with simple majority voting and the binary protocol is that they completely ignore the information that is encoded in each submitted preference ordering (they only loop at the top voted candidates).

The **Borda protocol** addresses such issue:

Borda protocol

- Each voter submit its preference ordering over the candidates
- a number equal to the cardinality of the set of candidates (i.e. $|\Omega|$) is assigned to the highest candidate in some agent's preference list
- a value of $|\Omega| - 1$ is assigned to the second and so on
- at the end we sum up the numeric value associated to each preference order and obtain the social choice result

This protocol is fast when compared to the binary protocol in the case of a large amount of candidates.

However it is not **independent of irrelevant alternatives**, i.e. removing one candidate will change the end result.

independent of irrelevant alternatives

Majority Graph: Condorcet's Winner and Slater ranking

An useful tool to analyse voting procedures or protocols is the **Majority Graph**. It can be considered as a succinct representation of the voter preferences:

Majority Graph

- each node in the majority graph is a candidate
- each edge in the majority graph represents a preference (the edge will start from the node most preferred and will terminate in the node less preferred)
- a **possible winner** is a candidate that is the overall winner for at least one agenda. (occurs when there are loops in the majority graph)
- a **Condorcet's winner** is a candidate that is the overall winner for all possible agenda (occurs when there are no loops in the majority graph). In simple terms, is that candidate that will beat all others in a pairwise election.

possible winner

Condorcet's winner

While the overall winner determination is straightforward in the case of a majority graph with no loops (cfr. Condorcet's Winner), it is otherwise in the case of a majority graph with loops.

In that specific scenario, the **slater rule** or **slater ranking** is considered: it, in fact, tries to find a consistent ranking that does not contain any cycle that is as close a possible to the majority graph.

slater rule

In other terms, it tries to "minimize the number of disagreements between the majority graph and the social choice".

slater ranking

In practice, the Slater ranking considers the Condorcet's winners obtained by inverting the least amount of edges in the majority graph.

2.2.3 Desirable Properties for Voting Procedures

1. **Pareto condition**

Pareto condition

There is no other outcome that makes one agent better off without making another agent worse off.

Borda and simple majority voting satisfy this condition.

Binary protocol does not (the result depends on the agenda).

2. **Condorcet winner condition**

Condorcet winner condition

The Condorcet winner should be selected by the social choice function.

Only Binary protocol satisfies this condition.

3. **Independence of irrelevant alternatives**

Independence of irrelevant alternatives

Given a set of candidates of which ω_i and ω_j are part of.

Let us assume that $\omega_i \succ^* \omega_j$.

A change in preferences in any other candidate should not change the relative ranking of ω_i and ω_j .

None of the protocol we have seen satisfies this property.

4. Dictatorship

Dictatorship

A social welfare function is said to be a dictatorship if for some voter i we have

$$f(\bar{\omega}_1, \bar{\omega}_2, \dots) = \bar{\omega}_i$$

All protocols we have seen so far are non-dictatorship.

Theorem 1 (Arrow's theorem).

Arrow's theorem

If $|\Omega| > 2$ then the only voting procedure that satisfies Pareto condition, Condorcet Winner condition and IIA is dictatorship.

2.2.4 Insincere Voters

- In reality it is seldom that all agent's preferences are known: usually agents have to reveal their preferences.
- Assuming knowledge of the preferences is equivalent to assuming that the agents reveal their preferences truthfully
- If an agent can benefit from insincerely declaring his preferences, it will do so.
- The goal is to generate protocols such that when agents use them according to some stability solution concept (dominant strategy equilibrium) the desirable social outcomes follow
- The strategies are not externally imposed on the agents, but instead each agent uses the strategy that is best for itself

However:

Let each agent i from A have some ordering ϑ_i from Θ which totally characterized his preferences. A social choice function $f : \Theta \rightarrow \Omega$ chooses a social outcome given the agent's orderings.

Theorem 2 (Gibbard-Satterthwaite impossibility theorem).

Gibbard-Satterthwaite impossibility theorem

Let each agent's ordering ϑ_i consists of a preference order \succ_i on Ω .

Let there be no restrictions on \succ_i (i.e. each agent may rank the outcomes Ω in any order).

Let $|\Omega| > 2$.

Now, if the social function $f(\cdot)$ is truthfully implementable in a dominant strategy equilibrium (or is not manipulable), then $f(\cdot)$ is dictatorial, i.e. there is some agent who gets one of its most preferred outcome chosen no matter what types the other reveal.

Broadly speaking, the only procedure or mechanism that is immune to strategic manipulation (in the sense of untruthful report of an agent preference) is dictatorship in the case of more than 2 candidates.

There are ways to circumvent the impossibility theorem, by relaxing the assumptions made by the theorem itself.

The individual preferences, in fact, may happen to belong to some restricted domain, thus invalidating the conditions of the impossibility theorem, and it is known that there are island in the space of agent's preferences for which non-manipulable non-dictatorial protocols can be constructed.

The solution in practice is to make agents precisely internalize the externality by imposing a tax on those agents whose vote changes the outcome. The size of tax is exactly how much its vote lowers the other's utility.

Such solution is known as the **Clark tax algorithm**:

Clark tax algorithm

- Every agent i from A reveals his valuation $v_i^*(g)$ for every possible g (which may be non-truthful)
- The social choice is

$$g^* = \operatorname{argmax}_g \sum v_i^*(g)$$

- Every agent is levied a tax:

$$\text{tax}_i = \sum_{j \neq i} v_j^*(g) \left(\operatorname{argmax}_g \sum_{k \neq i} v_k^*(g) \right) - \sum_{j \neq i} v_j^*(g)$$

It follows that

Theorem 3. *If each agent has quasilinear preferences, then, under the Clarke tax algorithm, each agent's dominant strategy is to reveal his true preferences, i.e.*

$$v_i^*(g) = v_i(g) \quad \forall g$$

In conclusion, the Clarke tax algorithm:

- the mechanism leads to the socially most preferred g to be chosen
- because of truth telling, the agents need not waste effort in counter speculating each other preference declarations
- participation in the mechanism may only increase an agent's utility
- the mechanism does not maintain budget balance: too much tax is collected
- it is not coalision proof

Other way to circumvent the Impossibility theorem:

- some fairness can be achieved by choosing the dictator randomly in the protocol
- to use a protocol for which computing an untruthful revelation (that is the better than the truthful one) is prohibitively costly computationally

2.3 Auctions

Auctions are mechanisms used to reach agreements on one very simple issue: that of how to allocate scarce resources to agents.

It is important to understand that the resource in question is scarce and it is typically desired by more than one agent (if one of the preconditions is not met then the allocation is trivial and straightforward).

Auctions provide a reasonable and principled way to allocate resources to agents, in particular they are effective at allocating resources efficiently, in the sense of allocating resources to those that value them the most.

2.3.1 Auction parameters for classification

In general terms:

- An auction takes place between an agent known as the **auctioneer** and a collection of agents known as the **bidders**
- The goal of the auction is for the auctioneer to allocate a good to one of the bidders
- The auctioneer desires to maximize the price at which the good is allocated.
Hence the agent auctioneer will attempt to achieve its desire through the design of an appropriate auction
- The bidders desire to minimize the selling price.
Hence the bidder agents will attempt to achieve their desires by using an effective strategy

There are several factors that can affect both the auction protocol and the strategy that agents use:

- The good has a **private value**, **public/common value** or a **correlated value** (i.e. an agent valuation of the good depends partly on private factors and partly on other agents' valuations of it).
- **winner determination**: who gets the good that the bidders are bidding for and how much do they pay.
In this setting, there are **first-price auctions** (the price goes to the highest bidder) and **second-price auctions** (the price goes to the highest bidder but it will pay the amount bid by the second highest bid)
- Whether or not the bids made by the agents are known to each other.
In this setting, we will differentiate between **open-cry** and **sealed-bid**

- The mechanism by which bidding proceeds.

In this setting, we will differentiate between one shot, ascending auctions or descending auctions (in which the price starts at a reservation price: in the case of ascending the reservation price is proposed by the first bidder, whereas in descending the reservation price is proposed by the auctioneer).

one shot

ascending auctions

descending auctions

reservation price

2.3.2 English auctions

English auctions are: first-price, open cry, ascending auctions.

- The auctioneer sets a reservation price for the good (low price) and the good is allocated to the auctioneer for this amount
- Bids are then invited from agents, who must bid more than the current highest bid. (all agents can see the bid)
- When no agent is willing to raise the bid, then the good is allocated to the agent that has made the current highest bid at the amount of its bid.

The dominant strategy is to bid a small amount more than the current highest bid until the bid price reaches their private valuation and then to withdraw.

English auction's however are sensible to the winner's curse: should the winner feel "happy" that they have obtained the good for less than or equal to their private valuation or should they feel worried because no other agent valued the good so highly?

winner's curse

2.3.3 Japanese auctions

Japanese auctions are: open cry, ascending auctions

- The auctioneer sets a reservation price
- Each agent must choose whether or not to be in
- The auctioneer successively increases the price
- After each increase an agent must say if he stays or not. When agent drops out it is irrevocable
- The auction ends when exactly one agent is left
- The winner must buy the good for the current price

2.3.4 Dutch auctions

Dutch auctions are: open-cry, descending auctions:

- The auctioneer sets a reservation price
- The auctioneer then continually lowers the offer price of the good by some small value, until some agent makes a bid for the good
- The good is then allocated to the agent that made the offer

Dutch auctions are also susceptible to the winner's curse.

The dominant strategy is to shade bid a bit below the true willingness to pay.

2.3.5 First-price sealed-bid auctions

First-price sealed-bid auctions are: first-price, sealed-bid, one-shot auctions.

- A single round of proposals is considered
- Bidders submit to the auctioneer a bid for the good
- The good is awarded to the agent that made the highest bid
- The winner pays the price of the highest bid

The dominant strategy for an agent is to bid less than its true valuation. How much less will of course depend on what the other agents bid (hence there is no general solution).

2.3.6 Vickrey auctions

Vickrey auctions are: second-price, sealed-bid auctions.

- There is a single bidding round
- Each bidder submits a single bid.
- The good is awarded to the agent that made the highest bid
- The winning bidder pays the price of the second-highest bid

The dominant strategy is truth telling: a bidder's dominant strategy in a private value Vickrey auction is to bid their true valuation.

As such Vickrey auction are not prone to strategic manipulation, however it makes possible for antisocial behaviour to occur: one agent may bid close to the highest bid just to make the winner pay close to the amount that they have bid.

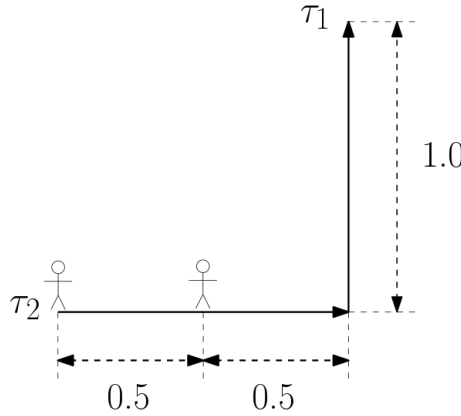
antisocial
behaviour

2.3.7 Interralated auctions

Some auctions are interralated to each other:

- Two good are sold separately, but the bidders would like to acquire them together
- In this case the strategy to consider for more than one auction but for several interrelated auctions and then accomodate some valuations and bids according to this strategy but not for some particular auction.

Let us consider the example of the proposed figure:



Two agents (agent 1 on the left and agent 2 on the right) are concurring for the acquisition of two tasks: τ_1 and τ_2 .

It makes no sense for them to acquire just one of the two tasks. Please notice that in order to complete the full task an agent must go to the start of the arrow/task and fully traverse its edge.

Condering all of the above the valuation of the tasks for the two agents can be represented as a cost-to-go:

Agent 1:	$c_1(\tau_1) = 2.0$	$c_1(\tau_2) = 1.0$	$c_1(\tau_1, \tau_2) = 2.0$
Agent 2:	$c_2(\tau_1) = 1.5$	$c_2(\tau_2) = 1.5$	$c_2(\tau_1, \tau_2) = 2.5$

However if both agents decided to follow this strategy, task τ_1 would go to agent 2 (lower cost to go), whereas task τ_2 would go to agent 1 (lower cost to go).

In order for agent 1 to win both tasks, since it is of no use for an agent to win just one task in an interrelated auction, it can incorporate the full look ahead in its bid.

If in fact, agent 1 wins τ_1 , it will bid $c_1(\tau_2) = c_1(\tau_1, \tau_2) - c_1(\tau_1) = 0$ for the second task, otherwise it will bid $c_1(\tau_2) = 1$. So it makes sense to accomodate the first bid with this knowledge. If agent 1 wins τ_1 , it will win τ_2 at the price of 0 and gets a payoff of $c_1(\tau_2) - 0 = 1$ that can redistribute to the first bid.

In conclusion the dominant strategy is to accomodate the payoff into the first bid:

$$c_1(\tau_1) - \text{payoff} = 2 - 1 = 1$$

In other terms this implies that if agent 1 realizes that by winning τ_2 it will automatically win τ_1 , it will bid “higher” for τ_1 or say that the effort to complete task τ_1 will be lower by winning also τ_2 .

2.3.8 Lies and Collusion

It is in the auctioneer interest to have a protocol that is immune to collusion by bidders, i.e. that made it against the bidder’s best interests to engage in collusion with other bidders.

Similarly, as a potential bidder in an auction, we would like a protocol that made honesty on the part of the auctioneer the dominant strategy.

None of the auction discussed above is immune to collusion: for any of them the grand coalition of all agents involved in bidding for the good can agree beforehand to collude to put forward artificially low bids for the good on offer.

When the good is obtained, the bidders can then obtain its true value and split the profits among themselves. A solution to collusion of the bidder is to modify the protocol so that the bidders cannot identify each other which however it’s not possible in open cry auctions.

With regard to the honesty of the auctioneer, the main opportunity for lying occurs in the Vickrey auctions: the auctioneer can lie to the winner about the price of the second highest bid. A solution to this is to sign bids in some way so that the winner can independently verify the value of the second highest bid or use a trusted third party to handle bids.

In open cry auction settings there is no possibility for lying by the auctioneer, nor in the first-price sealed-bid auctions.

Lastly, another possible opportunity for lying by the auctioneer is to place bogus bidders (aka **shills**), in an attempt to artificially inflate the current bidding price.

shills

Moreover, there are main limitation of auctions is that they are only concerned with the allocation of goods and as such are not adequate for settling agreements that concerns matters of mutual interest.

2.4 Negotiation parameters

The basic components that make up a negotiation setting are:

- A **Negotiation set**, which represents the space of possible proposals that agents can make
- A **protocol**, which defines the legal proposals that agents can make, as a function of prior negotiation history.
- A collection of **strategies**, one for each agent, which determine what proposals the agents will make.
- A **rule** that determines when a deal has been struck, and what this agreement deal is.

Negotiation set

protocol

strategies

rule

Negotiation usually proceeds in a series of rounds, with some proposal made at every round. The proposals that agents make are defined by their strategy, must be drawn from the negotiation set, and must be legal, as defined by the protocol.

If agreement is reached, as defined by the agreement rule, then negotiation terminates with the agreement deal.

Several attributes may complicate negotiation:

- Multiple issues are involved: in case of a single attribute/price we have a symmetric scenario which is easy to analyze because it is always obvious what represents a concession. On the other hand, in multiple-issue negotiation scenarios, agents negotiate over not just the value of a single attribute, but the values of multiple attributes, which may be interrelated. In such scenarios, it is usually much less obvious what represents a true concession. Moreover multiple attributes also lead to an exponential growth in the space of possible deals. This means that, in attempting to decide what proposal to make next, it will be entirely unfeasible for an agent to explicitly consider every possible deal in domains of moderate size.

- Another source of complexity in negotiation is the number of agents involved in the process, and the way in which these agents interact. There are three obvious possibilities:

1. **One-to-one negotiation**

One-to-one negotiation

2. **Many-to-one negotiation**, as in the case of auctions or reverse auctions

Many-to-one negotiation

3. **Many-to-many negotiation**

Many-to-many negotiation

2.4.1 Task Oriented Domain

The idea behind Negotiation for task allocation is that agents who have tasks to carry out may be able to benefit by reorganizing the distribution of tasks among themselves; but this raises the issue of how to reach agreement on who will do which tasks.

Formally this scenario is known under the name of **Task Oriented Domain (TOD)**. A task oriented domain is a triple:

Task Oriented Domain (TOD)

$$\langle T, Ag, c \rangle$$

where

- T is the finite set of all possible tasks
- $Ag = \{1, \dots, n\}$ is the finite set of negotiation participant agents
- $c : 2^T \rightarrow \mathbb{R}_+$ is a function which defines the cost of executing each subset of tasks: the cost of executing any set of tasks is a positive real number

The cost function must satisfy two constraints:

1. It must be **monotonic**

monotonic

$$\text{If } T_1, T_2 \subseteq T \text{ are sets of tasks such that } T_1 \subseteq T_2, \text{ then } c(T_1) \leq c(T_2)$$

2. The cost of doing nothing is zero

$$c(\emptyset) = 0$$

We will restrict our attention as follows:

- One-to-one negotiation scenario, with two agents $\{1, 2\}$
- Given an encounter $\langle T_1, T_2 \rangle$, a **deal** will be an allocation of the tasks $T_1 \cup T_2$ to the agents 1 and 2.
- Three types of deal may happen under this conditions:

deal

1. **Pure deals:** agents are deterministically allocated exhaustive disjoint task set.

Pure deals

Formally, a pure deal is a pair $\langle D_1, D_2 \rangle$ where

$$D_1 \cup D_2 = T_1 \cup T_2$$

2. **Mixed deals:** specify a probability distribution over partitions

Mixed deals

3. **All-or-Nothing deals:** mixed deals where the alternatives only include partitions where one agent handles the tasks of all agents.

All-or-Nothing deals

- The **cost** to an agent i of a deal $\delta = \langle D_1, D_2 \rangle$ is defined to be $c(D_i)$ and it will be denoted as $cost_i(\delta)$

cost

- The **utility** of a deal δ to an agent i is the difference between the cost of agent i doing the tasks T_i that it was originally assigned in the encounter and the cost $cost_i(\delta)$ of the tasks it is assigned in δ :

utility

$$utility_i(\delta) = c(T_i) - cost_i(\delta)$$

Thus the utility of a deal represents how much the agent has to gain from the deal (a negative utility means that the agent is worse off than it was originally)

- If the agents fail to reach an agreement they must perform the tasks that they were originally allocated (**conflict deal**, $\Theta = \langle T_1, T_2 \rangle$)

conflict deal

The properties that govern this agent interactions are:

- Dominance

A deal δ_1 is said to be dominant if and only if:

1. Deal δ_1 is at least as good for every agent as δ_2

$$\forall i \in \{1, 2\}, utility_i(\delta_1) \geq utility_i(\delta_2)$$

2. Deal δ_1 is better for some agent than δ_2

$$\exists i \in \{utility_i(\delta_1) > utility_i(\delta_2)\}$$

A deal is said to be **weakly dominant** if at least the first condition holds.

weakly dominant

- Pareto optimal

A deal δ is Pareto optimal if there is no deal δ' such that $\delta' \succ \delta$

- Individual rationality

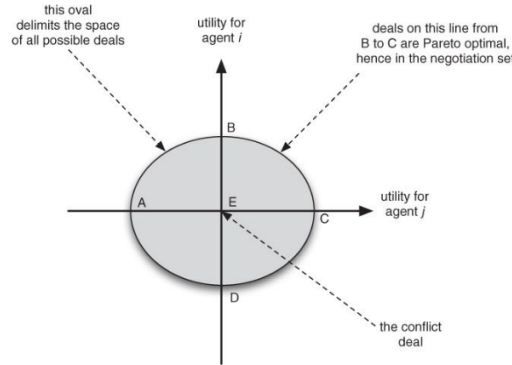
A deal δ is said to be individual rational if it weakly dominates the conflict deal

$$\delta \succeq \Theta$$

If a deal is not individual rational, then at least one agent can do better by simply performing the tasks it was originally allocated (it prefers the conflict deal)

Given all of the above, we are in the position to define the space of possible proposals that agents can make: the negotiation set consists of the set of deals that are individual rational and Pareto optimal.

In the following figure is proposed the set of possible deals in a 2 agent encounter



Here, the first, third and fourth quadrant includes the subset of deals that are not individual rational. (there is no point for an agent to accept a deal that produces negative utility).

Similarly, all deals strictly inside the ellipsis are not Pareto Optimal. Which brings as to the boundary of the negotiation set in the second quadrant.

Agent i (ordinate axis) will start at its best possible deal (B), whereas agent j (abscissa axis) will start at its best possible deal (C).

Both agent will then concede in one or more rounds until a point of mutual agreement on the boundary of the negotiation set is reached.

Task Oriented Domains assume that agents have symmetric cost functions (i.e. $c_i(T') = c_j(T')$) and that every agent is capable of handling tasks of all agents.

However, there exists other subtypes of Task oriented domains that consider different relations in the agents cost functions:

- **Subadditive TODs (STODs)** are TODs where:

Subadditive TODs (STODs)

$$c_i(T' \cup T'') \leq c_i(T') + c_i(T'')$$

- **Concave TODs (CTODs)** are subadditive TODs where:

Concave TODs (CTODs)

$$c_i(T' \cup T'') - c_i(T') \geq c_i(T'' \cup T''') - c_i(T'') \quad \text{and} \quad T' \subset T''$$

- **Modular TODs (MTODs)** are concave TODs where:

Modular TODs
(MTODs)

$$c_i(T' \cup T'') \leq c_i(T') + c_i(T'') - c_i(T' \cap T'')$$

	TOD			STOD			CTOD			MTOD		
	Hid	Pha	Dec	Hid	Pha	Dec	Hid	Pha	Dec	Hid	Pha	Dec
Pure	L	L	L	L	L	L	L	L	L	L		
Mixed	L		L	L		L	L			L		
All-or-nothing						L						

Table 2.1: The L states that lying is profitable and possible

2.4.2 Worth Oriented Domain

Worth Oriented domains are domains where agents assign a worth to each potential state (of the environment), which captures its desirability for the agent.

Worth Oriented
domains

- agent's goal is to bring about the state of the environment with highest value
- We assume that the collection of agents has available set of joint plans (a joint plan is executed by several different agents). In other terms there is no possibility to complete a task alone.

Contrary to TOD, where tasks could have been achieved separately by both agents, in worth oriented domain the outcome can be achieved only by joint efforts (e.g. buying and selling are part of the worth oriented domain).

Formally, Worth oriented domains can be defined as a tuple

$$\langle E, Ag, J, c \rangle$$

where:

- E : is the set of possible environment states/outcomes
- Ag : is the set of possible agents
- J : is the set of possible joint plans
- $c(j, i)$: is the cost for agent i of executing the plan j

Moreover, we will denote as $W(e, i)$ the value of worth of agent i in state e .

Unlike, TODs, agents negotiating over Worth Oriented Domains are not negotiating about a single issue:

- They are negotiating over both the state that they wish to bring about (which has a different value for different agent)
- They are negotiating over the means by which they will reach the state

Since this domain deals with multiple set of attributes, we are interested to find the Pareto Optimal solution. In order to do so we calculate the utility by:

- Weighting each attribute
- Rating or ranking each attribute value
- Using constraints on an attribute

The negotiation process will proceed to in rounds where each agent concedes, ultimately reaching an agreement or finding no agreement.

If the utility graphs representing the rating of each agent intersects at some point, then a point of acceptance is reached, otherwise the negotiation terminates in conflict.

2.4.3 Monotonic Concession Protocol (MCP)

The rules of this negotiation protocol are:

- Negotiation proceeds in a series of rounds
- On the first round both agents simultaneously propose a deal from the negotiation set
- An agreement is reached if the two agents propose deals δ_1 and δ_2 , respectively, such that either:

$$utility_1(\delta_2) \geq utility_1(\delta_1) \quad || \quad utility_2(\delta_1) \geq utility_2(\delta_2)$$

- If both agents offers match or exceed those of the other agent, then one of the proposals is selected at random
- If only one proposal exceeds or matches the other's proposal, then this is the agreement deal
- If no agreement is reached, then negotiation proceeds to another round of simultaneous proposals, where no agent is allowed to make a proposal that is less preferred by the other agent than the deal it proposed at the previous round
- If neither agent makes a concession in some round, then negotiation terminates with the conflict deal

Using such protocol negotiation is guaranteed to end (with or without agreement) after a finite number of rounds, however the protocol does not guarantee that the agreement (or lack of it) will be reached quickly.

2.4.4 The Zeuthen strategy

1. What should an agent's first proposal be?
2. On any given round, who should concede?
3. If an agent concedes, then how much should it concede?

With regard to the first question: an agent's first proposal should be its most preferred deal.

With respect to the second question: the idea of the **Zeuthen strategy** is to measure an agent's willingness to risk conflict (i.e. an agent is more willing to risk conflict if the difference in utility between its current proposal and the conflict deal is low). Zeuthen strategy

Agent i 's willingness to risk conflict at round t is:

$$risk_i^t = \frac{\text{utility } i \text{ loses by conceding and accepting } j\text{'s offer}}{\text{utility } i \text{ loses by not conceding and causing conflict}}$$

Until an agreement is reached, the value of risk is between 0 and 1 (the higher the value the higher the risk, which means that an agent has less to lose from conflict and as such it is more willing to risk conflict).

Formally:

$$risk_i^t = \begin{cases} 1 & \text{If } utility_i(\delta_i^t) = 0 \\ \frac{utility_i(\delta_i^t) - utility_i(\delta_j^t)}{utility_i(\delta_i^t)} & \text{otherwise} \end{cases}$$

Hence, the zeuthen strategy proposes that the agent to concede on round t of negotiation should be the one with the smaller value of risk.

Moreover, the agent in question should make the smallest concession necessary to change the balance of risk, so that on the next round, the other agent will concede.

Lastly, in the case of equal risk, a coin flip will decide which agent should concede, otherwise we are in the same situation of the prisoner's dilemma.

We notice that the Zeuthen strategy and the protocol itself:

- Does not guarantee success, but it does guarantee termination
- It does not guarantee to maximize social welfare
- If agreement is reached, then this agreement will be Pareto Optimal
- It is individual rational
- It is in Nash equilibrium (if an agent is using the Zeuthen strategy the other can do no better than using the same strategy)

2.4.5 Deception

There are three obvious ways in which an agent can be deceitful in Task oriented domain:

- **Phantom tasks**

An agent can pretend to have been allocated a task that it has not been allocated.

An obvious response to these is to ensure that the tasks an agent has been assigned to carry out are verifiable by all negotiation participants.

- **Decoy tasks**

An agent can produce an artificial task when asked for it.

Detection of decoy tasks is essentially impossible, making it hard to be sure that deception will occur in such domains.

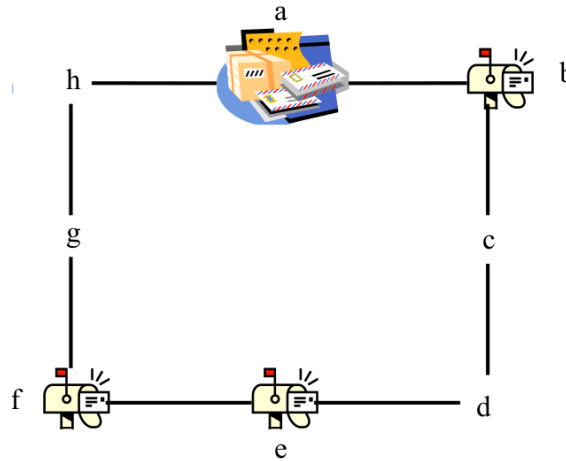
- **Hidden tasks**

An agent may benefit from deception by hiding tasks that it has to perform

Using mixed deals or all-or-nothing deals helps to get rid of deceptions:

- probability is assigned to each Agent task
- all or nothing deal is applied
- weighted coin (with probabilities) is used
- In case of phantom and decoy tasks, the deceiving agent can have a bigger probability to be assigned all the tasks, hence it has no advantage in lying
- However, it is possible that decoy tasks do not increase probability to be allocated all the tasks in some topology

This case aspect can be further proven with an example: Two postmen need, for some obscure



reason to redistribute their letters:

- Agent i , has to deliver letter b and f
- Agent j , has to deliver a letter to e

Agent i decides to deceive the other agent and hide the letter b .

However, if the two agents use a weighted coin and a all-or-nothing deal to reallocate their task, deceiving becomes disadvantageous from a probabilistic standpoint. In order to understand why let us consider a simple model of the probability based on the edges that an agent has to traverse:

- Agent i (the deceiving one) have an expected cost that has the following form:

$$expected\ cost = \frac{3}{8} \cdot 8 + \frac{5}{8} \cdot 2 = 4.25$$

The expected cost components are derived in the following way:

- Compute the probabilities based on the claimed letters to deliver.

Agent i claims to have only the letter f to deliver which is at a distance of 3 edges from the post office. Since there are a total of 8 edges, the associated probability is $3/8$. As a result, the probability of winning the coin flip is $1 - 3/8 = 5/8$

- Compute the cost of delivering the letter (which is the number of edges forward and back to traverse).

In the case of agent i , losing the coin flip will imply that he has to deliver all the letters (all-or-nothing deals). The shortest path to do so implies traversing all of the 8 edges of the graph, hence the associated cost is 8.

On the contrary if agent i wins the weighted coin flip, it has still to deliver the hidden letter b which would require him to traverse 1 edge forward and back, resulting in a total cost of 2.

- From the expected cost result we can then compute the utility that agent i obtained by hiding the letter: this value is compute as the difference of traversing the whole graph with the expected cost:

$$utility = 8 - 4.25 = 3.75$$

- We can notice that if agent i would have not hidden the letter, it would have gotten a coin flip probability of $4/8 = 0.5$ since the sum of the edges that he would have had to traverse is 3 for the letter f and 1 for the letter b . Whereas the cost of winning the coin flip would have been 0 (no letters to deliver), and the cost of losing the coin flip is 8 (the postman has to deliver all the letters which means that it has to traverse the whole graph). Hence the expected cost of not lying would have been:

$$expected\ cost = 0.5 \cdot 8 + 0.5 \cdot 0 = 4$$

and as a result the utility would have been:

$$utility = 8 - 4 = 4$$

which is higher than the utility of hiding the letter b

2.5 Contract Net Protocol (CNP)

Cooperating experts metaphor:

- work independently
- exchange results
- ask help when enable to solve individually

The assumptions that CNP makes is that

- If the problem is too large then partition it and find other experts who can solve the task
- If the problem is outside of expertise then also find another expert
- If expert is known then contact them directly, otherwise describe the task to the entire group of agents
- If somebody from the group agree then the agent will notifies it
- If more then one agree then choose one

The basic premise of the CNP is that, if an agent cannot solve an assigned problem using local resources/expertise, it will decompose the problem into subproblems and try to find other willing agents with the necessary resource/expertise to solve these subproblems

In this sense, each agent can take one of two roles: **manager** or **contractor**.

The overall contracting mechanism goes as follows:

1. contract announcement by the manager agent
2. submission of bids by contracting agents in response to the announcement
3. evaluation of submitted bids by the manager

manager

contractor

4. awarding a subproblem contract to the contractor with the most appropriate bids

Contrary to auctions, there is no limitations in respecting the bid that agent have made: this means that even though an agent wins a bid and accept a given task it is not forced to take it.

Formally, Let us consider:

- τ_i^t the set of tasks allocated to the agent i at time t
- e_i the resources available to i
- $\tau(ts)$ the announce task

The marginal cost proposed by Sandholm, takes the form: — marginal cost

$$\mu_i(\tau(ts)|\tau_i^t) = c_i(\tau(ts) \cup \tau_i^t) - c_i(\tau_i^t)$$

Hence the decision to bid happens if and only if

$$\mu(\tau(ts)|\tau_i^t) < (e(ts) + e_i)$$

where $e(ts)$ is reward for doing the new task

The problems with CNP are:

1. it does not detect conflicts
2. it assumes benevolent and non-antagonistic agents
3. it is still rather communication intensive

Chapter 3

Agent Communication

3.1 Approaches to software interoperation	37
3.1.1 Components of a system for effective interaction and interoperability . . .	38
3.1.2 Three Important Aspects	38
3.2 Speech Acts	39
3.2.1 Austin	39
3.2.2 Searle	39
3.2.3 Plan-based theory	40
3.2.4 Speech acts as rational actions	40
3.3 Agent Communication Languages (ACL)	40
3.3.1 KSE	41
KIF	41
Ontologies	42
KQML	43
3.3.2 FIPA ACL	45

Communication has been a topic of extensive study in the field of computer science. Particularly, the problem of synchronization of multiple processes was of key interest in the 1970s and 1980s.

synchronization

This is of importance since processes have fundamentally the same behaviour of agents. In fact, the object oriented paradigm would require communication via method invocation to allow an object to message another and change its internal state (this is not allowed in an agent-oriented setting).

communication
via method
invocation

Let us consider, for example, two agents i and j , where i has the capability to perform an action α (similar to a method).

In an agent-oriented world, contrary to object-oriented, there is no such thing as method invocation. This is because both i is an autonomous agent, and as such it has control over both its state and behaviour.

autonomous agent

Hence, it cannot be taken for granted that agent i will execute action α just because another agent j wants it to: performing the action may not be in the best interests of agent i .

In general, agents can neither force other agents to perform some action, nor write data onto the internal state of other agents, but this does not mean that they cannot communicate.

What agents can do is perform communicative actions in an attempt to influence other agents.

communicative
actions

3.1 Approaches to software interoperation

influence

We initially consider software interoperation, i.e. the exchange of information and services with other programs, thereby solving problems that cannot be solved alone.

software
interoperation

This is fundamentally different from communication (interaction between humans).

The main problem related with software interoperation is heterogeneity, in the sense that two or more software in need to interoperate might be written by different people, at different times and in different languages.

heterogeneity

Hence, in order for them to communicate successfully it should be provided:

- a standard communication language
- common libraries
- run time support

And particularly, we would like to answer the following questions:

- What is an appropriate agent communication language?
- How do we build agents capable of communicating in this language?
- What communication architectures are conducive to cooperation?

3.1.1 Components of a system for effective interaction and interoperability

The basic components of a system to achieve effective software interaction and interoperability are:

- a common language
- a common understanding of the knowledge exchanged (common understanding of the components of the language as well as their meaning)
- the ability to exchange whatever is included in the previous items.

The reason why we cannot use natural language as a common language for agent communication is that it is not easy to develop a system that understands it completely. Moreover, the use of other communication protocols such as xml or json is not ideal since agents have conversations (as opposed to exchange of single messages).

In addition to this the communication behaviour should allow to express agents' strategies, intentions, roles, ..., i.e. concepts that are high level than can be expressed in low level languages.

3.1.2 Three Important Aspects

There are three important aspects in communication:

1. **Syntax:** how the symbols of communication are structured. Syntax
It includes the grammatical rules, how we write and so on.
2. **Semantics:** what the symbols denote Semantics
3. **Pragmatics:** How the symbols are interpreted, what is the context of the communication. Pragmatics
The same sentence can be interpreted in different ways.

The combination of semantics and pragmatics is the **meaning** of the communication. meaning
From the above, we deduce that an agent communication language (ACL) should be:

1. Syntactic: should allow syntactic translation between the agents
2. Meaning: should allow meaning content preservation among applications.
3. Communication: should be able to communicate complex attributes about their information and knowledge.

Hence what distinguishes ACLs from other languages is:

- Semantic complexity
- ACLs can handle propositions, rules and actions instead of simple objects with no semantics associated with them. Hence ACL does not deal with a simple exchange of data, but instead with the exchange of information that has a meaning.
- An ACL message describes a desired state in a declarative language, rather than a procedure or a method.

3.2 Speech Acts

Speech acts theory treats communication as action. It is predicated on the assumption that speech actions are performed by agents just like other actions, in the furtherance of their intentions.

Speech acts theory

As such, speech act theories attempt to account for how language is used by people every day to achieve their goals and intentions.

3.2.1 Austin

The theory of speech acts is generally recognized to have begun with the work of the philosopher John Austin. He noted that a certain class of natural language utterances, referred to as **speech acts**, had the characteristics of actions, in the sense that they change the state of the world in a way analogous to physical actions.

speech acts

Austin identified a number of **performative verbs**, which correspond to various different types of speech acts (e.g. request, inform, promise).

performative verbs

In addition, Austin distinguished three different aspects of speech acts:

1. **locutionary act**: act of making an utterance
2. **illocutionary act**: action performed in saying something
3. **perlocution**: effect of the act

locutionary act

illocutionary act

perlocution

Austin referred to the conditions required for the successful completion of performatives as **felicity conditions**, that are as follows:

felicity conditions

- There must be an accepted conventional procedure for the performative, and the circumstances and persons must be as specified in the procedure
- The procedure must be executed correctly and completely
- The act must be sincere and any uptake required must be completed insofar as is possible

We are particularly interested in the illocutionary act.

Formally, an illocutionary act $F(P)$ is composed from:

- **propositional content** P : what is the utterance or message exchanged
- **context**: context of the message
- **illocutionary force** F : what is the intention of the message

propositional content

context

illocutionary force

The illocutionary force divides speech acts into categories described by :

- **Illocutionary point**
- **direction of fit**, is the conveyed message describing the world or changing the world
- **sincerity conditions**

Illocutionary point

direction of fit

sincerity conditions

3.2.2 Searle

Searle extended the work of Austin in his 1969 book *Speech Acts*. Searle identified several properties that must hold for a speech act performed between a **HEARER** and a **SPEAKER** to succeed.

1. **Normal I/O Conditions**: the HEARER is able to hear the performative of the speaker and the act was performed in normal circumstances (not in a film or a play).
2. **Preparatory conditions**: state what must be true of the world in order that SPEAKER correctly choose the speech act (in a request to perform ACTION, the HEARER must be able to perform such ACTION and the SPEAKER must believe the HEARER is able to perform such ACTION)
3. **Sincerity conditions**: these conditions distinguish sincere performatives of the request; an insincere performance of the act might occur if SPEAKER did not really want ACTION to be performed.

HEARER

SPEAKER

Normal I/O Conditions

Preparatory conditions

Sincerity conditions

Searle also attempted a systematic classification of possible types of speech acts identifying the following five key classes:

- **Representatives** (inform): a representative act commits the speaker to the truth of an expressed proposition Representatives
- **Directives** (request): a directive is an attempt on the part of the speaker to get the hearer to do something Directives
- **Commissives** (promise): Commit the speaker to a course of action Commissives
- **Expressives** (thanking): Express some psychological state such as gratitude Expressives
- **Declarations** (declaring war): Effect some changes in an institutional state of affairs Declarations

Later some additional speech acts were introduced: **Permissives** and **Prohibitives**

3.2.3 Plan-based theory

In order for an AI to make a plan about how to achieve goals from the interaction with humans or other autonomous agents, such plans must include speech actions. Formally the aim of the application of such mechanism is to develop a theory of speech acts

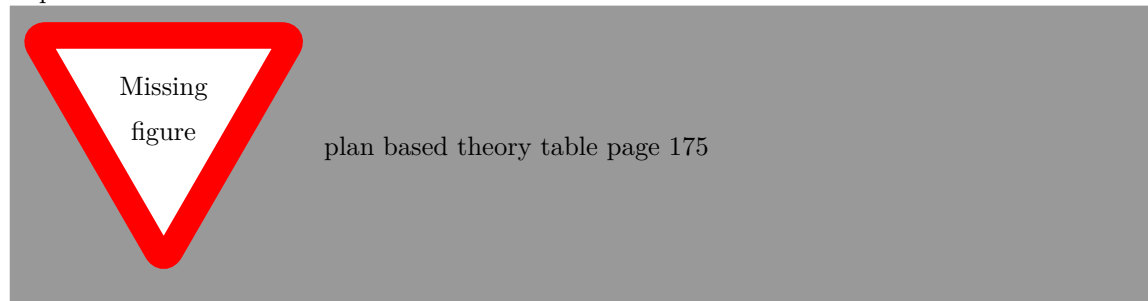
“... by modelling them in a planning system as operators defined... in terms of speakers’ and hearers’ beliefs and goals. Thus speech acts are treated in the same way as physical actions”.

Cohen and Perrault came up with a formalism called the **STRIPS** notation, in which the properties of an action are characterized via **preconditions** and **postconditions**. STRIPS

Cohen and Perrault also demonstrated how the preconditions and postconditions of speech acts could be represented in a multimodal logic containing operators for describing the beliefs, abilities and wants of the participants in the speech act. precondition
postcondition

In short, in order for a speech act to be successful the preconditions must be fulfilled; however the fulfillment of the preconditions are not enough in itself to guarantee that the desired action will actually be performed. This is because some speech act such as request or inform only models the illocutionary force of the act, not the perlocutionary force.

For this reason, Cohen and Perrault introduced some mediating act: **Convince** and **CauseToWant**; which respectively will make the hearer believe an inform act and believe that the speaker of a request act wants the hearer to do an action.



3.2.4 Speech acts as rational actions

While the plan-based theory of speech acts was a major step forward, it was recognized that a theory of speech acts should be rooted in a more general theory of rational action.

This led Cohen and Levesque to develop a theory in which speech acts were modelled as actions performed by rational agents in the furtherance of their intentions.

The foundation upon which they built this model of rational action was their theory of intention.

3.3 Agent Communication Languages (ACL)

In the ACL we strive to communicate or exchange the meaning explicitly by saying what is the intention in the language. This is in contrast with the human language in which the meaning is hidden by the words used, the intonation, the tone (it is not always explicitly said).

There are some fundamental components of the language that may help to achieve a language that explicitly communicate meaning:

- An illocutionary force represented by a performative verb. (e.g. request, inform)
- Propositional content, what the agent said.

This makes it so that different propositional content can be interpreted in different ways by the hearer based on the associated illocutionary force.

The semantic of speech acts can be represented via plan-based theory, which treats speech acts as physical actions. Thus, each action is characterised by preconditions (conditions that must be fulfilled for successful communication) and postconditions (effect).

3.3.1 KSE

Speech act theories have directly informed and influenced a number of languages that have been developed specifically for agent communication.

In the early 1990s, the US-based DARPA-funded Knowledge Sharing Effort (KSE) was formed.

The KSE generated three main deliverables:

- The **Knowledge Interchange Format (KIF)**.
This language was explicitly intended to allow the representation of knowledge about some particular domain of discourse (aka the content of the message). Knowledge Interchange Format (KIF)
- The **Ontolingua**
Ontology representation. Ontolingua
- The **Knowledge Query and Manipulation Language (KQML)**.
This language defines an envelope format for messages, but is not concerned with the content part of the messages. In short, it defines the language for both message formatting and message handling protocols Knowledge Query and Manipulation Language (KQML)

The Basic assumption that KSE makes is that “Software agents are applications for which ability to communicate with other applications and share knowledge is of primary importance.” In the KSE case, the basic components of an ACL are represented as follows:

- Communication, through a interaction protocol, communication language and a transport protocol
- Representation, through knowledge bases and ontologies (way of representing organization of knowledge, how concept are organized and what is their meaning, set of symbols with their associated meaning)
- Supporting components, through planning activities, modeling other agents and environments, meta-knowledge (how we can reason about what we know) and reasoning

KIF

The Knowledge Interchange Format (KIF) was intended to:

- create a language for development of intelligent applications.
- create a common interchange format that allows to translate from any language to it and vice versa.
- express the contents of a message but not the message itself.

KIF was not intended to:

- to model the interaction with human user
- to be internal representation for knowledge within computer programs.

The interchange format that KIF uses is best described with an example.

Let us assume we have two languages (L_1 and L_2). In this scenario we need to develop two translations in order to have communication between the two agents.

If we have three languages, the number of translations is 6

If we have four languages, the number of translations is 12

We can notice that as the number of languages increases the number of translations necessary increases drastically, for this reason an intermediate language from and to other languages are translated was proposed under the name of KIF. It means the for each language we need to develop only two translations.

KIF is a prefix version of first order predicate calculus.

- The prefix version tells that first we place the operation then the operands
- KIF has a declarative semantics
you do not need to say how it will be executed in the interpreter but instead you can present your statement in some arbitrary order and then an inference mechanism will find a way in which it can be operated
- KIF is logically comprehensive.
allows to represent all necessary logic constraints
- KIF provides for representatino of knowledge about representation of knowledge (meta-level)

Additional features are:

- Translatability, easy to represent
- Readability, easy to read
- Usability as a representation language

Using KIF, it is possible to express:

- Properties of things in a domain
- Relationships between things in a domain
- General properties of a domain

In order to do so, KIF has introduced:

- Variables: ordinary variable represented with a ? prefix and list variables represented with a @ prefix
- Operators
 - term operators: e.g. listof, if, ...
 - sentence operators: e.g. not, and, / =, ...
 - rule operators: e.g. =>, ...
 - definition operators: e.g. defobject, deffunction,...
- Constants
 - object constants
 - function constants
 - relational constants
 - logical constants
- Expressions/Sentences: word or a finite sequence of words

Ontologies

An ontology is a formal explicit specification of a shared conceptualization.

An ontology is a description of the concepts and relationships that can exist for an agent or a community of agents.

The reason why we need ontology is that agents need to have the same understanding of concepts that we use.

An example is the world VISA, which can be both a entering permit or a credit card. We therefore can specify an ontology for traveling and one for finance and distinguish between the two.

Hence, ontology is used to agree on a terminology to describe a domain, and by referencing this ontology we communicate the meaning of the communication. Ontolingua is one of the first ontologies developed that was used to give notion or meaning of words that we use in KIF.

KQML

KQML is a message-based language for agent communication. Thus KQML defines a common format for messages.

Each KQML object has a **performative** and a number of **parameters**.

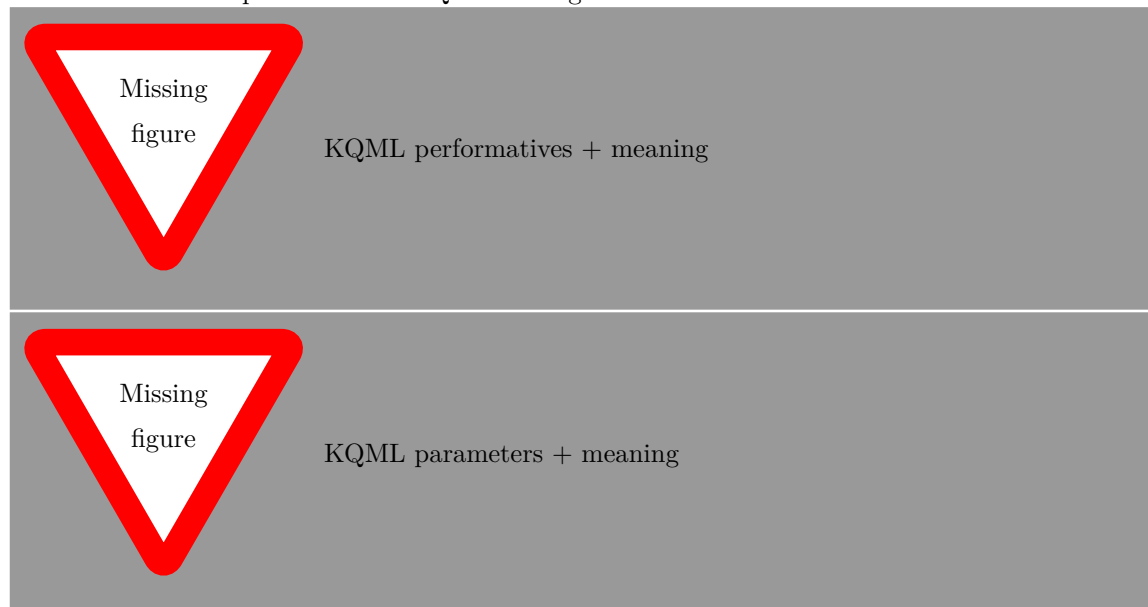
An example of a KQML object is

```
1 { $performative$
2   :content $content$
3   :receiver $receiver$
4   :language $language$
5   :ontology $ontology$
6 }
```

performative

parameters

KQML defines a set of standard performatives to choose from of which different parameters are required. In table ?? the list of 41 performatives are proposed with their meaning and in table ?? the list of the main parameters of KQML messages are summarized.



To more fully understand these performatives, it is necessary to understand the notion of a **virtual knowledge base (VKB)** as it was used in KQML. The idea was that agents using KQML to communicate may be implemented using different programming languages and paradigms and any information that agents have may be internally represented in many different ways. However, for the purpose of communication, it makes sense for agents to treat other agents as if they had some internal representation of knowledge.

This attributed knowledge is known as the virtual knowledge base.

virtual
knowledge base
(VKB)

Despite the initial success, KQML was subsequently criticized on a number of grounds:

- The basic KQML performative set was rather fluid. It was never tightly constrained, and so different implementations of KQML were developed that could not, in fact, interoperate
- Transport mechanisms for KQML messages were never precisely defined
- The semantics of KQML was never rigorously defined. This is because the meaning of KQML performatives was only defined using informal, English language descriptions, open to different interpretations (it was impossible to tell whether agents were using KQML language properly)
- The language was missing an entire class of performatives, such as commissives (which are a requirement for agent coordination)

- The performative set for KQML was overly large and, it could be argued, rather ad hoc.

In an environment it is good to have language, but we need some supporting elements which are **Facilitators**. Facilitators are used to route the message in case an agent does not know exactly the address of the receiver. Facilitators

In this sense, facilitators help to make communication protocol transparent.

We can think of facilitators as a special class of agents that perform useful communication services such as:

- Maintain registry of service names
- Forward messages to named services
- Routing messages based on content (not the content of the message but rather ontology and language)
- Provide matchmaking between information providers and requesters
- Provide mediation and translation services
-

In particular KQML defines a standard protocol to be implemented by facilitator:

- **Point-to-Point protocol** Point-to-Point protocol
If A is aware about B then it is appropriate to send query about X to B.
In other terms if agent A knows exactly agent B then it is allowed to reach and communicate with it directly
- **Subscribe performative** Subscribe performative
Request that Facilitator F helps find the truth of X. If B subsequently informs F that it believes X to be true, then F can in turn inform A
- **broker performative** broker performative
A asks Facilitator to find another agent (not F) which can process a given performative. (agent A does not ask value of X, but rather someone who can process X)
- **recruit performative** recruit performative
Asks Facilitator to find an appropriate agent to which an embedded performative can be forwarded. A reply is returned directly to the original agent
- **recommend performative** recommend performative
Asks Facilitator to respond with the name of another agent which is appropriate for sending a particular performative

Another element of interest of KQML is its internal structure.

The communication architecture is built around three main elements:

1. facilitators.
Facilitators are agents with own KQML routers, they are no different (in implementation) from other agents. The only things that makes them different from regular agents is that they have some predefined functionality about a particular facilitating communication.
Typically one facilitator for each local group of agents.
2. routers.
Content independent message routers.
Each KQML agent is associated with its own separate router process.
router handles all KQML messages going to and from the associated agent.
can try to find Internet address for service and deliver message to it.
3. Library of interfaces (KRIL)
Router Interface Library (KRIL) Router Interface Library (KRIL)
It is a programming interface between router and agent.
It is embedded into application
The main role of KRIL to make access to the router as simple as possible for the programmer
API are developed for different languages and then these API can be used directly in agent in order to make communication, typically with primitives to send message and it defines some point of listening in which messages from other agents will be accomodated and processed.

In general, KQML allows us to implement the system via some independent routing mechanism without involving a particular agent in the knowledge of such mechanism.

It says that we can provide routers that can route network between different engines and in order to communicate with routers we provide some predefined interface that one can embed in you agent.

3.3.2 FIPA ACL

In 1995, the **Foundation for Intelligent Physical Agents (FIPA)** began its work on developing standard for agent systems. The centerpiece of this initiative was the development of an agent communication language (ACL).

Foundation for
Intelligent
Physical Agents
(FIPA)

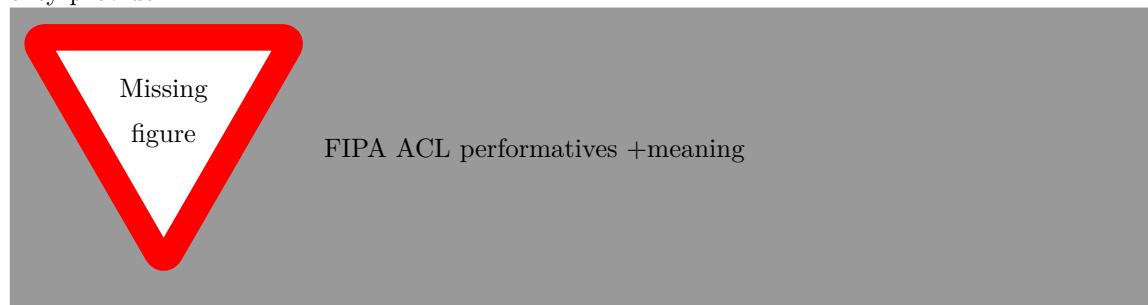
The FIPA ACL is superficially similar to KQML, since:

- It defines an outer language for messages
- It defines 20 performatives for defining the intended interpretation of messages,
- it does not mandate any specific language for message content

In addition the concrete syntax for FIPA ACL messages closely resembles that of KQML

```
1 { $performative$
2   :sender $sender$
3   :receiver $receiver$
4   :content $content$
5   :language $language$
6   :ontology $ontology$
7 }
```

Hence the structure of messages is the same and the message attribute fields are also very similar, however the most important difference between the two languages is the collection of performatives they provide.



FIPA provides some standardization of agent interaction protocols.

Ongoing conversations between agents fall into typical patterns. In such cases, certain message sequences are expected and at any point in the conversation other messages are expected to follow. These typical patterns of message exchange are called protocols.

FIPA does not allow a protocol to be up to interpretation, for this reason they provide some standardized version of each multiagent interactions such as actions or voting or others and specify exactly how these interactions should be carried on.

Chapter 4

Agent Coordination

4.1	General models	46
4.1.1	Motivation	47
4.1.2	Coordination properties and mechanisms	47
4.1.3	Coordination problem	48
	Control decisions and search	48
4.1.4	DAI and distributed search	48
	Network control	49
	Dependencies analysis	49
	Local control	50
4.2	Common coordination techniques	50
4.2.1	Comparing common coordination techniques	50
4.2.2	Organizational structures	51
	Product Hierarchy	51
	Functional Hierarchy	52
	Decentralized market	52
	Centralized market	53
	Summary of organization structures	53
4.2.3	Meta-level information exchange	53
	Partial Global Planning (PGP)	53
4.2.4	Multi-agent planning	56
	Centralized planning	56
	Distributed planning for centralised plans	56
	Distributed planning for distributed plans	56
4.2.5	Explicit analysis and synchronization	56
4.2.6	Social Norms and Laws	57
4.2.7	Coordination Models based on human teamwork	57
	Mutual Modelling	57
	Joint Commitments	57

Coordination is “the process by which an agent reasons about its local actions and the anticipated actions of other to try and ensure that the community acts in a coherent manner.”

4.1 General models

In some sense coordination is the normal way of operating MASs, in which agents can plan their activities based on what they perceive around them. However, during this process agents can incur into some conflicts that are solved via Negotiation.

As a consequence, Coordination is the normal behaviour of the agents, whereas Negotiation is exception handling.

4.1.1 Motivation

The reasons why we need cooperation between agents is for:

- Preventing anarchy or chaos.
If agents do not coordinate their behaviour than cause will arise in the system quite quickly
- Meeting global constraints.
In particular, if a budget is given to some agents when reasoning about a project, there is a budget constraint that needs to be satisfied.
- Distributed expertise, resources or information.
Because in many cases we have some sophisticated expertise by different actors and we would like them to work them together.
- Dependencies between agents' actions.
- Efficiency
The exchange of information with other agents may increase the efficiency of the solution.

4.1.2 Coordination properties and mechanisms

Each coordination mechanism needs to ensure:

- **Coverage.** Coverage
Given a common area of operation, all the portions of the problem are included into the activity of at least one agent.
- **Connectivity.** Connectivity
Agents interact in a way that allow their activity to be integrated into the final overall solution.
- **Rationality.** Rationality
Team members act in purpose in a consistent way.
- **Capability.** Capability
All objectives must be achievable within available computational and resource limitations.

Moreover the activities that the mechanism needs, while operating, to perform is to:

- supply timely information to needy agents
- ensure synchronization
- avoid redundant problem solving

The question remains on how a designer achieve coherent behaviour of the system and in particular of each agents. There are three approaches to achieve coherent behaviour:

- **complete knowledge.** complete knowledge
Each agent knows completely what other agents do and based on this knowledge the agent will reason about its own activity
- **centralized control.** centralized control
A designated agent will decide about the allocation of tasks and how these tasks can be used and synchronized
- **distributed control.** distributed control
No agent has overview of tasks and agents reach coordination/coherent behaviour via negotiation or taking into consideration the activity of nearby agents

Fundamental coordination processes:

- **Mutual adjustment.** Mutual adjustment
Agents will adjust their behaviour based on the behaviour of other agents.
- **Direct supervision.** Direct supervision
An agent will tell nearby agents to change their behaviour.
- **Standardization.** Standardization
Standardization of what can be done and what should be avoided, and based on that agents will try to adjust their own behaviour based on some rules.

4.1.3 Coordination problem

In order to tackle the coordination problem there are several steps that we must take:

- analysis of a perspective for coordination
 - external observation.
Based on the behaviour of others each agent adjust its behaviour. However it may be not enough because:
 - * behaviour can be coordinated but incoherent.
An agent might try to reason about the course of actions but it does not interpret other agents' actions correctly.
 - * behaviour can be coherent but non-coordinated.
 - examining internal goals and motivations is necessary.
Which implies that having a model of behaviour of other surrounding agents can help establish coordination in MASs
- applying appropriate coordination model.
An agent will need to have a general model of coordination that fits all the cases that might occur which will be a purely mathematical approach.

Control decisions and search

View to coordination as a matter of effective control of distributed search.

Almost every problem can be interpreted as a search problem, and it is a process of looking at a sequence of actions that react to a goal or look at some subgoal to reach a solvable goal.

In other terms, in any case an agent has complete knowledge of the current situation, has access to sequence of possible actions and it can try to combine every possible actions to reach a goal.

Thus, control in this sense is:

- control decisions are decisions about what actions to take next
- control decisions are choices
- control knowledge is any knowledge that informs control decisions
- each control choice is the outcome of an overall control regime which includes knowledge about
 - what are the control alternatives? What are the agent choices?
 - What are the decision criteria?
 - what is the decision procedure?

Hence, in principle agents will deal with a search problem and they must have a control procedure over this search. And this control decision will be the underlying coordination mechanism.

Control choices become more complicated to the degree that control decisions have

- numerous choices
- asynchronous behaviour
- decentralized control

4.1.4 DAI and distributed search

In the distributed search problem the space of alternative problem states (goals) can be seen as a large search space investigated by a number of agents. Each agent has to make local control decisions.

These local control decisions have impacts on the overall efforts done by the collection of problem solvers.

The coordination process kickstarts when these local control area between agents overlap.



Two kinds of control in DAI

1. **Network control or Cooperative control:**
Comprises decision procedures that lead to good overall performance
2. **Local control:**
refers to decision procedures that lead to good local decisions, and that are based on local information only

Network control

Cooperative control

Local control

Network control

Sets contexts for agent's individual control decisions based on network level information (which can be the information the dependencies of two different goals or the intersection between two areas). Network-level information is:

- aggregated from more than one agent or abstracted from data from more than one agent
- Information that concerns the relationships among a collection of agents

Network-level information can be utilized to influence:

- set of action alternatives to consider a control decisions
- the decision criteria applied to choose one of them
- the control decision procedure

One type of network control (or coordination) is allocation of search-space regions to agents.

- search space, alternative problem states (goals).
- establishing dependencies between nodes.
- search process explores that space by generating a tree of possibilities taking into account dependencies
- since a search process explores a tree of possibilities (and any tree is recursively composed of subtrees) it follows that any region of the search space can be characterized by a set of subtree roots
- allocation of search-space regions to agents takes place by allocating collections of search-subtree roots to agents
- dynamic nature of region allocation

Dependencies analysis

Two kinds of dependencies might occur in a tree:

1. **logical dependencies**, an action or goal depends on another action or goal
2. **resource dependencies**, both actions depends on a resource that goal consumes and the other produces.

logical dependencies

resource dependencies

A very important part of coordination is analysis of interdependencies because the behaviour of the agents involved in the coordination process is based on such analysis.

it may occur that some joint goals:

- team members are mutually responsible to one another

- the team members have a joint commitment to the joint activity
- the team members are committed to be mutually supportive of one another

Local control

Concerns the status and process of a single node in its own local environment and its own local search space region

Interaction with network control:

- network may increase or decrease local control uncertainty
- better local control may more efficiently uncover information that can focus network control decision

Control decision uncertainty: ambiguity in the next actino choice (often is characterized as the size of the set of next-states)

Control decision
uncertainty

Resucing degree and/or reducing impact of uncertainty will have an

- Impact on arbitrariness of control decisions
- Impact of control uncertainty can be reduced by reducing common dependencies that agent share

Activities in coordination

- Defining the goal graph or search space
- Assigning regions of search space to different agents
- controlling decisions about which areas of the graph to explore
- traversing the goal structure satisfying dependencies
- ensuring report of the successful traversal

Determining the approach for each of the phases is a matter of system design and it depends upon:

- The nature of the domain
- The type of agents included into community
- the desired solution characteristics

4.2 Common coordination techniques

- Organisational structures
- Meta-level Information exchange
- Multi-agent Planning
- Explicity analysis and synchronization
- Norms and social laws
- Coordination models based on human teamwork (Joint commitments and mutual modelling)

4.2.1 Comparing common coordination techniques

The first four common techniques can be compared and classified using three main concepts:

- **Predictability**, how easy is it to predict what happens next
- **Reactivity**, how easy is it to react to change
- **Information Exchange**

Predictability

Reactivity

Information
Exchange



Trade off between predictability, reactivity and information exchange.

4.2.2 Organizational structures

- It is the simplest coordination approach.
Someone allocate responsibility to each agent to some particular search space
- implicit coordination
- provides framework for defining
 - roles
 - communication paths
 - authority relationships
- pre-defined, long-term relations.
the relations that you have do not change often.
- specifies the distribution of specializations among agents
- a precise way of dividing the problem space without specifying particular problems
- agents are associated with problem types and problem instances circulate to the agents which are responsible for instances of that type

Organisational structures may be: **functional, spatial, product-oriented**

Hence, organizational structure models provide a pattern for decision-making and communication among a set of agents who perform tasks in order to achieve goals. The most well-known example of the application of organizational structure models is the automotive industry.

In fact, in such a field:

- Has a set of goals, i.e. to produce different lines of cars
- Has a set of agents to perform the tasks: designers, engineers and salesmen
- It bases its organizational structure based on various costs: production costs, coordination costs and vulnerability costs

functional

spatial

product-oriented

Product Hierarchy



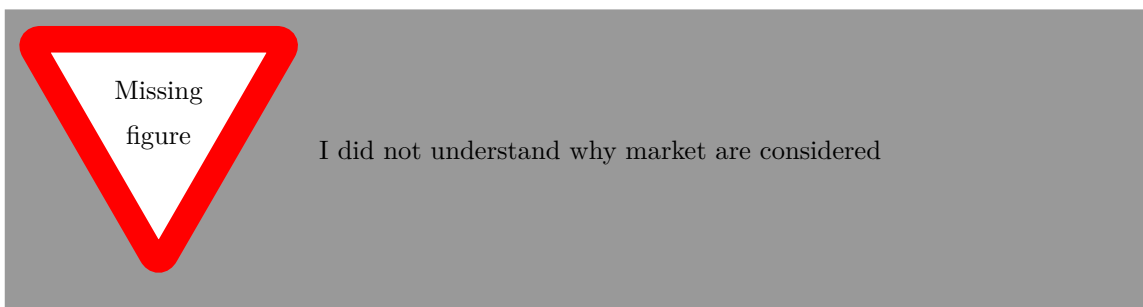
- several divisions for different product lines
- each division has a product manager
- each division has its own separate departments (agents) for different functions
- product manager assigns tasks to agents in its department
- communication links in product structure

- fails inside department do not affect other products
- one message to assign task and one message to notify result
- also model for set of separate companies

Functional Hierarchy



- a number of agents of similar types are pooled into functional departments
- each department has a functional manager
- reduce duplication of efforts
- executive office, production manager for all productshierarchilar task allocation
- 2 messages to assign task and 2 messages to notify about results
- failure of task aget results in a delay and task reallocation
- managers are critical



Decentralized market



- all buyers are in contact with all possible suppliers
- buyers play a role of product managers
- each has a communication link with each supplier
- buyers can choose the best supplier
- given m suppliers, $2m + 2$ messages are requires
- if the processor fails the task is reassigned
- if manager fails the whole product fails

Centralized market



- brokers are in contact with possible sellers
- fewer connections and communications are required
- brokers play a role of functional managers
- broker chooses the best supplier
- 4 messages needed
- similar to functional model
- failure of one product manager does not affect others

Summary of organization structures



- Organizational structures are useful when there are master/slave relationships in the MAS
- control over the slaves actions: mitigates against benefit of DAI such as reliability and concurrency
- Presumes that atleast one agent has global overview: an unrealistic assumption in MAS

4.2.3 Meta-level information exchange

- Exchange control level information about current priorities and focus
- Control level information
 - May change
 - Influence the decisions of agents
- Does not specify which goals an agent will or will not consider
- Imprecise
- Medium term: can only commit to goals for a limited amount of time

Among the most notable implementation of the Meta-Level Information exchange there is the **Partial Global Planning (PGP)** proposed by Durfee

Partial Global
Planning (PGP)

Partial Global Planning (PGP)

The basic condition of PGP is the requirement that several distributed agents work on solution at the same time.

An agent therefore can observe actions and relations between groups of other agents.



PGP involves 3 iterated stages:

1. Each agent decides what its own goals are and generates short-term plans in order to achieve them
2. Agents exchange information to determine where plans and goals interact
3. Agents alter local plans in order to better coordinate their own activities

Hence PGP involves:

- Task decomposition.
Starts with the premise that tasks are inherently decomposed.
Assumes that an agent with a task to plan for might be unaware of what tasks other agents might be planning for and how those tasks are related to its own.
No individual agent might be aware of the global tasks or states.
The purpose of coordination is to develop sufficient awareness
- Local plan formulation .
Before an agent communicates with others it must first develop an understanding of what goals it is trying to achieve and which actions to perform.
Local plans will most often be uncertain, involving branches of alternative actions depending on results of previous actions and changes in the environment
- Local plan abstraction.
Alternative courses of action for achieving the same goal are important for an agent, however, the detail of alternatives might be unnecessary considering the agent's ability to coordinate with others." An agent might have to commit to activities at one level of details without committing to activities at more detailed levels.
Agents are designed to identify their major plan steps that could be of interest to other agents
- Communication of local plan abstraction .
Agents must communicate about abstract local plans in order to build models of joint activities.
In PGP, the knowledge to guide this communication is contained in the meta-level-organization
- Partial global goal identification.
The exchange of local plans gives an opportunity to identify when the goal of one or more agents could be subgoals of a single global goal.
Only portions of the global goal might be known to agents. Hence the name partial global goal
- PGP construction and modification.
Local plans can be integrated into PGP. PGP can in fact identify opportunities for improved coordination (performing related tasks earlier, avoiding redundant task achievement). As a consequence, agents will undergo a reordering of actions (usage of action rates). With rates, it is meant:
 - Whether the task is unlikely to have been accomplished already by another agent
 - how long it is expected to take
 - how useful its results will be to others in performing their tasks

Hence the algorithm of action reordering goes as follows:

1. For the current ordering, rate the individual actions and sum the ratings
2. For each action, examine the later actions for the same agent and find the most highly-rated one. If it is higher rated, swap the actions.

3. If the new ordering is more highly rated than the current one, then replace the current ordering with the new one and go to step 2.
 4. Return the current ordering
- Communication planning.
Agent must next consider what interactions should take place between agents. Interactions in the form of communicating the results of tasks are planned. By examining PGP an agent can determine when a task will be completed by one agent that could be of interest to another agent and can explicitly plan the communication action to transmit the result.
Formally, the algorithm for communication planning goes as follows:
 1. Initialize the set of partial task results to integrate
 2. While the set contains more than one element:
 - (a) For each pair of elements: find the earliest time and agent at which they can be obtained
 - (b) For the pair that can be combined earliest: add a new element to the set of partial results for the combination and remove the two elements that were combined
 3. Return the single element in the set
 - Acting on PGP.
Once a PGP has been constructed and the concurrent local and communication actions have been ordered, the collective activities of the agents have been planned. These activities must be translated back to the local level.
An agent responds to a change in its PGP by modifying the abstract representation of its local plans.
The modified representation is used by agent when choosing its next local action
 - Ongoing modifications.
As agents pursue their plans, their actions or events in the environment might lead to changes in tasks.
A change in coordination is deciding when the changes in local plans are significant enough or defining a threshold (significant temporal deviations)
 - Task reallocation.
in case of disproportional task load, agents, through PGP, can exchange abstract models of their activities and detect whether they are overburdened.
When this happens a possible task reallocation might occur.

In short: the main principle of PGP is that cooperating agents exchange information in order to reach common conclusions about the problem solving process.

It is said to be **partial** because an agent does not generate a plan for the entire problem. partial
It is said to be **global** because agents form non-local plans by exchanging local plans and cooperating to achieve a non-local view of problem solving. global

To summarize: PGP is a cooperatively generated data structure containing the actions and interactions of a group of agents.

It contains:

- **Objective**, the larger goal of the system Objective
- **Activity map**, what agents are actually doing and the results generated by the activities Activity map
- **Solution construction graph**, a representation of how the agents ought to interact in order to successfully generate a solution Solution construction graph

PGP focuses on dynamically revising plans in cost-effective ways given an uncertain world. PGP is particularly suited to applications where some uncoordinated activity can be tolerated and overcome.

PGP works well for many tasks, but could be inappropriate for domains such as air-traffic control where guarantees about coordination must be made prior to any execution

4.2.4 Multi-agent planning

Agents generate, exchange and synchronize explicit plans of actions to coordinate their joint activity. they arrange a priori precisely which tasks each agent will take on.

Plans specify a sequence of actions for each agent.

Consideration of uncertainty is moved to the planning activity.

More specific than organizational structures or PGP and shorter time-horizon.

There are two basic approaches to Multi-agent planning:

1. Centralised: a central coordinator develops, decomposes and allocated plans to individual agents
2. Distributed: a group of agents cooperate to form either a centralised or a distributed plan

Centralized planning

- Given a goal description, a set of operators and an initial state description, generate a plan
- Decompose the plan into subproblems such that ordering relationships between steps tend to be minimized across subproblems
- Insert synchronization actions into subplans
- Allocate subplans to agents using task-passing mechanisms
- Initiate plan execution and optionally monitor progress

Distributed planning for centralised plans

In air traffic control domain, the aim is to enable each aircraft to maintain a flight plan that will maintain a safe distance with all aircrafts in its vicinity.

Hence each aircraft sends a central coordinator information about its intended actions. The coordinator builds a plan which specifies all of the agents' actions including the ones that they should take to avoid collision.

Another example is a general technological process such as manufacturing: the plan is centralized but each step can be planned in parallel. As a consequence, there is a distributed expertise even though the control is centralized.

Distributed planning for distributed plans

Individual plans of agents, coordinate dynamically.

No individual with a complete view of all the agents' actions.

More difficult to detect and resolve undesirable interactions.

Agents in these different scenarios share and process a huge amount of information, hence these approaches require more computing and communication resources

4.2.5 Explicit analysis and synchronization

Analysis of situation in each decision-making step (possible-next-action-set).

Interacting with other agents:

- Exchange among all interdependent agents
- locks actions
- uses reply information to prune its next-action set
- send synchronization unlocking messages

A lot of time for communication during planning.

If the level of dependency is low and the granularity of actions is high, this approach can provide useful coordination.

Short time-horizon

4.2.6 Social Norms and Laws

Norm: an established, expected pattern of behaviour

Norm

Social Laws: similar to Norms, but carry authority.

Social Laws

Social laws in an agent system can be defined as a set of constraints:

- A constraint is formally represented as a tuple $\langle E \alpha \rangle$, where:
 - $E' \subseteq E$ is a set of environment states
 - $\alpha \in Ac$ is an action (in this case Ac is the finite set of actions possible for an agent)
- If the environment is in some state $e \in E'$, then the action α is forbidden.
An agent or plan is said to be legal wrt a social law if it never attempts to perform an action that is forbidden by some constraint in the social law.

4.2.7 Coordination Models based on human teamwork

In this section we will see that it is possible to achieve coordination without communication. Since some the method that we will see are based on human teamwork it is worth making a distinction:

- Coherent behaviour that is not cooperative, e.g. individual drivers in traffic following traffic rules
- Coordinated cooperative action, e.g. implicit sharing a common goal like dancers
- Teamwork action, e.g. conovy-combining individual efforts

Formally teamwork is defined as a cooperative effort by the members of a team to achieve a common goal.

In such a scenario an individual intention towards a particular goal ay differ from being a part of a team with a collective intention towards a goal. However, teamwork is enforced with the notion of Responsibility towards the other members of the team

Mutual Modelling

In Mutual Modelling techniques, each agent builds a model of the other agents, in particular their beliefs and intentions.

Based on this model, the agent will coordinate its own activities and achieve cooperation without communication.

Joint Commitments

Joint Intentions models are based on human teamwork models: when a group of agents are engaged in a cooperative activity, they must have a joint commitment to the overall aim as well as their individual commitments.

The term commitment refers to a pledge or promise and carries around several properties:

- Commitments are persistent, in the sense that if an agent adopts a commitment, it is not dropped until for some reason it becomes redundant
- Commitments may change over time, due to a change in the environment

The main problem with joint commitment si that it is hard for agents to be aware of each others states at all times.

Conventions, refer to means of monitoring a commitment. The overall mechanism of conventions is neccessary to describe when to change a commitment, or more in particular:

- When to keep a commitment (retain)
- When to revise a commitment (rectify)
- When to remove a commitment (abandon)

Joint action by a team involves more than just the union of simultaneous individual actions. When a group of agents are engaged in a cooperative activity, they must have:

- Joint commitment to the overall activity
- Individual commitment to the specific task that they have been assigned to

More in particular Individual conventions describe how an agent should monitor its commitments, but not how it should behave towards other agents. In this sense it is both asocial and sufficient for goals that are independent.

However, individual conventions do not work for inter-dependent goals, for which it is necessary to have social conventions, which specify how to behave with respect to the other members of the team.

Team members must be aware of the convention that govern their interaction.

Chapter 5

MAS Architecture

5.1	Low-level architectures	60
5.1.1	Blackboard Architecture	60
	The control problem	60
	Agenda-based Control	60
	Event-based Control	61
	Goal-directed Control	61
	Hierarchy of Blackboard Servers	61
5.1.2	ACTORs	62
	Behaviour	62
	Communication	62
5.2	Message sending based architecture: Agent Factory	63
5.3	Testbeds	63
5.3.1	DVMT	63
5.3.2	MACE	64
5.4	Infrastructures that use wrappers: ARCHON	64
5.4.1	ARCHON Layer	64
5.5	Infrastructures that use Middle Agents: RETSINA	65
5.6	Market-based architectures	65
5.6.1	MAGNET	66
5.7	Conclusion	67

The infrastructure for a MAS is a set of services, conventions and knowledge that support complex social interactions (e.g. negotiations, agree on commitments...)

Agents need services to:

- Enable them to find each other in open environments
- Communicate
- Warrant that proper security constraints are satisfied
- ...



4

5.1 Low-level architectures

5.1.1 Blackboard Architecture

Metaphor: a collection of intelligent agents gather around a blackboard, loot at pieces of information written on it, think about them, and add their conclusions.

Some basic assumptions:

- all of the agents can see all of the blackboards all the time, and what they see represents the current state of solution
- any agent can write his conclusions on the blackboard at anytime without getting in anyone else's way
- the act of an agent writing on the blackboard will not confuse any other agents as they work

The key ideas of the blackboard architecture is that problem solving should be:

- **Incremental:** complete solutions are constructed piece by piece, first hypothesizing a partial solution based on incomplete data and then attempting to verify additional data to verify hypothesis Incremental
- **Opportunistic:** the system chooses the action to take next that it determines will allow it to make the best progress towards meeting its goals in the current situation. Opportunistic

The main components of the blackboard architecture are:

- A **blackboard:** a global database containing data and hypotheses (potential partial solutions) blackboard
- A set of **Knowledge Sources (KS)** or agents Knowledge Sources (KS)
- A **Control mechanism** Control mechanism

The control problem

The term control problem refers to the problem of selecting the best action to execute next.

Blackboard systems, in fact, must have some control mechanism:

- Effective control requires to take into account
 - **Goal-directed factors:** based on what an agent wants Goal-directed factors
 - **Data-oriented factors:** based on what an agent is best able to do Data-oriented factors
- Blackboard control is difficult because it can be difficult to determine the expected value of an action by an agent as there may be complex interrelationships among the agents

Agents are schedulable entities and only one can be running at any time.

The control mechanism selects only the most productive agent at any given moment to work on the problem

The blackboard is not globally visible. Agents generally work on a limited area of the blackboard, known as the agent's context.

Implicit assumption: a knowledge source/agent operates within a valid, or consistent context

Agenda-based Control



In the basic agenda-based blackboard architecture, all the control (strategy) knowledge of the system is represented in a single scheduler rating function.

This makes it difficult to encode and modify complex control strategies. The knowledge and reasoning are not explicit.

Event-based Control



Goal-directed Control

Control that considers the role and the ultimate value of actions in satisfying the system's goals



Goal processor instantiates goals on the goal blackboard.

Goal processor is driven by the 3 mapping functions.

Integrates goal-directed and data-directed factors:

- Goal-directed goals are created in response to the creation of other goals based on the goal-to-subgoal map
- Data-directed goals are created in response to the creation or modification of hypotheses on the blackboard based on the hypothesis-to-goal map

When a goal is inserted onto the goal blackboard, it may trigger KSs that can achieve the goal identified by the goal-to-KS map.

If KS is likely to generate a hypothesis to achieve the goal, KS is added to the agenda.

A possible problem may emerge: subgoalings needs to be carefully controlled

Hierarchy of Blackboard Servers



5.1.2 ACTORs

An ACTOR is a computational system with the following properties:

- **Social**, can send messages to other ACTORs
- **Reactive**, carry out computation in response to a message received from another actor

In the ACTOR model, computation itself is viewed as message passing
It can be considered as consisting of:

- An address
- A behaviour which specifies what the ACTOR will do upon receipt of a message

The ACTOR approach is formulated around three main design objectives:

1. Shared, mutable data
2. Reconfigurability
3. Inherent concurrency

An ACTOR is an object that carries out its actions in response to communication it receives.
ACTOR may perform three basic actions:

- Sending messages to itself or other ACTORs
- Creating more ACTORs
- Specify a replacement behaviour, which is essentially another actor that takes the place of the actor that creates it, for the purpose of responding to certain communications.

Behaviour

How an ACTOR works:

- Upon receipt of a message, the message is matched against the ACTOR's behaviour (script)
- Upon a match, the corresponding action is executed, which may involve:
 - Sending more messages
 - Creating more ACTORs
 - Replacing the ACTOR by another

Actor computation is reactive.

An actor is dormant until it receives communication.

In any computation, each actor receives a linearly ordered sequence of computations.

Messages are not guaranteed to arrive in the order in which they are sent

There is no assignment to local variables in basic actor model

Every communication must be sent to a mail address: mail system is an important part of the model.



Communication

A communication event is called a task and it has 3 parts:

1. A unique tag, distinguishing it from tasks in the system
2. A target, the mail address of intended receiver
3. A communication which is the data passed by this communication event

Actor model is asynchronous.

Communication is:

- explicit, through mail addresses, without shared variables
- buffered and asynchronous

Weak fairness is assumed:

- every message which is sent is eventually delivered
- every computation eventually progress (no starvation)

5.2 Message sending based architecture: Agent Factory

A few words about basic principles of Agent Factory:

- Linear discrete model of time which can be visualized as a sequence of numbers
- A guaranteed delivery assumption. Messages are delivered correctly: the content of the message does not change in transaction, the message is sent to destinations and only to them
- For any message there is only one sender
- In spite of process synchronization: communication is asynchronous via message pool



5.3 Testbeds

The main purpose of DAI testbeds is to support the implementation of ideas so that they can be evaluated in a useful context.

Most DAI testbeds provide three classes of facilities:

- Domain facilities: representation and simulation of the problem being solved
- Development facilities: an environment or tools for building the agents that will solve the problem
- Evaluation facilities: tools for display, data collection, and analysis to understand how well the agents perform

5.3.1 DVMT

The Distributed Vehicle Monitoring Testbed (DVMT) is a DAI testbed developed to successfully track a number of vehicles that pass within the range of a set of distributed sensors (agents).

Distributed
Vehicle
Monitoring
Testbed (DVMT)

DVMT is a problem dependent testbed and agents (problem solvers) have a blackboard architecture

5.3.2 MACE

MACE provides tools for constructing DAI systems at different level of abstraction:

- Each rule can be an agent
- coarse-grained systems with large scale agents

MACE had no fixed domain for problem solving activity

5.4 Infrastructures that use wrappers: ARCHON

In many industrial applications, a substantial amount of time, effort and money was spent on developing complex and sophisticated software systems (e.g. expert systems and databases)
Can these sub-systems be integrated into a coherent community in which they work together to better meet the needs of the entire applications?

ARchitecture for Cooperative Heterogeneous ON-line systems (ARCHON) was (in 1996) Europe's largest project in the area of DAI.

It was originally focused on getting a number of expert systems to pool their expertise in solving problems and diagnosing faults in several industrial domains.

Supports a cooperating community that has decentralized control and individual problem solving agents.

Consists of a:

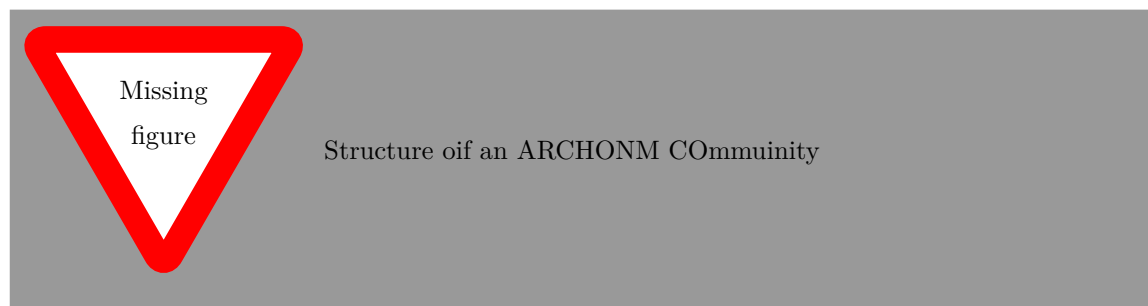
- **Framework:** which provides assistance for interaction between constituent subcomponents
- **Methodology:** which provides a means for structuring these interactions

ARCHON's individual problem solving entities are agents; they have the ability to control their own problem solving and to interact with other community members

Agents are large grain loosely coupled and semi-autonomous.

Each agent consists of an **ARCHON Layer (AL)** and an application program (known as **Intelligent System (IS)**)

The ISs can be heterogeneous as their differences are masked by a standard AL-IS interface.



The system's overall objective is expressed in the separate local goals of each agent.

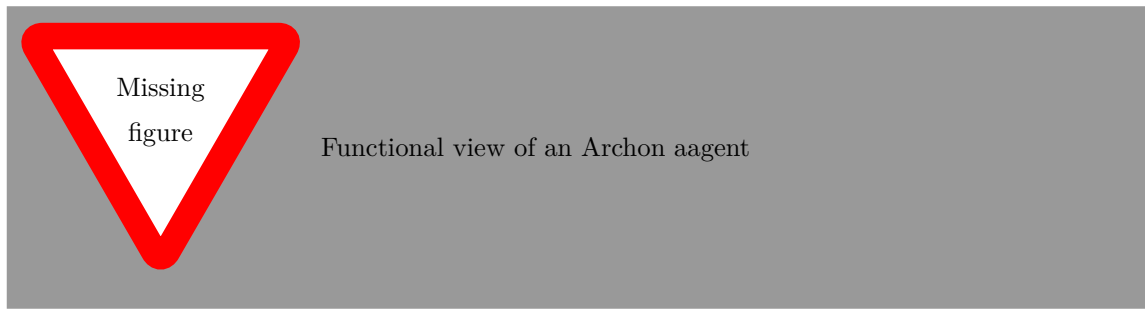
Agents' goals are usually interrelated. Therefore, social interactions are required to meet global constraints.

Such interactions are controlled by the ARCHON layer.

5.4.1 ARCHON Layer

Functions of the ARCHON Layer:

- Control tasks within the local IS
- Decide when to interact with other agents (it needs to model the capabilities of its own IS as well the ISs of the other agents)
- Communicate with other agents



5.5 Infrastructures that use Middle Agents: RETSINA

In an open system, the set of agents is not known a priori.

The infrastructure should provide ways for its agents to locate each other based on name, functionality or capability.

Agents that provide this service are called Middle agents which may also take the role of Facilitators or Matchmakers.

REusable Task Structure-based Intelligent Network Agents (RETSINA) is an open MAS infrastructure that supports communities of heterogeneous agents.

The main idea of RETSINA is that agents should form a community of peers that engage in peer-to-peer relations.

There is no central control and it implements distributed infrastructural services that facilitate the relation between agents.

REusable Task
Structure-based
Intelligent
Network Agents
(RETSINA)



RETSINA middle agents are called Matchmakers, i.e. information agents that look for other agents rather than information:

- Records a mapping between agents in the system and the services they provide
- Two types of data: advertisements and requests
- the task of matchmakers is to match advertisements to requests
- Two types of protocols: single short and monitor

5.6 Market-based architectures

Online market places offer an opportunity to buyers and sellers to meet electronically and conduct trade.

Offers benefits for both buyers and seller:

- Buyers: ease to process of searching for and comparing sellers
- Sellers provide access to much broader customer bases

The major challenges are:

- to go beyond simple buying and selling
- to incorporate time constraints, enforce deadlines, interact with a highly distributed web of suppliers with different capabilities and resources, interact over long periods of time and deal with failure in contract execution

The requirements of a Market-based Architecture are to:

- Provide support for a variety of transaction types (buying and selling, complex multi-agent contract negotiation, auctions)
- Control fraud and misrepresentation
- Discourage counterspeculation
- Provide for secure and private credit and payment mechanisms
- Provide a language in which the rich array of semantic content about commerce can be expressed
- Provide for robust exception handling
- Scale smoothly from local to global
- Be extensible, by third parties
- Interoperate with other new and existing electronic commerce services

5.6.1 MAGNET

The Multi-AGent NEgotiation Testbed (MAGNET) is a testbed to support multiple agents in negotiating contracts.

Multi-AGent
NEgotiation
Testbed (MAGNET)

Supports negotiation of contract for tasks that have temporal and precedence constraints.

Distinguishes between the agents:

- Customer: needs resources outside its direct control in order to carry out its plans
- Supplier: provides the resources and services required by customers, for a specified price, over specified time periods



The interaction among agents goes as follows

1. A customer issues a Request for Quotes (RFQ), which specifies tasks, the precedence relations and a timeline for the bidding process
2. Supplier agents submit a bid, which includes a set of tasks, a price, a portion of the price to be paid as a non-refundable deposit and estimated timeline
3. The customer decides which bid to accept based on cost, risk and time constraints
4. The customer awards bid, notifies the suppliers of their commitments and specifies the work schedule

The interactions between the customer and supplier agents are encapsulated in a market session.

The market session:

- finds suppliers interested in bidding for the customer
- provides a catalog of services (market ontology)
- time-stamps all the interactions in order to avoid dispute among customers and suppliers

The session:

- Truthfully informs the suppliers of the conditions under which the bidding is being done and enforces these conditions
- Can limit the number of bids sent by each supplier

- May provide information about suppliers to customers
- Enforces the rules of the market
- Can act as a trusted auctioneer

5.7 Conclusion

We consider our MAS infrastructure as middleware on the top of system software. Cooperative work support is an important element of the infrastructure and it needs conceptual solutions. Extensibility and default components are important features. We should be as much as possible close to standards (if they do not exist then to general tendencies).

Chapter 6

Agent Oriented Software Engineering

6.1	When is an Agent-Based Solution Appropriate?	68
6.2	Agent-Oriented Analysis and Design	68
6.2.1	The AAIL methodology	69
6.2.2	The GAIA methodology	70
6.2.3	The Tropos methodology	70
6.2.4	The Prometheus methodology	71
6.2.5	Agent UML	71
6.2.6	Discussion	72
6.3	Pitfalls of Agent Development	72

As MASs become more established in the collective consciousness of the computer science community, we might expect to see increasing effort devoted to devising methodologies to support the development of agent systems.

6.1 When is an Agent-Based Solution Appropriate?

There are a number of factors which point to the appropriateness of an agent-based approach:

- The environment is open or at least highly dynamic, uncertain or complex
- Agents are a natural metaphor.
Many environments are naturally modelled as societies of agents, either cooperating with each other to solve complex problems, or else competing with one another.
- Distribution of data, control or expertise.
In some environments, the distribution of either data, control or expertise means that a centralized solution is at best extremely difficult or at worst impossible.
- Legacy systems.
A problem increasingly faced by software developers is that of legacy software, that is, legacy software technologically obsolete but functionally essential to an organization.
Such software cannot generally be discarded, because of the short-term cost of rewriting. And yet it is often required to interact with other software components which were never imagined by the original designers. One solution to this problem is to wrap the legacy components, providing them with an agent layer functionality, enabling them to communicate and cooperate with other software components.

6.2 Agent-Oriented Analysis and Design

An analysis and design methodology is intended to assist first in gaining an understanding of a particular system and secondly in designing it.

Methodologies generally consist of a collection of models, and associated with these models, a set of guidelines. The models are intended to formalize understanding of the system being considered.

Analysis and design methodologies of agent-based systems can be broadly divided into two groups:

1. Those that take their inspiration from OO development, and either extend existing OO methodologies or adapt OO methodologies to the purposes of **Agent-Oriented Software Engineering (AOSE)**
2. Those that adapt knowledge engineering or other techniques

Agent-Oriented
Software
Engineering
(AOSE)

6.2.1 The AAIL methodology

The **Australian AI Institute (AAIL)** developed a range of agent-based systems using their PRS-based belief-desire-intention technology and the distributed multiagent reasoning system (DMARS).

Australian AI
Institute (AAIL)

This methodology draws primarily upon OO methodologies and enhances them with some agent-based concepts. The methodology itself is aimed at the construction of a set of models which, when fully elaborated, define an agent system specification.

The AAIL methodology provides two types of model:

1. The **External model** presents a system level view: the main components visible in this model are agents themselves.

External model

The external model is thus primarily concerned with agents and the relationships between them.

Particularly the external model is intended to define inheritance relationships between agents classes, and to identify the instance of these classes that will appear at run time.

It is itself composed of two further models: the **agent model** and the **interaction model**.

agent model

Furthermore the agent model is divided into an **agent class model** and an **agent instance model**.

interaction
model

2. The **Internal model** is concerned with the internals of agents: their beliefs, desires and intentions

agent class
model

agent instance
model

Internal model

These two models define the agents and agent classes that can appear, and relate these classes to one another via inheritance, aggregation and instantiation relations. Each agent class is assumed to have at least three attributes: beliefs, desires and intentions. The analyst is able to define how these attributes are overridden during inheritance. Details of the internal model are not given but it seems clear that developing an internal model corresponds fairly closely to implementing a PRS agent.

The AAIL methodology is aimed at elaborating the models described above. It may be summarized as follows:

1. Identify the relevant roles in the application domain and on the basis of these, develop an agent class hierarchy
2. Identify the responsibilities associated with each role, the services required by and provided by the role and then determine the goals associated with each service.
3. For each goal, determine the plans that may be used to achieve it and the context conditions under which each plan is appropriate
4. Determine the belief structure of the system, the information requirements for each plan and goal.

Note that the analysis process will be iterative, as in more traditional methodologies. The outcome will be a model that closely corresponds to the PRS agent architecture. As a result, the move from end-design to implementation using PRS is relatively simple

6.2.2 The GAIA methodology

The **GAIA methodology** is intended to allow an analyst to go systematically from a statement of requirements to a design that is sufficiently detailed that it can be implemented directly. GAIA methodology

In applying GAIA, the analyst moves from abstract to increasingly concrete concepts. Each successive move introduces greater implementation bias and shrinks the space of possible systems that could be implemented to satisfy the original requirement statement. Gaia borrows some terminology and notation from OO analysis and design. However, it is not simply a naive attempt to apply such methods to Agent-oriented development. Rather, it provides an agent-specific set of concepts through which a software engineer can understand and model a complex system. In particular, Gaia encourages a developer to think of building agent-based systems as a process of **organizational design**. organizational design

The main Gaia concepts can be divided into two categories:

- **abstract** entities are those used during analysis to conceptualize the system, but which do not necessarily have any direct realization within the system abstract
- **concrete** entities are used within the design process, and will typically have direct counterparts in the run-time system. concrete

The objective of the analysis stage is to develop an understanding of the system and its structure without reference to any implementation detail. In the Gaia case, this understanding is captured in the system's **organization**. organization

An organization is viewed as a collection of roles that stand in certain relationships to one another and that take part in systematic, institutionalized patterns of interactions with other roles.

The idea of a system as a society is useful when thinking about the next level in the concept hierarchy: **roles**. A role is defined by four attributes: roles

1. Responsibilities

They determine functionality and as such are perhaps the key attribute associated with a role. Responsibilities are divided into two types: Responsibilities

- (a) **Liveness properties** describe those states of affair that an agent must bring about, given certain environmental conditions. Liveness properties
- (b) **Safety properties** are invariants, which in other terms states that an acceptable state of affairs is maintained across all states of execution. Safety properties

2. Permissions

A role has a set of permissions which identify the resources that are available to that role in order to realize its responsibilities. Permissions tend to **information resources**. Permissions

3. Activities

The activities of a role are computations associated with the role that may be carried out by the agent without interacting with other agents. activities are thus private actions. Activities

4. Protocols

A role is also identified with a number of protocols, which define the way that it can interact with other roles. Protocols

6.2.3 The Tropos methodology

The **Tropos methodology** aims to give an agent-oriented view of software throughout the software development lifecycle. Tropos methodology

It provides a conceptual framework for modelling systems based on the following concepts:

- **Actor** Actor
An entity with strategic goals and intentionality within the system or the organizational setting.
Associated with actors are the notions of role and position.

- A role is an abstract characterization of the behaviour of a social actor within some specialized context
- A position is a set of roles, typically played by one agent

- **Goal**
A goal represents the actors' strategic interests. Tropos distinguishes **hard goals** (system functional requirements) and **soft goals** (non-functional requirements)
- **Plan**
A recipe for achieving a goal.
- **Resource**
Physical entities or information
- **Dependency**
A relationship between two actors, indicating that one agent needs the other to carry out some part of a plan, deliver some resource, or similar
- **Capability**
The ability of an actor to achieve some goal or carry out some plan
- **Belief**
Knowledge that actors have about their environment.

The first phase of analysis in Tropos involves developing an :

- **actor model**, which captures the key stakeholders in the system and their strategic interests in the form of their goals
- **dependency model**, which documents the dependencies between these actors

A **goal model** is then developed, which decomposes goals into their constituent parts, and, associated with this, a **plan model** captures the structure of recipes for achieving goals.

6.2.4 The Prometheus methodology

The **Prometheus methodology** consists of three main stages:

1. **System specification**, which focuses on identifying the goals and basic functionalities of the system, and specifies the interface between the system and its environment in terms of actions and percepts
2. **Architectural design**, which focuses on identifying agent types, the system structure and the interactions between agents
3. **Detailed design**, which first involves refining agents into their capabilities and specifying the processes on the system and then involves the detailed design of capabilities

Prometheus provides a rich collection of models for each stage and detailed guideline for each step. It also has software tool support

6.2.5 Agent UML

The **Undefined Modelling Language (UML)** is an attempt by three of the main figures behind object-oriented analysis and design to develop a single notation for modelling OO systems. It is important to note the UML is NOT a methodology, but rather a language for documenting models of systems; however, associated with UML is a methodology known as the rational unified process.

When looking for agent-oriented modelling languages and tools, many researchers felt that UML was the obvious place to start. The result has been a number of attempts to adapt the UML notation for modelling agent systems.

The proposed modifications include:

- support for expressing concurrent threads of interaction thus enabling UML to model such well-known agent protocols as the Contract Net

- A notion of role that extends that provided in UML and in particular allows the modelling of an agent playing many roles

Both the Object Management Group and FIPA are currently supporting the development of UML-based notations for modelling agent systems, and there is therefore likely to be considerable work in this area.

6.2.6 Discussion

The predominant approach to developing methodologies for MASs is to adapt those developed for OO analysis and design. There are several disadvantages with such approaches:

- the kind of **decomposition** that OO methods encourage is at odds with the kind of decomposition that agent-oriented design encourages.
- OO methodologies simply do not allow us to capture many aspects of agent systems. The extensions to UML proposed address some, but by no means all of these deficiencies.
- At the heart of the problem is the problem of the relationship between agents and objects which has not yet been satisfactorily resolved.

6.3 Pitfalls of Agent Development

- You oversell agent solutions, or fail to understand where agents may usefully be applied
- You get religious or dogmatic about agents
- You do not know why you want agents
- You want to build generic solutions to one-off problem
- You believe that agents are a silver bullet
- You forget that you are developing software
- You forget that you are developing multithreaded software
- Your design does not exploit concurrency
- You decide that you want your own agent architecture
- Your agents use too much AI
- You see agents everywhere
- You have too few agents
- You spend all your time implementing infrastructure
- Your agents interact too freely or in a disorganized way

Chapter 7

Agent Theory

7.1 Agents as intentional systems	73
7.1.1 Attitudes	73
7.1.2 Theories of Attitudes	74
7.1.3 Study of Knowledge	74
7.2 Foundation of formal logic	74
7.2.1 Logical inference	76
7.3 Formalising attitudes	76
7.3.1 Possible worlds	77
7.3.2 Modal Logic	77
7.4 Logic of Knowledge	79
7.5 BDI architecture	80

Formal theory has arguably had little impact on the general practice of software development, however, they are relevant in agent-based systems because we need to be able to give a semantic to the architecture, languages and tools that we use (i.e. a meaning),

Without semantics, it is never clear exactly what is happening and why it works.

We need a theory to reach any kind of profound understanding the tools.

Formalization of agents has been used for 2 distinct purposes:

1. As internal specification language to be used by the agent in its reasoning or action
2. As external metalanguage to be used by the designer to specify, design and verify certain behavioural properties of agents situated in a dynamic environment.

Agent theory gives both an overview of the ways in which an agent is conceptualised and semantics to the architecture, language and tools.

An agent model is needed to develop a theory of agents.

7.1 Agents as intentional systems

Theorists start from the notion of an agent as an intentional system.

So, agent theorists start with the view of agents as intentional systems: where agent's behaviour is explained in terms of attitudes.

7.1.1 Attitudes

Attitude represents a summary evaluation of a psychological object (e.g. oneself, other people, issue, plan, behaviour).

Attitudes are formed throughout the interaction with the surrounding environment

Attitudes help to manage individual's cognitive resources to deal with uncertainties of complex dynamic domains,

Formally an attitude is the use of a folk psychology, by which human behaviour is predicted and explained through the attribution of attitudes.

The attitudes employed in such folk psychological descriptions are called the intentional notions.

An approach is to describe agent's behaviour in terms of intentional systems, "whose behaviour can be predicted by the method of attributing belief, desire and rational acumen".

There exist first-order, second-order ,..., intentional systems.

Is it useful to consider agents (similar to humans) as intentional systems?

- It is legitimate when it express the same information about the machine that it expresses about a person
- It is useful when it helps us understand the structure of the artifact
- It perhaps never logically required even for humans
- Ascription of mental qualities is most straightforward for machines of known structure but most useful for entities whose structure is incompletely known.

The following description of a light switch is not appropriate because of we essentially understand the mechanism sufficiently to have a simpler, mechanistic description of its behaviour:

"Light switch is perfectly coherent to treat a light as a (very cooperative) agent with the capability of transmitting current at will, who invariably transmits current when it believes that we want it transmitted and not otherwise; flicking the switch is simply our way of communicating our desires".

The more we know about a system the less we need to rely on intentional explanations of its behaviour.

An autonomous agent is a system that is most conveniently described by the intentional stance

7.1.2 Theories of Attitudes

We want to be able to design and build computer systems in terms of mentalistic notions.

Before we can do this, we need to identify a manageable subset of these attitudes and a model of how they interact to generate system behaviour. So first, which attitudes?

There exists 2 categories of attitudes:

1. **information attitudes:** such as belief and knowledge information attitudes
2. **Pro-attitudes:** such as desire, intention, obligation, commitment, choice... Pro-attitudes

7.1.3 Study of Knowledge

The study of knowledge tries to answer a series of open questions:

- What do we know?
- What can we know?
- What does it mean to say someone knows something?
- What does an agent need to know in order to perform an action?
- How does an agent know whether it knows enough to perform an action?
- At what point does an agent know enough to stop gathering information and make a decision?

The study of knowledge tries to answer these questions both from an individual perspective and a group perspective.

7.2 Foundation of formal logic

A formal logic is a game for producing symbolic objects according to given rules. The general syntax or alphabet of the formal logic includes the following notation:

- Variables (X, Y, \dots)
- Constants ($a, abc, 15, \dots$)
- Functors (f/n)
- Predicate symbols (p, q, \dots)

- Logical connectivities ($\neg, \vee, \wedge, \rightarrow, \iff$)
- Quantifiers (\forall, \exists)
- Auxiliary symbols

Given a term (T):

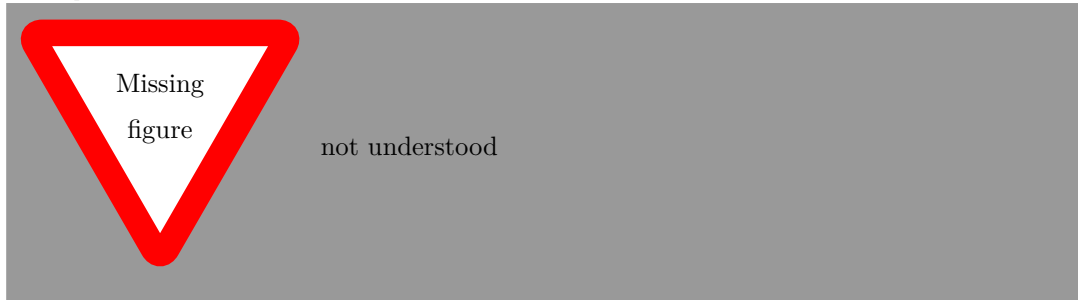
- Any constant in A is in T
- any variable in A is in T
- if f is an n -ary functor in A and $t_1, \dots, t_n \in T$ then $f(t_1, \dots, t_n) \in T$

Let T be the set of terms over alphabet A and F is the set of formulae:

- If p is an n -ary predicate symbol and $t_1, \dots, t_n \in T$ then $p(t_1, \dots, t_n) \in F$
- If H and $G \in F$ so are

$$\neg H \quad H \vee G \quad H \wedge G \quad H \rightarrow G \quad H \iff G$$

- If $H \in F$ and X is a variable then



Formulae of the form $p(t_1, \dots, t_n)$ are called atomic formulae/

Interpretation:

An interpretation T of alphabet A is a non-empty domain D and a mapping that associates:

- $c \in Const$ with an element $c_t \in D$ [$Const \subseteq A$]
- $f/n \in Func$ with an element $f_t : D_n \rightarrow D$ [$Func \subseteq A$]
- $p/m \in Pred$ with an element

$$p_T \subseteq D_m (= D \times \dots \times D) [Pred \subseteq A]$$

Under an interpretation, each term has a value and each atomic formula is either true or false.

Semantics of formulae:

- **Negation** Negation
 $\neg A$ is true if A is false
- **Conjunction** Conjunction
 $A \wedge B$ is true if both A and B are true
- **Disjunction** Disjunction
 $A \vee B$ is true if either A or B is true
- **Implication** Implication
 $A \rightarrow B$ is true if either $\neg A$ or B are true
- **Universal quantifier $\forall X$** Universal quantifier
 $A(x)$ is true if A is true for every X
- **Existential quantifier $\exists X$** Existential quantifier
 $A(x)$ is true if A is true for some X
- Propositional logic is the logic of connectives
- Adding quantifiers give first-order logic, sometimes called predicate calculus
- adding quantifiers over formula variables give Higher Order Logic

An interpretation T is a model of a set of formulae P iff every formulae of P is true in T :

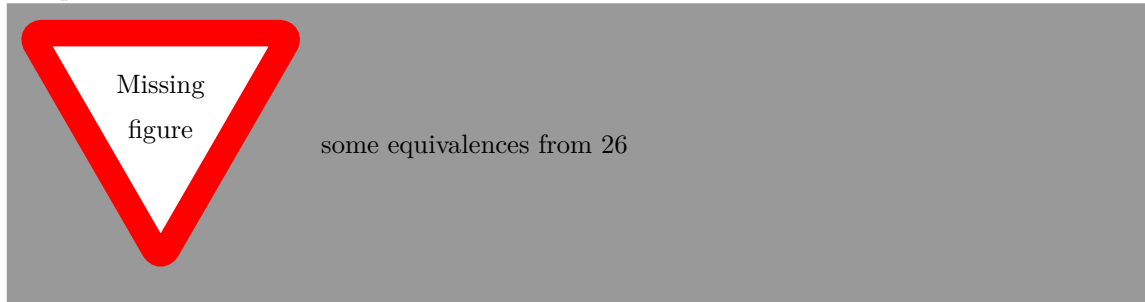
- every P has infinitely many interpretations
- Not every P has a model
- A set of formulae is unsatisfiable if it has no model
- A set of formulae is satisfiable if it has at least one model

Logical consequence:

Let P be a set of formulae. F is a logical consequence of P ($P \models F$) iff F is true in every model of P .

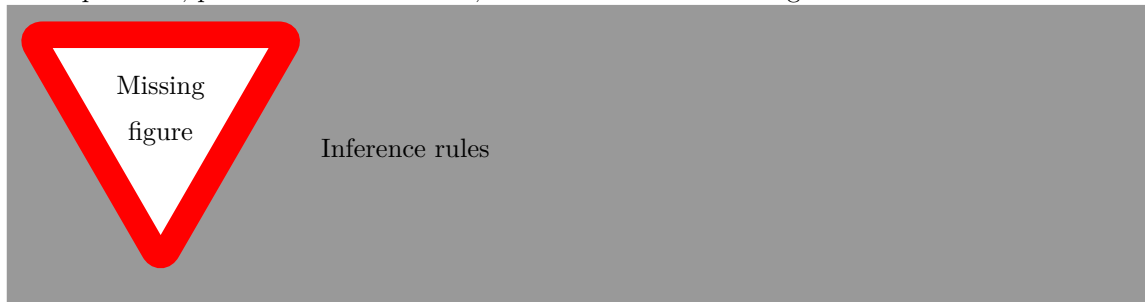
Logical equivalence:

F and G are logically equivalent ($F \equiv G$) iff F and G have the same truth value for every interpretation



7.2.1 Logical inference

Reasoning can be seen as a process of manipulation of formulae, which from a given set of formulae, called premises, produces a new formula, called the conclusion using inference rules



7.3 Formalising attitudes

Turns out that when we try to formalize attitudes or intentional systems, the application of formal logic makes them referentially opaque: hence standard substitution rules of first-order logic do not apply (intentional notions are not truth functional)

There are 2 sorts of problems to be addressed in developing a logical formalism for intentional notions:

1. Syntactic
2. Semantic

With respect to the syntactic problem, there are two fundamental approaches:

1. Use a modal language, which contains modal operators, which are applied to formulae
2. use a meta-language: a first-order language containing terms that denote formulae of some other object language

Likewise, two basic approaches to the semantic problem:

1. Possible worlds semantics
2. Interpreted symbol structures

Of the four combinations we will focus on the possible world semantics and modal logic

7.3.1 Possible worlds

The intuitive idea behind possible worlds is that besides the true states of affairs there are a number of states of affairs or “worlds”.

Each world represents one state of affairs.

Given his current information, an agent may not be able to tell which of a number of possible worlds describes the actual state of affairs. Consequently, an agent’s beliefs can be characterized as a set of possible worlds.

Moreover, the possible worlds approach can be represented using modal logic.

The main advantages of such approach is:

- Mathematical theory is appealing
- Neutral on the subject of the cognitive structure

Consider an agent playing a card game, who possessed the ace of spades. How could the agent deduce what cards were possessed by the opponents?

First, calculate all the various ways that the pack of cards could possibly have been distributed among the various players

Then, systematically eliminate all those configurations which are not possible given what the agent knows (any configuration in which the agent did not possess the ace of spades could be rejected).

Each configuration remaining after this is a world: a state of affairs considered possible given what the agent knows (aka epistemic alternatives).

We can notice that something true in all our agent’s possibilities is known by the agent.

7.3.2 Modal Logic

Possible worlds can be incorporated into the semantic framework of modal logic. In fact, modal logic was used by philosophers to investigate different modes of truth.

In the study of agents, it is used to give meaning to concepts such as belief and knowledge.

Modal logic can be considered as the logical theory of necessity and possibility.

It is essentially classical propositional logic extended by two operators:

- **Necessity** (\Box) Necessity
- **Possibility** (\Diamond) Possibility

Let $S = \{p, q, \dots\}$ be a set of atomic propositions

- If $p \in S$ then p is a formula
- If A, B are formulae, then so are $\neg A$ and $A \wedge B$
- if A is a formulae, then so are $\Box A$ and $\Diamond A$

other connectives can be expressed by abbreviation:

$$F \rightarrow G \equiv \neg F \vee G \quad \neg(F \wedge G) \equiv \neg F \vee \neg G$$

The duality of operators:

$$\Box A \equiv \neg \Diamond \neg A \quad \Diamond A \equiv \neg \Box \neg A$$

Two basic properties:

1. **K axiom schema** K axiom schema

$$\Box(A \rightarrow B) \rightarrow (\Box A \rightarrow \Box B)$$
2. **Necessitation rule**: if A is valid, then $\Box A$ is valid Necessitation rule

The semantics of modal logic is traditionally given in terms of possible worlds:

- The formula $\Box A$ is true if A is true in every world accessible from the current world
- The formula $\Diamond A$ is true if A is true in at least one world accessible from the current world

With sets of worlds as primitive, the structure of the model is captured by relating the different worlds via a binary accessibility relation

Formalizing possible worlds via Kripke structure:

$$(S, \pi, K_1, \dots, K_n$$

- S is the set of possible worlds
- π is the set of formulae true at a world
- K_i is a binary accessibility relation on S (a set of pairs of elements of S)



Possible properties of accessibility relations:

- **Reflexive** Reflexive
For all $s \in S$, we have $(s, s) \in K$
- **Symmetric** Symmetric
For all $s, t \in S$, we have $(s, t) \in K \iff (t, s) \in K$
- **Transitive** Transitive
For all $s, t, u \in S$, we have that if

$$(s, t) \in K \quad \wedge \quad (t, u) \in K \quad \text{then} \quad (s, u) \in K$$

- **Serial** Serial
For all $s \in S$ there is some t such that $(s, t) \in K$
- **Euclidean** Euclidean
For all $s, t, u \in S$ whenever

$$(s, t) \in K \quad \wedge \quad (s, u) \in K \quad \text{then} \quad (t, u) \in K$$

If K is reflexive and Euclidean, then K is symmetric and transitive

If K is symmetric and transitive, then K is Euclidean

The following are equivalent:

- K is reflexive, symmetric and transitive
- K is symmetric, transitive and serial
- K is reflexive and Euclidean

Properties of accessibility relation are represented by axiom schemas:

- **T axiom:** corresponds to reflexive accessibility relation T axiom
$$\Box A \rightarrow A$$
- **D axiom:** corresponds to serial accessibility relation D axiom
$$\Box A \rightarrow \Diamond A$$
- **4 axiom:** corresponds to transitive accessibility relation 4 axiom
$$\Box A \rightarrow \Box \Box A$$
- **5 axiom:** corresponds to Euclidean accessibility relation 5 axiom
$$\Diamond A \rightarrow \Box \Diamond A$$

7.4 Logic of Knowledge

The formula $\Box A$ is read “It is known that A” or “agent knows A” and denoted as K
For group knowledge we have an indexed set of modal operators:

$$K_1, \dots, K_n \quad \text{for } \Box$$

In this frame of reference $K_1 A$ is read as “agent1 knows A”

As a consequence we can interpret the 4 axiom of accessibility relation:

- T axiom (Knowledge axiom) $K_i A \rightarrow A$
“what is known is true”
- D axiom $K_i A \rightarrow \neg K_i \neg A$
“If agent i knows A then agent i does not know $\neg A$ ”
- 4 axiom (positive introspection) $K_i A \rightarrow K_i K_i A$
“If agent i knows A then agents i knows that it knows A”
- 5 axiom (negative introspection) $\neg K_i \neg A \rightarrow K_i \neg K_i \neg A$
“agent i is aware of what it does not know”

Knowledge is often defined as true belief, i.e. an agent knows A if the agent believes A and A is true.

Axioms KTD45 are often chosen as a logic of knowledge

Axioms KD45 are often chosen as a logic of belief

How well does normal modal logic serves as a logic of knowledge and belief?

Consider the K axiom and the necessitation rule:

- Necessitation rule: an agent knows all valid formulae (an agent will have an infinite number of items of knowledge)
If A is valid, then $\Box A$ is valid
- K axiom: agent’s knowledge is closed under implication

$$\Box(A \rightarrow B) \rightarrow (\Box A \rightarrow \Box B)$$

- **Logical omniscience:** knowing all truth of logic
- **Logical omniscience problem:** constituted by that of knowin all valid formulae and that of knowledge/belief being closed under consequence (must know all logical consequences of one’s knowledge or belief)
- Disadvantages of using possible world semantics for agents are:
 - Agents believe/know all valid formulae
 - Agents’ beliefs/knowledge are closed under logical consequence

Logical
omniscience

Logical
omniscience
problem

Other approaches:

1. Levesque

In order to avoid logical omniscience problem a distinction is made between explicit and implicit belief

Levesque

2. Konolige

Deduction model of belief

The deduction model defines a belief system as a tuple

Konolige

$$d = (\Delta, \rho)$$

containing a base set of formulae in some internal, logical language of belief and a set of deduction rules (may be incomplete) for deriving new beliefs

Agent with such a belief system believe A if A can be derived from its base set using its deduction rules

7.5 BDI architecture

Systems and formalisms that give primary importance to intentions are often referred to as **BDI architecture**

Formalization of intentions based on branching-time possible worlds future and single past model

Crucial elements are :

- Intentions are treated on a pair with beliefs and goals
- Distinguishes between choices and the possibilities of the different outcomes of actions
- Interrelationship between belief, goals and intentions are specified (goals are consistent desires of an agent)

Informal semantics:

- The world is modeled by using a temporal structure with a branching time future and a single past, this is called a **time tree**
- A particular time point in a particular world is a **situation**
- Event types transform one time point to another
- Primitive events are those events directly performable by the agent and uniquely determine the next time point
- The branches in a time tree represent the choices available to an agent

Uses 2 modal operators:

- **Optional**: a path formula is said to be optional if, at a particular time point in a time tree, it is true of at least one path emanating from the point
- **Inevitable**: a path formula is said to be inevitable if it true of all paths emanating from that point

Temporal operators: next eventually always, until

A combination of these modalities can be used to describe the options available to an agent



Formal definitions:

1. **Beliefs**
In each situation a set of belief-accessible worlds is associated. Those worlds that the agent believes to be possible.
Each belief-accessible world is a time-tree
2. **Goals/Desires**
For each situation a set of goal-accessible worlds is associated. Those represent the goals of the agent.
Goals are chosen desires of the agent that are consistent and agent should believe that the goal is achievable; goals must be compatible with beliefs.
For each belief-accessible world w in time t , there must be a goal accessible sub-worlds of w at time t
3. **Intentions**
Intentions are represented by a set of intention-accessible worlds
These worlds are ones that an agent has committed to attempt to realize

The intention-accessible worlds of an agent must be compatible with its goal-accessible worlds
For each goal-accessible world w in time t , there must be an intention accessible sub world of w at time t



Chapter 8

Agent Architecture

8.1	Abstract agent architectures	82
8.2	Deliberative Architectures	82
8.2.1	BDI	82
8.2.2	PRS	82
8.2.3	IRMA	82
8.3	Reactive Architectures	82
8.3.1	Brook's subsumption Architecture	82
8.3.2	Steel's Mars Explorer	82
8.4	Hybrid Architectures	82
8.4.1	Touring Machine	82
8.4.2	InteRRaP	82
8.5	Discussion	82

We want to build agents that enjoy the properties of autonomy, reactivity, proactivity and social ability.

How do we construct computer systems that satisfy properties specified by agent theorists?

The area of agent architecture.

Originally (1956-1985), all agents designed within AI were symbolic reasoning agents: agents use explicit reasoning in order to decide what to do.

Problems with symbolic reasoning led to a reaction against this, the so-called reactive agents movement (1985 onwards).

From 1990-present, a number of alternatives was proposed: hybrid architectures, which attempt to combine the best of reasoning and reactive architectures.

8.1 Abstract agent architectures

Assume the environment may be in any of a finite set E of discrete, instantaneous states:

$$E = \{e_1, e_2, \dots\}$$

Agents are assumed to have a repertoire of possible actions available to them, which transform the state of the environment

$$A = \{a_1, a_2, \dots\}$$

The interaction of agents and environment can be represented as a history (run):



Two important points:

1. Environments are assumed to be history dependent, i.e. the next state of an environment may not solely be determined by the action performed by the agent and the current state of the environment
2. Possible non-determinism in the environment, i.e. there is uncertainty about the result of performing an action in some state

The non-deterministic behaviour of an environment can be modeled as a state transformer function

$$\tau : r(\text{ended with } a) \rightarrow \rho(E)$$

which takes a run and maps it to a set of environment states $\tau(r)$ those that could result from performing action a in state e .

it is said to be:

- non-deterministic if

$$\rho(E) = \{e_x, e_y\}$$

- deterministic if

$$\rho(E) = \{e_x\}$$

Agents can be viewed as a function:

$$Ag : r(\text{ended with } e) \rightarrow A$$

The characteristic behaviour of an agent in an environment is the set of all runs.

$R(Ag, Env)$ is the set of all histories/runs of agent in environment ($Env = \{E, e_0, \tau\}$).

If some property holds of all these histories, this property can be regarded as an invariant property of the agent in the environment.

Two agents are behaviourally equivalent wrt to environment Env if and only if

$$R(Ag1, Env) = R(Ag2, Env)$$

Two agents are simply behaviourally equivalent iff they are behaviorally equivalent wrt to all environment. Certain types of agents decide what to do without reference to their history: decision making based entirely on the present.

They are agents without internal states.

Behaviour of purely reactive agents can be represented as a function:

$$Ag : E \rightarrow A$$

A thermostat is a purely reactive agent.

The see function is the agent's ability to observe its environment.

The action function represents an agent's decision making process

The output of a see function is a percept:

$$see : E \rightarrow Per$$

which maps environment states to percepts and action is now a function

$$action : Per \rightarrow A$$

which maps sequences of percepts to actions. An agent has a perfect perception if it can distinguish every environment state.

The agents have some internal data structure, which is typically used to record information about the environment state and history.

let I be the set of all internal states of the agent.

Perception function is unchanged

The action-selection function $action$ is now defined as a mapping from internal states to actions:

$$action : I \rightarrow A$$

A new function $next$ maps an internal state and percept to an internal state

$$next : I \times Per \rightarrow I$$

Behaviour of an agent:

1. Starts in initial state $i = i_0$
2. Observes its environment state e and generates a percept $see(e)$
3. The internal state of the agent is then updated via the next function

$$next(i, see(e))$$

4. The action selected by the agent is then

$$action(next(i, see(e)))$$

5. The action is performed and the agent enters a new cycle (i.e. goes to 2)

```
1 function action( $\Delta$ : D) : A
2 begin
3   for each a in A do
4     if  $\Delta \models Do(a)$  then
5       return a
6     end if
7   end for
8   for each a in A do
9     if  $\Delta \models \neg Do(a)$  then
10      return a
11    end if
12  end for
13  return null
14 end function action
```

8.2 Deliberative Architectures

8.2.1 BDI

8.2.2 PRS

8.2.3 IRMA

8.3 Reactive Architectures

8.3.1 Brook's subsumption Architecture

8.3.2 Steel's Mars Explorer

8.4 Hybrid Architectures

8.4.1 Touring Machine

8.4.2 InteRRaP

8.5 Discussion

Chapter 9

Mobile Agents

9.1 Remote Procedure Calls vs Mobile Agents	83
9.1.1 Remote Procedure Calls	83
9.1.2 Remote execution	84
9.1.3 Advantages of RE over RPC	84
9.2 Mobile Agent Environment	85
9.3 Issues with Mobile agents	85
9.3.1 Security	86
Delegation	86
Viruses	86
Security for hosts	86
Security for Agents	87
9.4 Requirements for Mobile Agents	87

Mobile agents

Mobile agents are agents that are capable of transmitting themselves, their program and their state, across a computer network, and recommencing execution at a remote site.

The program in this way can choose when and where to migrate, therefore suspending its execution at an arbitrary point and transport itself to another machine where it would resume execution.

The original motivation behind mobile agents is fairly simple: the idea was that mobile agents would replace remote procedure call as a way for processes to communicate over a network.

9.1 Remote Procedure Calls vs Mobile Agents

9.1.1 Remote Procedure Calls

With remote procedure calls the idea is that one process can invoke a procedure (method) on another process which is remotely located.

Suppose one process A invokes a method m on process B with arguments $args$; the value returned by process B is to be assigned to a variable v . This mechanism can be summarized with the notation:

$$v = B.m(args)$$

Crucially, in remote procedure calls, communication is **synchronous**, i.e. process A blocks from the time it starts executing the instruction until the time that B returns a value. If B never returns a value, because the network fails, then A may remain indefinitely suspended, waiting for a reply that will never come.

synchronous

The network connection between A and B may well also remain open, and even though it is largely unused (no data is being sent for most of the time), this may be costly.

In other terms, remote procedure calls enable one computer to call procedures in another. In order to do so however, the two computers must agree in advance upon a protocol: the effects of each remotely accessible procedure and the types of its arguments and results.

Each interaction entails two acts of communication: request and acknowledge, which, consequently, means that the ongoing interaction requires ongoing remote communication.

The overall general architecture is depicted in the following figure:



9.1.2 Remote execution

The idea of mobile agents is to replace the remote procedure call by sending out an agent to do the computation. Thus instead of invoking a method:

1. Process *A* sends out a program/a mobile agent to process *B*.
2. the program then interacts with process *B*
3. Since the agent shares the same address space as *B*, these interactions can be carried out much more efficiently than if the same interactions were carried out over a network.
4. When the agent has completed its interactions, it returns to *A* with the required result.

During the entire operation, the only network time required is that to send the agent to *B*, and that required to return the agent to *A* when it has completed its task.

This is potentially a much more efficient use of network resources than the remote procedure call alternative.

One computer not only calls procedures on another computer, but also provides the procedures. Hence each exchanged message contains the procedure and its arguments.

The two computers agree in advance upon a language, i.e. instructions and the types of data that are allowed.

A user agent and a server can interact without using the network once the agent is transported which means that the ongoing interaction does not require ongoing remote communication.

In the frame of reference of remote executing a mobile agent is a program that can migrate from machine to machine in a heterogeneous network. Moreover, the program is able to choose when and where to migrate and in doing so it will suspend its execution at an arbitrary point, transport itself to another machine and resume execution.

The distinction at the core between pure mobile agents and remote execution is that:

1. A program which is sent without execution state to remote CPU executes there, possibly communicating with other CPUs and then terminates (remote execution)
2. A program which carries execution state with it and is sent to a remote CPU executes there possibly communicating with other CPUs and then moves again to a third CPU or return to its origin (mobile agent)

9.1.3 Advantages of RE over RPC

We can distinguish two main classes of advantages of remote execution over remote procedure calls:

1. Tactical:

- **Performance:** due to less message passing over the network

Tactical

Performance

- **Less connection time:** need network connection only to transport the agent

Less connection
time
Strategic

2. Strategic:

- **Customization:** agents let manufacturers of client sw extend the functionalities of the server sw.
- In a RPC application, the server component needs to be statically installed by the user. In RE, they are dynamically installed by the application itself which is an agent.
- The use of new RPC-based applications must be a decision that has to be taken by the providers.
The use of new RE-based applications must be a decision that has to be taken by the user.
- A public network becomes like a platform

Customization

9.2 Mobile Agent Environment

A mobile agent environment is a software system which is distributed over a network of heterogeneous computers. Its primary task is to provide an environment in which mobile agents can execute. It implements the majority of models which appear in the mobile agent definition.

A mobile agent environment is responsible to:

- Support services related to the mobile agent environment itself
- Support services pertaining to the environments on which the mobile agent environment is built
- Provide services to support access to other mobile agent systems
- Provide support for openness when accessing non-agent-based software environments

9.3 Issues with Mobile agents

There are a number of technical issues that arise when considering mobile agents:

- **Serialization**, how is the agent serialized (i.e. encoded in a form suitable to be sent across the network), and, in particular, what aspects of the agent are serialized, the program, the data, or the program and its data? Serialization
- **Hosting and remote execution**, what the agent arrives at its destination, how is it executed, for example if the original host of the agent employs a different operating system or processor from the destination host? Hosting and remote execution
- **Security**, when the agent from A is sent to the computer that hosts process B, there is obvious potential from the agent to cause trouble. It could potentially do this in a number of ways: Security
 - It might obtain sensitive information by reading filestore or RAM directly
 - It might deny service to other processes on the host machine, by either occupying too much of the available processing resource (processor cycles or memory) or else by causing the host machine to malfunction (e.g. writing over the machine's RAM)
 - It might simply cause irritation and annoyance, for example by causing windows to pop up on the user's GUI

Many different answers have been developed to address these issues.

With respect to the first issue, that of how to serialize and transmit an agent there are several possibilities:

- Both the agent and its state are transmitted and the state includes the program counter. In this way, the agent "remembers" where it was before it was transmitted across the network, and when it reaches its destination, it recommences execution at the program instruction following that which caused it to be transmitted

- The agent contains both a program and the values of variables, but not the program counter, so the agent can remember the values of all variables, but not where it was when it transmitted itself across the network.
- The agent to be transmitted is essentially a script, without any associated state (although state might be downloaded from the original host once the agent has arrived at its destination).

9.3.1 Security

The issue of security dominates discussions about mobile agents, in fact we can say that security is a significant concern with mobile agent-based computing.

The key difficulty is that, in order for an agent to be able to do anything useful when it arrives at a remote location, it must access and make use of the resources supplied by the remote host. However, providing access to these resources is inherently dangerous: it lays open the possibility that the host will be abused in some way.

Some general issues in using agents are:

- | | |
|---|------------|
| • Delegation: you are delegating to the agent some of your authority. This means that agents are doing things that you cannot always see. | Delegation |
| • Mobility: they may be doing it on the other side of the planet. Or, an agent from the other side of the planet may be doing it on your server | Mobility |
| • Viruses: mobile agents share many characteristics with viruses. In creating an environment for agents, there is the additional risk that we expose weaknesses that may enable viruses to breed | Viruses |
| • Trust: humans have classified their co-workers into those who are reliable and those who are not. | Trust |

Delegation

The purpose of an agent is to perform some tasks that would otherwise be performed by its user. The agent may need many, if not all, of the access rights of the user.

In a security environment, this can be readily achieved by passing the copy of the user's certificate to the agent.

In this regard, the agent is indistinguishable from any other applications employed by the user.

The certificates are valid for a finite period, defined by the security administrators.

Performing the full delegation is not a big problem. However, a problem is to limit delegated authority.

An agent is more flexible and unpredictable than a traditional application.

Viruses

It is impossible, in principle, to verify with complete certainty if an arbitrary program is a virus or not.

In practice, the problem of writing a program that can verify the correct behaviour of another program is unsolved.

It is difficult to define the necessary and sufficient tests that an agent must pass in order to determine its intentions.

Some precautions that can be enforced are:

- restriction of access to critical resources
- restriction on altering other programs

Security for hosts

In order to enforce security of hosts, the designer needs to design a system that:

- | | |
|--|----------------------|
| • Limits delegation.
In other terms give the agent and the user separate identities.
A way to enforce this limitation is via Secure co-processors: have a physically separate processor on which the agent runs execute the agent in a padded cell. | Limits
delegation |
|--|----------------------|

As a result, the approach allows the agent to interact with the system environment only in a language with limited system level expressiveness

- **Limits resource consumption.**

In particular, enforcing a limit on the amount of each resource that an agent is permitted to consume or a limit on the amount of budget/CPU time an agent can access.

Limits resource
consumption

Security for Agents

On the contrary we need to protect mobile agents from malicious hosts because:

- agents have a right to privacy
- We often do not want to send our programs to a remote host, as to do so might enable the recipient to determine, its purpose and hence our intent
- the agent might be modified (sabotaged) in some way, without the owner's knowledge or approval

In practice, however, the current consensus is that it is computationally impossible to protect a mobile agent from malicious host.

In fact:

- the use of authentication of the executing server is easy to implement for a single host but quickly becomes difficult for multiple dynamic hosts
- enforcing agent privacy would require its execution in a highly trusted environment, which consequently would require encapsulating all methods and data and high protection in a Multi agent environment

Still there are some possibilities for protection:

- **Data integrity**
an agent can be protected in transit by using conventional encryption techniques
- **Origin authentication**
certification
- **Access itinerary control**
restriction on visiting some environments
- **Privacy and integrity of gathered information**
via stateless gathering or stateful gathering

Data integrity

Origin
authentication

Access itinerary
control

Privacy and
integrity
of gathered
information

9.4 Requirements for Mobile Agents

From the previous sections we can conclude that the general requirements to mobile agent environments are:

- Expressiveness as a programming language
- ability to execute remotely or to transport state
- Support for agent communication language
- Security support
- Management support

Bibliography

- [1] Michael Wooldridge. *An introduction to multiagent systems*. John wiley & sons, 2009.