Elisa Burato

Meaning Negotiation in Multiple Agent System: an Automated Reasoning Approach

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Università degli Studi di Verona
Dipartimento di Informatica

Advisor:
prof. Matteo Cristani

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Università di Verona
Dipartimento di Informatica
Strada le Grazie 15, 37134 Verona
Italy

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Abstract Meaning Negotiation is the process by which two or more than two agents discuss about the meaning of a set of terms in order to find an agreement about it. Meaning Negotiation begins with inconsistent viewpoints of the agents.

This mechanism of reaching an agreement is important in automating intelligent systems that behave on behalf of humans (e-Commerce, e-Learning, Finders, etc.). Meaning Negotiation was widely studied by the Artificial Intelligence community but, to the best of my knowledge, there are no formalisms modelling the Meaning Negotiation that are independently of the number of participants and of their expression language. Moreover, the current approaches deal with Meaning Negotiation as a process in which the issue is “quantitative”, i.e. it can be divided, increased or decreased numerically. The issue of Meaning Negotiation is *knowledge*, thus it is straightforward to model its negotiation since it is not immediately evident how to divide, to increase and to decrease *knowledge*.

In this thesis, I make a survey of the current Meaning Negotiation approaches and formalise it in a game theoretic perspective to model the interaction protocol, and in a deductive manner to represent the reasoning mechanism of agents. Moreover, I assume and formalise the strategical behaviour of negotiation’s participants in Defeasible Logic.

This pathway brings to a comprehensive formalism, that, within he game theoretic endeavour, describes the process, the behaviour of the agents, their goals, and the governing mechanism of Meaning Negotiation in a compact fashion.

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Introduction

1.1 Motivation

In recent years it has become clear that computer systems do not work in isolation. Rather, computer systems are increasingly acting as elements in a complex, distributed community of people and systems. In order to fulfill their tasks, computer systems must cooperate and coordinate their activities and communicate with other systems and with people. This phenomenon has been emphasized by the huge growth and success of the Internet. However, cooperation and coordination are needed almost everywhere computers are used. Few examples include health institutions, electricity networks, electronic commerce, robotic systems, digital libraries, military units etc.

Cooperation and coordination are required whenever complex problems have to be solved and they are irresolvable for a single system. Furthermore, there are heterogeneous intelligent systems that were built in isolation, and their cooperation may be necessary to achieve a new common goal.

An obvious problem, related to the issue of cooperation, is that *reaching agreements* and *sharing information* in a society of self-interested agents. In the multi-agent world we all inhabit every day, we are regularly required to interact with other individuals with whom we do not share common goals.

Problems of coordination and cooperation are not unique to automated systems. They exist at multiple levels of activity in a wide range of populations. People achieve their own goals through communication and cooperation with other people or machines. The main difficulty in agent cooperation and communication, is to understand each other. People and, in general, *intelligent agents* come from different organisations and individuals and thus they have different backgrounds and, maybe, different expression languages. Conflicts, i.e. litigations, misunderstandings, inconsistent viewpoints etc., between such agents frequently arise and the reason is above all due to the human factor in the engineering of the agents.

Intelligent agents are developed for a wide number of reasons and applications, that is in all the situations in which people can delegate their interests to somebody else. In fact the word *intelligent* refers to the ability to behave, to reason and to perceive situations and the environment the agents are in as humans do. Some of the applications of the intelligent agents ares:

Informational retrieval and management : the widespread provision of distributed, semi-structured information resources as the World Wide Web presents enormous potential, but it also presents a numbers of difficulties as information overload. An information agent is able to enter all the information, to manipulate them and to build a complete and not redundant answer to external request. Examples of information agents are [63]:

Web agents for tour guide : they help users in answering the question "Where do I go next?" when searching the web. These agents can learn about the preferences of the user and adjust the information retrieved;

Indexing agents : they organise information retrieved by search engines as Google, Yahoo, etc. with respect to the preferences the user expresses;

FAQ-finders : the idea is to use direct users to "Frequently Asked Questions" documents in order to answer specific questions. Since FAQs tend to be knowledge-intensive, structured documents, there are a lot of potential automated FAQ finders;

Expertise finders : they help users to find information about a given topic by first of all understanding the intended meaning and models of the information the user is looking for.

Electronic Commerce : the boom in interest in the Internet throughout the 1990s went with the explosion of interest in electronic commerce. The first generation e-commerce systems allowed a user to browse a catalogue, to find the item she wants and to buy it using a credit card. The second generation systems, many aspects of the buyer's behaviour are automated: the user informs the system about the item she is looking for and it behaves by acting as the part of the user. The steps those systems have to pass through in an e-Commerce scenario are [126]:

- Need identification;
- Product brokering;
- Merchant brokering;
- Negotiation;
- Purchase and delivery;
- Product service and evaluation.

Examples of automated e-Commerce systems are: *Bargain Finder*, *Jango*, *KasBah*, *Auction Bot* and *Têtê-à-Têtê*[1].

e-Learning : Early E-Learning systems, based on Computer-Based Learning/ Training often attempted to replicate autocratic teaching styles whereby the role of the e-learning system was assumed to be for transferring knowledge, as opposed to systems developed later based on Computer Supported Collaborative Learning (CSCL), which encouraged the shared development of knowledge [90]. Two of the collaborative learning systems are *ANGEL* [1] and *Coffee* [4].

Legal Reasoning : Systems supporting legal reasoning help the user to construct the closing argument to the jury in order to prevent attacks and to foresee the possible objections. The legal reasoning systems have a diagrammatic interface which facilitates the reasoning mapping and the development of the legal

[1] Some of these e-Commerce systems are web application and other are web sites

debate. Examples of legal system supporters are *Araucaria* [2] and *Carneades* [3].

In all the applications of intelligent agents, a basic mechanism of agreement is required: information agent, electronic commerce agent, e-learning systems and legal reasoning have to know the meaning of all the information they receive from the user. In all the situations in which a misunderstanding arises, the system does not work as the user's expectations and it produces negative or wrong outcomes.

Negotiation is one of the main mechanisms for reaching an agreement among entities, i.e. computer systems or humans or a mix of them.

1.2 Meaning Negotiation Problem

Negotiation is a common activity in daily life. It consists in reaching an agreement about something when the negotiators begin the discussion starting from different viewpoints about the sharing object. In particular, *Meaning Negotiation* is a negotiation process in which the sharing object is the meaning of a set of terms. To negotiate the meaning of a set of terms means to propose definitions, properties, typical memberships of the terms' definitions, and/or to accept or to reject definitions.

The participants may disagree in many ways:

- The properties used to define are inconsistent and contradictory;
- The relevant properties for an agent are more/less than those expressed by another agent or different ones;
- Some agents do not know the properties used by someone in the multiple agent system.

In each of the above disagreement situations, the participants behave as they think is good. For instance in the last two cases, one agent may ask to the others to use only a set of properties to define the negotiated terms.

Differently from quantitative negotiations, in meaning negotiation the proposals are pieces of knowledge, i.e. the expressions of what an agent knows about the negotiated terms, and they may be accepted or rejected.

The negotiation activities take place when there is a tension between the desire to reach an agreement and the ambition to preserve the most of the viewpoint they started the negotiation with. This situation is naturally solved by humans by means of many different rational behaviors, that are coded in the notion of strategy. Strategies implement tensions in a double sided way. From one side, an agent tends to cease to the other agent, encouraging the counterpart to look for a solution together. From the other side, she tends to persuade the counterpart that the right viewpoint is hers, not the counterparts one. Therefore an argument that supports a viewpoint is presented both as a defending position (I am right) and as a conceding step (You may be right).

In more complicated scenarios, when more than just two parties are involved, negotiation with a mediator takes place when an agent claims to be able to provide a synthesis of the viewpoints of the others, and they believe her. In this situation the mediator assumes a tension between the viewpoint she has, and the viewpoints of the other agents involved. In other terms, the strategy is a tension between the position of the mediator (I am right) and the viewpoints of the other agents (You may all be right). Conversely, the agents play in tension between the position of defense (I am right) and the conceding position (Someone else can be right).

The problem of the Meaning Negotiation was largely studied by Artificial Intelligent community and the approaches depend upon

- The number of the involved agents;
- The communication language;

The current formalisation of the MN are for particular configurations of the system. For instance, Argumentation Theory (Arg) and Game Theory (GT) scholars only deal with the MN in a bilateral configuration.

Moreover, an important aspect of MN is the strategical behaviour of the involved agents. The goal of each involved agent is to share knowledge, i.e. the meaning of a set of terms, with the opponents, but the agents differently hope to reach such an agreement. As in real life, people may be agreeable or not, the same for the negotiating agents. I name this feature of agents, the attitude. The choice of proposals and actions of agents depends upon their attitudes: the strategical behaviour is in this sense an implementation of the agent's attitude. Only few approaches to MN consider the participants as entities evaluating feasible action with respect a set of relevant criteria, as the Context Based Reasoning (CBR) and the Belief Merging with Updating (BMU).

Figure 1.1 depicts a graphical representation of the collocation of the formalism proposed in this thesis, named Automated Reasoning Negotiation.

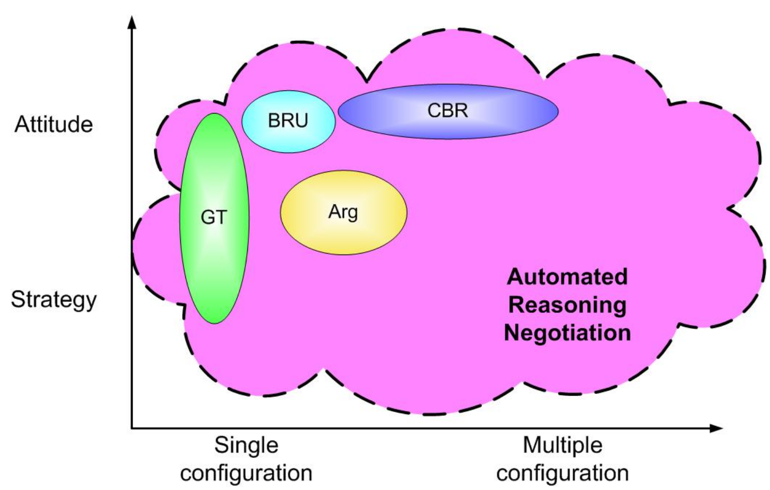


Figure 1.1. The research space of the Artificial Intelligence areas dealing with Meaning Negotiation.

The problem this thesis deals with is to find a model to formalise the Meaning Negotiation in which there is no assumption about the number and roles of the involved agents. Moreover, in this thesis I do not want to make constraints upon the languages of the agents.

The central question of the thesis is

> "Does a general model for the Meaning Negotiation problem exist in which the number of the participating agents is not fixed and no assumption about roles and reciprocal position is established in front of the Meaning Negotiation beginning? Is it possible for agents to express themselves in a not unified way?"

This question produces some sub-questions:

1. "What is a negotiating agent? Which are the features defining it?"
   The definition of an agent involved in a Meaning Negotiation is the first point to focus upon. In the Meaning Negotiation the agents negotiate their knowledge about the subject of the negotiation. They are identified by their knowledge and it is an active and fundamental part of the negotiation. The agents have to be able to manage their knowledge in order to make proposal to the opponents.

2. "Which are the feasible actions of a negotiating agent? How does an agent choose the next action to perform?"
   The agents negotiate knowledge then they make proposals about it. The proposal have to change over time otherwise the negotiation is a stable process and possibly infinite when the initial proposals of the agents do not produce an agreement. The changing of the proposals of the agents have to be in some relation with the initial one and agents have to be able to manage their knowledge in order to find them.

3. "When are the negotiating agents in agreement? How do they may been in disagreement?"
   The Meaning Negotiation may end in two ways: the agents share a knowledge or not. The identification of the ending condition depends upon the definition of agents and in particular upon what they propose and know during the negotiation. The important point is who controls the process and how it states that the process is ending, both positively or negatively.

4. "Does an agent have a strategy in Meaning Negotiation?"
   In the literature about negotiation, in particular the Game Theory literature, the participants choose the next proposal consistently with their strategy. They have an utility function giving a value to each proposal. The strategy consists of choosing the proposal that have the maximum utility value. In Meaning Negotiation is not so clear the definition of utility function, i.e. when an agent has to prefer one proposal with respect to the other one. The qualitative nature of the subject of the Meaning Negotiation makes it more difficult than in a quantitative subject negotiation. The definition of agent's strategy seems to be linked to the relationship between the received offer and the last made proposal because it gives to the agent a "measure" about the closeness between the two and thus how much the opponent conceded. Moreover, a social

component is relevant in the choose of the next proposal: the reputation of the opponents and the willingness to cooperate with others. If an opponent has an high reputation, probably all proposal she makes will be accepted. Conversely, an agent having no predisposition to cooperate in the multiple agent system, will not accept the received proposals.

5. "What does an agent know about the other agents in negotiation?"
   The amount of knowledge of an agent about the opponents may change the result of the negotiation. If Alice knows the opinion of Bob about the subject of the Meaning Negotiation and which is the part that he will concede, then Alice also knows which will be the result of the negotiation and how to reach it. Nevertheless, if Alice does not know the proposal of Bob, then she does not recognise when they are in agreement or not and it is impossible for her to choose the next proposal coherently with the negotiation development. To understand how much Alice knows about Bob and how it may change and unbalance the negotiation process is one of the main point in the formalisation of the Meaning Negotiation process.

6. "Can an agent behave in a fraudulent way? When? Are the agents allowed to make coalitions among them?"
   The fraudulent behaviour are defined in literature as a set of actions that do not respect some moral and social laws even if they comply with the communication protocol, i.e. with the set of rules for the interaction between agents. It is not clear which are the social and moral rules in a Meaning Negotiation context and if a fraudulent behaviour may exist. However, the negotiating agents live in a group of agents and the investigation about the social and moral behaviour makes sense.

1.3 Methodology

The approach I follow is incremental. I initially focus upon the definition of the agent: the representation of the knowledge of the agent and the actions she may perform. I assume that an agent always has an opinion about the subject of the negotiation. This assumption is important in the formalisation of the Meaning Negotiation because without it the agents may be submissive and then not an active part of the negotiation. In fact an agent with no opinion about the subject of the negotiation will accept every proposal she receives. With this assumption I do not want to superimpose that an agent is strongly committed to her beliefs otherwise she is not-negotiating in an inverse way: she never concedes during the negotiation and never accepts a proposal different from her one.

The first step of modeling the Meaning Negotiation as a process is to find a way to represent the interaction between only two agents. I choose the game of Bargaining because it is the simplest game in which there are only two players that have to discuss about how to split one dollar. In the Bargaining game the agents play by making proposals and evaluating the received offers. Following this game, I study how the agents reason during the negotiation: how they evaluate the received offer and how they build the next proposal to perform. The result of this study is a deduction system.

An important step in the formalisation of the Meaning Negotiation is the definition of the agreement and disagreement between agents, that is when the Meaning Negotiation process is considered positively ending and when negatively. The result of the Meaning Negotiation is a shared viewpoint about the subject of the negotiation then the agreement is reached when agents propose the same thing or, more generally, one agent accepts the offer received from someone else. Conversely the agents are disagreement. However, in real life people disagree in many ways: sometimes Alice says the opposite thing of Bob and sometimes she says something different from Bob but not opposite. For this reason, I investigate the different degrees of disagreement between agents because they may be informative for the participants. In fact, the situation in which Alice is saying something in contradiction with Bob's proposal is more far away from the agreement than the situation in which the two agents have different but not contradictory proposal. The two situations are informative in this sense, because the disagreement situation inform agents about the reason of their conflict.

Finally, I complete the modelisation of the Meaning Negotiation problem by adding the strategical component in the behaviour of the agents. I do this by studying the attitude of the agents when they are part of a Multiple agent system and involved in a negotiation. I investigate to find a way to formalise the choice of the next proposal in a strategical way that depends upon the attitude of the agent.

I extend the model to the Meaning Negotiation in which more than two agents are involved. The approach is the same that of bilateral negotiation: find the game, build the deduction system and formalise the strategical behaviour of the agents.

In this thesis I do not focus upon the last question about the fraudulent behaviour of an agent in a Meaning Negotiation because it is left for future work.

1.4 Structure of the thesis

- Chapter 2 presents the basic notions underlying the definition of the *Meaning Negotiation* problem. In particular in Section 2.2 I show the features of the negotiation participants by stressing the main features that are fundamental to negotiate, i.e. how their knowledge is, which are the proposals they make. In Section 2.3 I define a set of negotiating agents as a multiple agent system and I focus upon the way they communicate to each other, how they behave in such a agents' society and I define the different ways in which the participants can be in conflict.
- Chapter 3 presents the Meaning Negotiation processes as games belonging to the Game Theory literature by distinguishing the case of bilateral negotiation (Section 3.3) and of a more then two agents one (Section 3.4). I provide the algorithms for both the games and I prove they are correct and complete.
- Chapter 4 formalises a deductive system, which I call MND, to reason about the MN process. The deductive system has two types of rules: a set of deductive rules for each participating agent and a set of rules for the monitoring system. I prove that the rules are consistent and adequate.

- Chapter 5 formalises the strategies of agent by means of Defeasible Theory of an agent depending upon her attitude when involved in a multiple agent system. I first define the possible attitudes of negotiating agent in Section 5.2; after I formalise the strategy defeasible theory for a negotiating agent in Section 5.3.2 and next for the auctioneer as an extension of the previous one in Section 5.3.2.
- Chapter 6 presents the main contributions of the Artificial Intelligence scholars to the solution of the problem of the Meaning Negotiation and to all the formalisms on which it is based. In particular, I present how the knowledge of the agents has been modeled (Section 6.2), I discuss about the current literature of the Meaning Negotiation process (Section 6.3) and finally a presentation of the strategic agent formalisations is in Section 6.4.

Every further chapter is opened by a first section used to introduce the material and contents of the chapter itself. In Chapters 2, 3 and 4 I introduce the specific sections with a general introduction to the theme. In Chapters 5 and 6 the introduction section is employed to provide a reading scheme for the rest of each chapter and to provide basic definitions and issues related to the contents of the chapters.

2

Agents, Beliefs and Attitudes in Multiple-agent Systems

2.1 Introduction

In this chapter, I present the basic notions underlying the definition of the *Meaning Negotiation* problem. Generally, a *negotiation* is described as a dialog (i.e., a conversation between two or more entities) intended to resolve disputes, to produce an agreement upon courses of action, to bargain for individual or collective advantage, or to craft outcomes to satisfy various interests. *Meaning negotiation* (MN) is the process that takes place when the involved agents have some knowledge (some data or information) to share but do not agree on how the sharing has to be. There are many ways in which people are in conflict: the situation in which people disagree only about marginal things is different to the situation in which they are in conflict in a total way. The participants negotiate the meaning of a set of terms and the proposals are subsets of knowledge thus they are partial representation of the meaning the agents intend. When defining a the meaning of a concept, the information used describe aspects of the concept. For instance to identify a person I may specify the physical properties and sometimes her moral principles. Physical properties and moral principles are two ways by which a person may be described. In general, people use different properties and features to represent things and during the process of Meaning Negotiation the participants discuss in order to identify a shared set of properties to describe a concept. I call the knowledge of each agent a *viewpoint*, that is the whole set of properties used to negotiate, and each of its subsets an *angle*.

Therefore, the knowledge of a negotiating agent is built by a single viewpoint and many angles.

I formalise the MN independently of the topic of the negotiation because I assume that when involved in a negotiation agents choose the knowledge they want to negotiate, before entering into the process. Therefore the agents always know the topic of the negotiation they are in. The independence of the topic allows both the representation of both qualitative and quantitative negotiation issues.

Here, I assume that angles are presented as *logical theories*, and in particular *propositional* ones. At the beginning of a MN process, entities are in disagreement, i.e., they have mutually inconsistent knowledge. By MN, they try to reach a common angle representing a shared acceptable knowledge, where the MN ends in positive way when the agents have a common knowledge, and it ends in a negative way otherwise: agents are in

- *agreement* when they have the same knowledge, namely they have found a set of constraints on the meaning of the negotiated terms that is accepted by both agent (this new theory is named, here, a *common angle*);
- *disagreement* when they are not in agreement.

The MN problem requires the definition of entities participating into a negotiation (Section 2.2) by stressing the main features that are fundamental to negotiate, i.e. how their knowledge is, which are the proposals they make. In Section 2.3 I define a set of negotiating agents as a multiple agent system and I focus upon the way they communicate to each other, how they behave in such an agents' society and I define the different ways in which the participants can be in conflict.

2.2 Agents

The concept of *agent* has become important both in Artificial Intelligence (AI) and mainstream Computer Science. There is not a single universally accepted definition of agent in the AI community. This term is largely used by many people working in closely related areas.

A very general definition of agent can be:

> An agent is a computer system that is capable of *independent* action on behalf of its user or owner; an agent can figure out for itself what it needs to do in order to satisfy its design objectives. [183]

A few other definitions are:

> The term agent is commonly meant to be an entity, human or machine, that functions continuously and autonomously in an environment in which other processes take place and other agents exist. Agents are often taken to be "high-level" , meaning that they can be described in mental terms such as beliefs, knowledge, capabilities, plans, goals, desires, intentions, obligations, commitments, etc. [95]

> An agent system is a finite set A, where each $x \in A$ is a ground term representing the name of an agent, equipped with a knowledge base $\mathcal{K}(x)$. [156]

> An agent is a computer system that is *situated* in some *environment*, and that is capable of *autonomous action* in its environment in order to meet its design objectives. [184]

In [184], the authors distinguish two general usages of the term "agent", a weak use and a strong one. A weak notion of agent denotes a hardware or software-based computer system having the following properties:

- *autonomy*: agents operates without the direct intervention of humans or others, and have some kind of control over their actions and internal state (Castelfranchi, [43]);

- *social ability*: agents interact with other agents (and possibly humans) via some kind of *agent-communication language* (Genesereth and Ketchpel [72]);
- *reactivity*: agents perceive their environment, (which may be physical world, a user via a graphical user interface, a collection of other agents, the Internet, or perhaps all of these combined), and respond in a timely fashion to changes that occur in it;
- *pro-activeness*: agents do not simply act in response to their environment, they are able to exhibit goal-directed behaviour by taking the initiative.

There are properties in the above definitions of agent that are common. An agent may be a human person or a computer system, software or hardware, that is designed by humans. Agents are situated in an environment and they can perceive information about it by means of *sensors* (Figure 2.1 from [183]). The sensors are input/output devices and each agent has a finite number of them. By means of the sensors the agent *knows* the environment state, i.e. whether it is sunny or whether there are some polecat etc., but the knowledge she has about the environment is *incomplete* because of the finiteness of the sensors of the agent. Thus, it may be the case that the agent considers equals two different environment states. For instance, if the agent has not the sense of smell then she does not perceive the presence of a polecat. Moreover, it can be the case that an agent's act produce different outcomes in the same environment and that the agent does not recognize the difference.

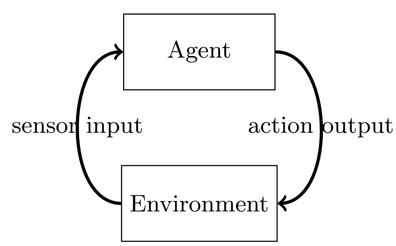


Figure 2.1. An agent in its environment. The agent takes sensory input from the environment, and produces as outputs actions that effect it. The interaction is usually an ongoing, non-terminating one.

An important component in agent definition is *knowledge*. Human people have beliefs, desires, goals, wishes, etc. and learn day by day something new about the world. Agents that are designed to represent and behave in behalf of their owner, typically human, must know which are the beliefs, the desires, the goals, the wishes, etc. of their owner. Therefore, the agents have the *intentionality*'s capability in all the situations in which it is an important component for the agent's design purposes. For instance, if the software agent a is designed in order to find the best red skirt for Alice, then a has to know what does *best* means for Alice.

The intentionality depends upon the goals. The intention to perform an action supposes the capability to do it as the goal of obtaining something requires the intention of performing the action that produce it. In this sense, the knowledge of the agent can be of three types:

beliefs : the information about the world;
desires : the motivational states describing the situations the agent wishes, as "the best red skirt";
intentions : they represent the deliberative state of the agent, i.e. what the agent wants to do. The intentions are desires with respect to which the agent has a plan to reach them.

In my thesis, I implicitly distinguish beliefs from desires, goals, etc. I consider the set of the beliefs as *information* the agent has about the subject of the negotiation and the set of the intentions, goals and desires as a representation of the strategical behaviour of the agent during the negotiation development. Henceforth, an agent is defined in terms of her knowledge and by her strategy.

2.2.1 The knowledge of the agent

The knowledge of the agent is the set of the information about the world that the agent perceives by her sensors: the limited number of the sensors produces an incomplete knowledge.

Fagin et al. in [64] model the knowledge of the agent by possible world semantics. Each state of the world satisfies some information and does not satisfy other ones. The knowledge of one agent is identified by an epistemic modal operator $\mathcal{K}$. The meaning of $\mathcal{K}_i\varphi$ is "the agent i *knows* that φ is true". The semantics of $\mathcal{K}_i\varphi$ is the set of the worlds that satisfy it. The operator $\mathcal{K}$ is proved to produce an equivalent relation between the worlds.

In [53], the knowledge of an agent has three representation axioms:

K4 Axiom of memory: is i knows φ in a situation s, then in any subsequent situation, i remembers that she knew φ;
K5 i knows all the actions that she has begun, both those that she has completed and those that are ongoing. That is, she knows which actions she has already performed and which she may perform, her feasible actions;
K6 the knowledge cannot change over time, it can only acquire new information but not lose it.

In MN, the agents have to agree with each other with respect to a common meaning of a set of terms. It may be the case that somebody has to give up some information in order to reach an agreement. The knowledge of the agent is not lost, but only left aside.

The operations on the knowledge as a set of beliefs are:

Revision : new information is added to the knowledge base;
Contraction : some information is removed.

The ways a logical theory of beliefs changes was studied by Alchourrón, Gärdenfors and Makinson in [10]. Both the operations require a consistency analysis to the outcomes and the consistency is guaranteed by the AGM postulates ([176]).

The AGM postulates for belief revision are:

(K*1) $K * \varphi$ is a theory of $\mathcal{L}$;
(K*2) $\varphi \in K * \varphi$
(K*3) $K * \varphi \subseteq K + \varphi$
(K*4) If $\neg\varphi \notin K$ then $K + \varphi \subseteq K * \varphi$;
(K*5) If φ is consistent then $K * \varphi$ is also consistent;
(K*6) If $\vdash \varphi \leftrightarrow \psi$ then $K * \varphi = K * \psi$;
(K*7) $K * (\varphi \wedge \psi) \subseteq (K * \varphi) + \psi$;
(K*8) If $\neg\psi \notin K * \varphi$ then $(K * \varphi) + \psi \subseteq K * (\varphi \wedge \psi)$.

Any function $* : \mathcal{K}_{\mathcal{L}} \times \mathcal{L} \to \mathcal{K}_{\mathcal{L}}$ satisfying the AGM postulates for revision (K*1) - (K*8) is called an AGM revision function. The first six postulates (K*1)-(K*6) are known as the basic AGM postulates (for revision), while (K*7)-(K*8) are called the supplementary AGM postulates. Postulate (K*1) says that the agent, being an ideal reasoner, remains logically omniscient after she revises her beliefs. Postulate (K*2) says that the new information φ should always be included in the new belief set. (K*2) places enormous faith on the reliability of φ. The new information is perceived to be so reliable that it prevails over all previous conflicting beliefs, no matter what these beliefs might be. Essentially (K*3) and (K*4) express the notion of minimal change in the limiting case where the new information is consistent with the initial beliefs. (K*5) says that the agent should aim for consistency at any cost; the only case where it is acceptable for the agent to fail is when the new information in itself is inconsistent (in which case, because of (K*2), the agent cannot do anything about it). (K*6) is known as the irrelevance of syntax postulate. It says that the syntax of the new information has no effect on the revision process; all that matters is its content (i.e. the proposition it represents). Hence, logically equivalent sentences φ and ψ change a theory K in the same way. Finally, postulates (K*7) and (K*8) are best understood taken together. They say that for any two sentences φ and ψ, if in revising the initial belief set K by φ one is lucky enough to reach a belief set $K * \varphi$ that is consistent with ψ, then to produce $K * (\varphi \wedge \psi)$ all that one needs to do is to expand $K * \varphi$ with ψ; in symbols $K * (\varphi \wedge \psi) = (K * \varphi) + \psi)$. The motivation for (K*7) and (K*8) comes again from the principle of minimal change. The rationale is (loosely speaking) as follows: $K * \varphi$ is a minimal change of K to include φ and therefore there is no way to arrive at $K * (\varphi \wedge \psi)$ from K with less change. In fact, because $K * (\varphi \wedge \psi)$ also includes ψ one might have to make further changes apart from those needed to include φ. If however ψ is consistent with $K * \varphi$, these further changes can be limited to simply adding ψ to $K * \varphi$ and closing under logical implications - no further withdrawals are necessary.

The AGM postulates for belief contractions are:

(K÷1) $K \div \varphi$ is a theory.
(K÷2) $K \div \varphi \subseteq K$
(K÷3) If $\varphi \notin K$ then $K \div \varphi = K$;
(K÷4) If $\nvdash \varphi$ then $\varphi \notin K \div \varphi$;
(K÷5) If $\varphi \in K$, then $K \subseteq (K \div \varphi) + \varphi$;
(K÷6) If $\vdash \varphi \leftrightarrow \psi$ then $K \div \varphi = K \div \psi$;
(K÷7) $(K \div \varphi) \cap (K \div \psi) \subseteq K \div (\varphi \wedge \psi)$;
(K÷8) If $\varphi \notin K \div (\varphi \wedge \psi)$ then $K \div (\varphi \wedge \psi) \subseteq K \div \varphi$.

Any function $\div : \mathcal{K}_\mathcal{L} \times \mathcal{L} \rightarrow \mathcal{K}_\mathcal{L}$ that satisfies (K÷1)-(K÷8) is called an AGM contraction function. Like the postulates for revision, (K÷1)-(K÷8) split into two groups: the first six postulates (K÷1)-(K÷6) are known as the basic AGM postulates for contraction, while (K÷7)-(K÷8) are called the supplementary AGM postulates for contraction. Given the agentfs logical omniscience, postulate (K÷1) is self-evident. Also self-evident is (K÷2) since by its very nature, contraction produces a belief set smaller than the original. Postulate (K÷3) says that if φ is not in the initial belief set K to start with, then there is no reason to change anything at all. (K÷4) tells us that the only sentences that are immutable are tautologies; all other sentences φ can in principle be removed from the initial beliefs K, and contraction will perform this removal no matter what the cost in epistemic value might be. Postulate (K÷5), known as the recovery postulate says that contracting and then expanding by φ will give us back (at least) the initial theory K; in fact, because of (K÷2), I get back precisely K. The motivation behind (K÷5) is again the notion of minimal change: when contracting K by φ I should cut off only the part of K that is related to φ and nothing else. Hence adding φ back should restore our initial belief set. Postulate (K÷6), like its belief revision counterpart (K÷6), tells us that contraction is not syntax-sensitive: contraction by logically equivalent sentences produces the same result. The last two postulates relate the individual contractions by two sentences φ and ψ, to the contraction by their conjunction $\varphi \wedge \psi$. Firstly notice that to contract K by $\varphi \wedge \psi$ I need to give up either φ or ψ or both. Consider now a belief $\chi \in K$ that survives the contraction by φ, as well as the contraction by ψ (i.e. $\chi \in K \div \varphi$ and $\chi \in K \div \psi$). This in a sense means that, within the context of K, χ is not related to neither φ nor ψ and therefore it is also not related to their conjunction $\varphi \wedge \psi$; hence, says (K÷7), by the principle of minimal change χ should not be affected by the contraction of K by $\varphi \wedge \psi$. Finally, for (K÷8) assume that $\varphi \notin K \div (\varphi \wedge \psi)$. Since $K \div (\varphi \wedge \psi)$ is the minimal change of K to remove φ, it follows that $K \div (\varphi \wedge \psi)$ can not be larger than $K \div \varphi$ Postulate (K÷8) in fact makes it smaller or equal to it; in symbols $K \div (\varphi \wedge \psi) \subseteq K \div \varphi$.

Changing belief is a relevant operation during a Meaning Negotiation process because it is a description of how an agent can build a new proposal from the previous one (contraction) and it is also a representation of how an agent evaluates the acceptability of a received offer (revision).

In the following subsection I discuss the features of the agent definition when designed to participate to a Meaning Negotiation.

2.2.2 Agents in Negotiation

When participating to a negotiation dialogue, one agent has to be able to make proposals that are increasingly interesting to the opponents and to evaluate the opponents' ones. For instance, suppose that the agent a proposed x and that her opponent, b, did not accept it; a cannot make a more advantageous proposal y with respect to herself. The agent a correctly negotiates when she *possibly* ceases the last proposal x. The possibility of ceasing depends on the utility function of the agent. Thus, it may be the case that it is more useful to remake the last proposal than to cease it.

The *ceasing* of a proposal is the key mechanism in negotiation. The agent may have many different ways of doing it. For instance, suppose that Alice would buy a red skirt in the Bob's shop. Alice wants to pay as little as possible, thus she offers 20$ to Bob. Bob rejects the offer and asks 40$ to Alice. Alice has to make a new offer or to accept the request of Bob. Suppose Alice does not want to accept Bob's request and wants to make a new offer. There are many ways in which Alice may bid. Alice may propose 21$, 22$, ... 39$. The choice of the next bid depends on the utility function of Alice: she offers 21$ to Bob if she considers it better to pay less than to have the red skirt soon, otherwise she offers 39$.

There may exist negotiation mechanisms in which ceasing is not the only way to look for an agreement. For instance, an agent may be able to advance a proposal that improves the proposals of other agents, or she may be allowed to re-advance proposals she disagreed about before.

In this case, I can speak of non-monotonic negotiation mechanisms.

The utility function of the agent produces a *preference* relation among the bids of the agent. In the Meaning Negotiation scenario, the object of the negotiation is knowledge and the proposals that the agent can make in the Meaning Negotiation, are pieces of the knowledge of the involved agents. Thus, the *preference* relation among the possible bids of an agent is a preference relation among pieces of the agent's knowledge. When an agent makes an assertion during a meaning negotiation process, she assert a partial viewpoint with respect to her initial one and, as in the simple scenario of Alice and Bob about a red skirt described above, the choice of which assertion has to be performed in the next step of the negotiation process depends on the utility function of the agent, i.e. it depends on the *preference relation* of the agent with respect to her partial viewpoints. An agent participating in a Meaning Negotiation process, has presumably one initial viewpoint that is her best description of the concept in negotiation.

Typically, when defining a concept, an agent mentions the requirements that:

1. mandatorily have to hold;
2. mandatorily have not to hold;
3. mandatorily have not to be used;
4. presumably have to hold;
5. presumably have not to hold;
6. presumably have not to be used.

The requirements number 3 and 6 are about the relevance of properties in defining a concept. It may be the case that Alice does not consider it to be important to say that a red skirt has a black bell. The having a black bell predicate is not relevant to Alice in defining what she means for red skirt.

The relevance of a predicate in definitions may be mandatory. There are situations in which a property is considered necessarily irrelevant. For instance, suppose that Alice thinks that a red skirt is necessarily not defining the predicate having a black bell.

In this thesis, I do not directly deal with the problem of the relevance of terms in concept definition. However, I assume that when negotiating the meaning of a concept, the agents assert only propositions that are relevant about it. Henceforth, the agents never make proposals about irrelevant properties.

The requirements number 1 and 2 are *mandatory* or *stubborn*, i.e. they hold for all the instances of the negotiated concept. The mandatory properties are important in negotiation because they represent how much is powerful the agent in the negotiation, i.e. how much the shared knowledge, if it exists, is similar to the agent's initial one. The mandatory properties cannot be negotiated. An agent never ceases with respect to necessary properties because it is mandatory, thus the agent thinks it has obligatorily to be used in the concept definition. The more are the mandatory properties of the agent and the more powerful she is. Again, the stubborn knowledge of a negotiating agent represents the *breaking point* of the negotiation with respect to the agent. In fact, no mandatory property can be given and if it is the case, the agent exits the negotiation and the process ends with failure.

The requirements number 4 and 5 are *plausible* or *flexible*, i.e. they may or may not hold in an instance of the negotiated concept. The plausible properties described those features that are often but not always present at an instance of the Meaning Negotiation subject. During a Meaning Negotiation the involved agents negotiate only about the features they do not consider mandatory. Thus, more are the plausible properties and *presumably* more are the stages of the negotiation process. The length of a negotiation process does not exclusively depend on the dimension of the plausible knowledge of the agent. In general, it is an overestimation of the meaning negotiation process cost in time-space complexity. I focus on this problem in the next chapter (Chapter 3). The necessary and the characterizing properties of a concept definition are related to *EGG/YOLK* objects, introduced by [109] to represent class membership based on typicality of the members:[1] the egg is the set of the class members and the yolk is the set of the *typical* ones (Figure 2.2). For instance, the class of "employees" of a company

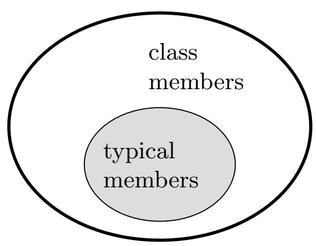


Figure 2.2. The Egg/Yolk membership representation.

A may be defined as "the set of people that receive money from the company in exchange for carrying out the instructions of a person who is an employee of that company", thus excluding, e.g., the head of the company (who has no boss), and the typical employee would include regular workers like secretaries and foremen. Another company B might have a different definition, e.g., including the

[1] The EGG/YOLK model is not the only possible presentation of this aspect of my modelisation. In particular, three-valued fuzzy logic, or basic possibilistic logic systems can be equivalently employed. However, since the modelisation I propose insists upon a set-theoretic framework, it is quite easy to present the theory within the EGG/YOLK model, that is fully embedded into that framework and has an immediate spatial, and thus pictorial, presentation.

head of the company, resulting in a mismatch. Nevertheless, if both companies provide some typical examples of “employees” it is possible that all of A’s typical employees fit B’s definition, and all of B’s typical employees fit A’s definition: $YOLK_B \leq EGG_A$ and $YOLK_A \leq EGG_B$, in the terminology of [109]. Differently than in the original model, concept definitions are here restricted by stubborn properties to the largest acceptable set of models, hence represented by the egg, whilst the yolk is employed to denote the most restricted knowledge, that is, the one on which the agents are flexible.

The stubborn properties never change during the negotiation; therefore, the egg is fixed at the beginning of the MN. Instead, the flexible part of the definition of a concept is the core of the proposal of a negotiating agent. Each proposal differs from the further ones in two possible ways: it may give a definition of the negotiated object that is more descriptive than the next ones, or the given definition specifies properties that the next ones do not and vice versa. In the former case, we say that the agent carries out a *weakening action*, in the latter the agent carries out a *changing theory action*. However, none of weakening or changing theory actions can be carried out with respect to a proposal if the proposal describes the necessary properties of the object in the MN. I say that in such a situation the agents always make a *stubbornness action* that is equivalent to *no more change*.

The proposals of a negotiating agent are built by two components: a mandatory and a plausible one. As said above, only the flexible features are negotiated. Thus, the proposals of an agent differ about the plausible part and the mandatory one is their common part.

The preference about proposals reflects in a preference about flexible properties: an agent prefers to cease first about the feature x and then about the features y_1, y_2, etc. For instance, suppose that Alice considers the features of having a black bell and of being short as adds in the identification of a red skirt and that she prefers a short skirt over a skirt with a black bell. When Alice asks to Bob about the insertions of the selling of three red skirts, she asks their features. Alice will buy the shorter skirt if there was, otherwise the red skirt with the black bell if there was, otherwise the remaining one.

The preference relation is a necessary component for the definition of a negotiating agent. If there is no preference relation about the feasible knowledge, the agent does not know which is the next proposal to perform and she is not autonomous in the negotiation.

The preference relation about the feasible knowledge reflects in a hierarchical structure of the agent’s knowledge. I call this structure as the *subjective hierarchy* of the agent. The subjective hierarchy has presumably one root, that is the initial viewpoint of the agent and many intermediate nodes which are the partial viewpoint the agent is willing to propose in the negotiation and that are ordered by the preference relation. The subjective hierarchy may have many root if there are flexible properties that the agent consider in contrast (for instance, a short red skirt and a long red skirt). There is an ending node which represents the last proposal the agent can perform. It is the stubborn knowledge of the agent, i.e. the mandatory properties that have to hold in the negotiated concept’s instances.

2.3 The Multiple Agent System (MAS)

In the previous section I give a general definition of *agent* and the main components of a *negotiating agent*. In this section, I discuss how agents interact and negotiate.

A multiple agent system, henceforth MAS, is built by a set of agents that share the environment and that interact with one another, in many real-world cases by exchanging messages through some computer network infrastructure. As said above, the agents in a MAS will be representing or acting on behalf of users or owners with very different goals and motivations. In [183], the author says that in order to successfully interact, these agents will thus require the ability to *cooperate*, *coordinate*, and *negotiate* with each other, in much the same way that we cooperate, coordinate and negotiate with other people in our everyday lives. Moreover, the author mentions the slogan "there's no such thing as a single agent system". The point of the slogan is that interacting systems are in fact the norm in the everyday computing world. All but the most trivial of systems contain a number of sub-systems that must interact with one another in order to successfully carry out their tasks. Figure 2.3 (from [93]) shows the typical structure of a MAS. The agents are able to perform actions in the environment. Different agents have

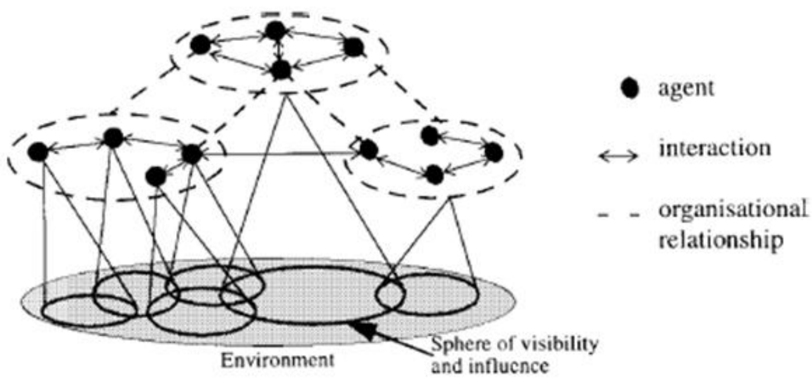


Figure 2.3. Typical structure of a multiple agent system

different *spheres of influence*, i.e. they have the control over different parts of the environment. It may be the case that the spheres of influence coincide or have shared parts. Therefore, the actions made by an agent could change the state of the environment perceived by other agents and thus change the set of the feasible actions of other agents. The fact that these spheres of influence may coincide may give rise to dependency relationships between the agents. For example, two robotic agents may both be able to move through a door but they may not be able to do so simultaneously. Thus, some type of coordination and cooperation between agents is needed. Coordination is fundamental in automating MAS problems. The agents in a MAS have to establish the feasible actions of each agent and whether there is a hierarchical structure between agents. For instance, there may be "power" relationships, where one agent is the "boss" of another, or there may be "priority" relationships, where one agent can act only when another particular agent finished her task.

Cooperation represents the social behaviour of the agents and the main goal of the development of the multiple agent system. A distributed system solves a task by branching it into subtasks. Each subtask is solved by a distributed system component or may by branched itself. The components of a distributed system coordinate themselves in order to accomplish the task of the distributed system. A distributed system is a kind of a MAS. The task is the common goal of the system and the subtasks are the goals of the agent in the MAS.

Coordination, cooperation and all of the interactions between the agents need a *communication*, i.e. a form of message exchange allowing the agents to say to other ones the status of the task, or which agent has to act, or what she needs to fulfill her task, etc.

However, there are situations in which the agents in a MAS do not have to complete a task to win something, i.e. they have contrasting goals. In such a situation, there is no cooperation but *competition* and the agents are as players of a game. In general, the way the agents behave in the MAS is called *attitude*; there are two main attitudes in MAS: *collaborative* and *competitive*.

In the following subsection I discuss about how agents communicate one another (Section 2.3.1); next I discuss about the agent attitudes in MAS and give some notion of normative and ethical MAS (Section 2.3.2). Finally, I focus upon the multiple agent system in a Meaning Negotiation scenario (Section 2.3.3).

2.3.1 Communication

Communication has long been recognized as a topic of central importance in computer science. Many formalisms have been developed for representing the properties of communicating concurrent systems [88, 124]. These formalisms focused on a number of key issues that arise when dealing with systems that can interact with one another. In this thesis, I treat the communication problem in a object oriented manner, i.e. as method invocation. Whenever Alice wants to say something to Bob, she invokes the available method `says(arg,rec)` by `Alice.says(something,Bob)`.

The main problems in specifying how agents communicate are:

1. which kind of messages they can send;
2. how they coordinate in making communication acts;
3. which language they use in building messages.

There are many types of communication acts that an agent can perform. The agent may asks some information about something, or she may imperatively order somebody of doing something, etc. Each message produces a particular answer. When requesting information about something, the receiver of the message replies by making an *assertive* locution into the message. Instead, when imperatively ordering about something, the receiver answers by accepting or rejecting the command. In this thesis, I assume that the messages are simply *assertion*, i.e. they are propositions only about the world.

The second problem (how the agents coordinate in making communication acts), was largely studied by the Artificial Intelligence community [20, 53, 62, 87, 96, 115, 164, 167, 168, 182]. Hamblin in [87], provided a formalism for the analysis of dialogue. Hamblin defines the action of making assertion as *locution act*. Let Ag the set of the participants (people) and *Loc* the set of *locutions.* A *locution act* is a pair in which the former component is the name of a participant and the latter is the content of the message. A locution act is in $\text{Ag} \times Loc$.

Henceforth, locution and assertion are used in interchangeable way. A *dialogue* is generally defined as a sequence of assertions. Agents may interminably speak with each others and the dialogue between them may be infinite. A never-ending sequence of locution acts is not tractable with computer system. Restrictions are needed in order to automate and regulate the communication between agents. Thus, a dialogue is defined by a parametrisation that is its length.A dialogue *of length* n is a sequence of n locution-acts in $(\text{Ag} \times Loc)^n$. In general, a *dialogue* is an element of D defined as follows

$$D = \bigcup_n (\text{Ag} \times Loc)^n \;\; n \in N$$

Each member $d \in D$ is of the form $< n, < p, l >>$ with $n \in N, p \in \text{Ag}, l \in Loc$. There are many types of dialogue depending upon:

- the initial situation between the participants: the participants are in conflict, somebody needs information, etc.
- the main goal describing which is the situation the participants have to reach as a whole: all the participants have to be in agreement, the participants have to complete a task cooperatively, etc.
- the participant's aims representing the desires of each agent in the system: somebody wants to perform an action, the participants want to resolve a conflict, etc.

Walton and Krabbe in [181], describes all the types of dialogue and they summarise them in Figure 3.1 page 66. The classification of the dialogues is reported in Figure 2.4.

When an agent wants to communicate something to somebody, she has to check whether nobody is already making a communication act and to build the message in a correct way. Thus, there has to be a defined *interaction protocol*. Generally, when the communication is for a Meaning Negotiation purposes, the interaction protocol is based upon game theoretic guidelines [20, 115].

Finally, the choice of the agent communication language is not a trivial issue. As said above, the agent are designed by humans who express themselves in different languages (Italian, English, French etc.). Agents belonging to different countries, express themselves in different languages and thus when communicating each other they have to translate messages into the language of the receiver. The Artificial Intelligence community has dealt with this problem and the main approach is to assume the existence a shared communication language into which all agents translate their assertions. Figure 2.5 depicts a simply scenario of foreign agents in communicating.

In [101] authors present the current issues in agent communication language, henceforth ACL, research. An ACL is born from the need of information and knowledge sharing among different agents in distributed environments. There are

Types	Subtypes	Initial Situation	Main Goal	Participant's Aims	Side Benefits
I Persuasion Dialogue (Critical Discussion)	Dispute, Formal Discussion, Discussion of proposal	Conflicting point of view	Resolution of such conflicts by verbal means	persuade the other(s)	develop & reveal positions, build up confidence, influence onlookers, add prestige
II Negotiation	Bargaining, making a package deal	conflict of interests & need for cooperation	making a deal	get the best out of it for oneself	agreement, build up confidence, reveal positions, influence onlookers, add to prestige
III Inquiry	scientific research investigation examination	general ignorance	growth of knowledge & agreement	find a "proof" or destroy one	add to prestige, gain experience, raise funds
IV Deliberation	Means-end discussion, discussion of ends, board meeting	need for action	reach a decision	influence outcome	agreement develop & reveal positions, add to prestige, vent emotions
V Information-seeking dialogue	expert consultation, didactic dialogue, interview, interrogation	personal ignorance	spreading knowledge & revealing positions	gain, pass on, show, or hide personal knowledge	agreement, develop position, influence onlookers, add to prestige, vent emotions
VI Eristics	Eristic discussion quarrel	Conflict & antagonism	reaching a (provisional) accomodation in a relantionship	strike the other party & win in the eyes of onlookers	develop & reveal positions, add to prestige, gain experience, amusement, vent emotions
VII Mixed	A. Debate (Persuasion & Eristics)	Conflicting point of view in front of a third party	accomodating, conflicting points of view	persuade or influence each other & a third party	develop & reveal positions, add to prestige, amusement
	B. Commitee Meeting (mainly deliberation)	Conflict & antagonism & need for agreement and practical matters	working out a policy & endorsing it	influence outcome	agreement, build up confidence, develop& reveal positions, air objections
	C. Socratic Dialogue (mainly inquiry)	illusion of knowledge	healing the soul from this vice to get ready for real knowledge & virtue	refute & avoid being refuted agreement	develop & reveal positions, gain experience, amusements

Figure 2.4. Types of dialogue [181].

several types of ACL dealing with very different purposes but in [101] essential ACL design principles are presented; these are:

- **Heterogeneity**: the meaning of the message has to be context independent;
- **Cooperation and Coordination**: messages have to be meaningful to assist agents to solve complex tasks;
- **Separation**: content, structure and transport of a message do not have to be handled;
- **Interoperability**: heterogeneous agents have to be able to interoperate;

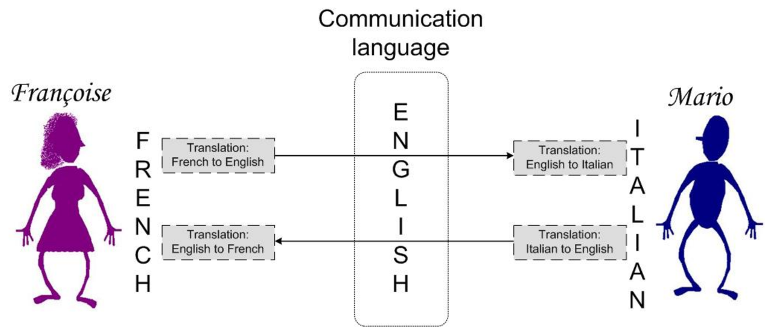


Figure 2.5. François is Frenchwoman and Mario is an Italian man. In order to communicate with each other they choose English language. François and Mario translate the messages from French to English and from Italian to English respectively.

- **Transparency**: agents should be shielded from the complexity of the underlying language;
- **Extensibility and Scalability**: it has to be possible to add new messages in the language;
- **Performance**: the implementation of the language has to be efficiently usable by system resources.

The ACL specifications are concerned with the description of message structure, its semantic model, and the underlying interaction protocols. These specifications define a language and supporting protocols and encompass the following:

- **Message format**: defines the primitive communicating acts and message parameters by mean of expressions describing which is the action (assertion, question, command, etc.) and the content of the message;
- **ACL semantics model**: this is subordinate on the communicative behavior and capabilities of the agent and it is necessary to unambiguous meaning of the messages. When agents interact to achieve a goal, the mutual understanding of the messages exchanged depends on the semantics given to communication actions. The general approaches in providing semantics to an ACL are based upon mental concepts of beliefs, desire and intention [46,108,163], social agency [162] or logic-based [9, 84, 136];
- **Interaction protocols**: they are sets of well-defined patterns design to regulate and facilitate agents interaction in communication. Although protocols are optional, the communication of the agent must be consistent with a chosen protocol. The main protocols used in ACL design are the following:
  - *Direct communication protocol*: the sender knows the receiver and his capabilities;
  - *The contract net protocol*: designed by Davis and Smith [54], it sets the interaction patterns between an agent, the *manager*, who enlists the support, trough a *call for proposals*, of a number of other agents, the *contractors*, to perform some complex task. Contractor submit proposals to the manager. The manager evaluates and assigns tasks under some conditions. The

  successfully contractors commit themselves to performing the assigned task and sending back the result to the manager;
  - *The mediated communication protocol* uses the services of special agents, called *facilitators*. The facilitators act as brokers between agents in need of some service and other agents that provide them. Mediation involves needy agents subscribing to services, and facilitators brokering, recruiting, and recommending agents that registered their identity and capabilities.
- **Shared ontologies and Content language**: they are the *prerequisites* to knowledge sharing because they assure the agents in understanding the content of the message.

Generally agent communication languages are designed following different approaches depending on the communication purpose the language is used for: KQML [6], ARCOL [155], FIPA [5] and AOP [160] are examples of declarative languages; ICL and Mobile Agent Communication are procedural, finally there also exist *social agency* languages to coordinate agents towards a common goal.

Translation from a language into another one leads to the problem of *misunderstanding* or *misconception* [118–120, 144]. Consider the Italian word "fiera"; there are two ways in which it can be translated in English: "fair" and "wild beast". The right English word for "fiera" depends upon the context in which the word is used. A misunderstanding occurs when, for instance, an agent intends "fair" and another one intends "wild beast" for "fiera". The resolution of this critical situation is trivial when all the agents in the MAS knows the *universe of the discourse* (UoD by [95]) otherwise a *syntactic negotiation* or preliminary negotiation begins. The syntactic negotiation goal is to ensure agents in correctly translating the assertions they receive and the ones they would send. In this thesis, I will not focus upon the problem of the misunderstanding. I assume that every agent, participating into a MAS, uses a translation function that is chosen before entering in the MAS. A complete study of the misunderstanding as an possible situation in the MAS is left as future work.

2.3.2 Agent Attitudes

"Man is a social animal" said Aristotele. Man is part of the society and he has to obey to its laws. Human people also have rights with respect to the society.

An agent relates to a MAS as a man relates to the society. Usually, multiple agent systems are designed with political rules, i.e. a set of rules expressing what the agents have to do and what it is forbidden for them. It is a *normative system*. The Artificial Intelligence community has largely dealt with the definition and the influence of norms in multiple agent systems, i.e. the *normative multiple agent system*, [11,37,38,40,107,112,130,171,177,178,185]. Norms in multiple agent systems are as legal and social laws for human societies. The main problems in introducing social and legal laws in multiple agent system are concerned with the representation of a norm. A norm is not only an assertion about actions of agents. It has an effectiveness and an "in force" time. Moreover, norms can be created, modified and repealed. A norm may be eventually violated and thus causing a punishment with respect to an agent or a set of agents. It is not the goal of this thesis to tackle the problems around the normative multiple agent system. However, it is relevant to my thesis to analyse how agents in a MAS choose the actions to perform without making violations and by regarding their obligations. I assume that each agent knows every time her *feasible* actions. The feasible actions of an agent may be obligations, permissions or prohibitions with respect to the norms of the MAS and it may be the case that a dilemmas situation arises. For instance, suppose that Alice has two feasible obligations: go at work at 8 a.m. and drive her son at school at 8.30 a.m. Alice cannot do both obligations simultaneously; she has to choose which action to perform first. Whatever the choice is, she makes a violation. Situations like the one described here are called *Moral dilemma* in the Artificial Intelligence literature [59, 75, 113, 171].

Moral dilemmas are not solvable. In [48, 49] the authors propose a model to approximatively solve it.

A general approach of dealing with agency in MAS is by representing the choice of the action to perform by *attitudes*.

> ... the attitudes are driving forces behind the actions of agents. [121]

Attitudes are the representation of the reasons that guide the agents in behaving. They are preferences between the criteria used to evaluate the feasible actions. The criteria, or contexts, are the features that are relevant for the MAS as the legitimacy, the social utility, etc.

In general, the main criteria for evaluating action are:

1. the MAS welfare: is the action positive for the agents in the MAS?
2. the personal advantage: is the action individually positive for the agent in choosing the action?

Therefore, the evaluation of actions is *contextualised*, i.e. each agent gives a value for each criteria: an action may increase the MAS welfare but be not personal advantageous.

By attitude I mean the preference order of the evaluation context (Definition 2.1).

Definition 2.1 (Agent Attitude). *Given a set of evaluation criteria* $C = \{c_1, c_2, \ldots, c_n\}$*, the* attitude *of an agent is a partial order between the elements in* C*,* $\langle \trianglelefteq, C\rangle$*. If* $c_1 \trianglelefteq c_2$ *then the context* c_1 *is more relevant then* c_2 *in choosing an action to perform.*

The evaluations of actions are individual; different agents in a MAS may evaluate the same action in different ways so that it is not always possible to *abduce* the opponent attitudes by only observing her behaviour, i.e. which actions she performed (see [50]).

Following the enumeration in the list above, the main attitudes in agency are:

- *collaborative*: the main goal of the agent is the welfare of the MAS: $1 \trianglelefteq 2$;
- *competitive*: the action performed by a competitive agent are advantageous or not damaging herself: $2 \trianglelefteq 1$.

The behaviour of an agent may change over time. A collaborative agent may become competitive and viceversa. The change of the attitude is generally connected to conditions of the environment and the realisation of the agent goals. Agents have many goals, wishes, intentions etc., and they chose to accomplish one goal because it is the simplest, but events change the world and sometimes facilitate the occurring of more successful goals. Maintaining or changing the attitude is a personal matter and depends on the design of the agent. An agent that never changes her behaviour has a *static* attitude, otherwise it is *dynamic* (see [128]). Table 2.1 shows the graphical representations of the main attitudes of an agent with respect to the collaborative and competitive perspective. Nodes are the contexts and the edges represent the preference between two nodes. In this table, I distinguish the attitudes between static and dynamic.

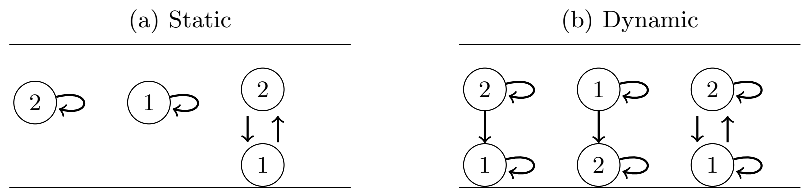


Table 2.1. Attitudes in a competitive and collaborative perspectives.

The determinism of the behaviour of an agent does not depend upon the dynamism of her attitude. An agent with a static attitude has a non-deterministic behaviour whenever she is in moral dilemma. The same situation for an agent with a dynamic attitude.

2.3.3 Meaning Negotiation in MAS

The agents involved in a Meaning Negotiation process have the goal of sharing a viewpoint that is a set of terms whose meaning is the same for all of them.

In general, a negotiation protocol establishes the actions the agent can perform. The actions allowed are:

- *propose*: an agent makes a proposal to the opponents;
- *receive*: an agent receives the proposal made by opponents, i.e. the offer of the opponent;
- *accept*: an agent accepts the offer of some of the opponent when she agrees with it;
- *rejects*: an agent rejects the offer of some of the opponent when she does not agree with it;

The protocol also limits the execution of an action by giving constraints to it. In fact, in a bilateral negotiation, one agent, say Alice, can make a new proposal only if her opponent, say Bob, already does it because the protocol establishes that the agents make proposals in turns. Moreover, an agent may accept or reject an offer only if it has been proposed by someone else.

Differently, in a more than two agents negotiation, the turns may be of very different types and they are establishes by the protocol. For instance, Alice proposes something only after Bob proposed and Charles cannot make proposals, or

Alice proposes something only if Bob already proposed and Bob proposes only if Charles already proposed.

Each agent chooses the next proposal to perform depending on her preference, so different agents choose proposals in different ways. Instead, the evaluation of a received offer is done in the same way by all the agents.

The knowledge of a negotiating agent is stratified because it contains a minimal set of beliefs that are unquestionable, i.e. stubborn beliefs, and another set of beliefs she may give up, i.e. flexible beliefs. Each time an agent receives an offer, she tests if it contains all the information she considers as necessary. In the E/Y perspective the above condition translates in verifying if the stubbornness knowledge is consistent with the received offer, i.e. the egg is not disjoint with respect to the yolk of the opponent. The unquestionable beliefs are a generalisation of each flexible belief, the consistency of the stubbornness set with the received offer does not exclude the eventuality that the offer is a generalisation of the stubbornness knowledge, i.e. that it does not contains all the stubbornness beliefs. In his situation, the agent cannot accept the offer because she has to give up some of the unquestionable knowledge. I name this negotiation situation as *call-away* and it causes the end of the negotiation in a negative way.

Cohn and Gotts [47] identify all the possible relations between two E/Ys, see Figure 2.6. Thus, when an agent evaluates the received offer she checks in which relations their E/Ys are.

However, an agent does not distinguish the egg from the yolk of the opponent in the received offer. Thus, she has to check the relation between her egg and her yolk with respect to the yolk of the opponent. The agent evaluates the received offer, say Y_2, by making the following tests in order:

1. Y_2 is equivalent to a subset of the unquestionable beliefs (Figure 2.7(a)): $EGG_1 \subset Y_2$;
2. Y_2 does not contains any minimal information (Figure 2.7(b)): $EGG_1 \cap Y_2 = \emptyset$;
3. Y_2 contains some or all of the minimal information but none of the flexible ones (Figure 2.7(c)): $EGG_1 \cap Y_2 \neq \emptyset$ and $YOLK_1 \cap Y_2 = \emptyset$;
4. Y_2 contains some or all the minimal information and some of the flexible ones (Figure 2.7(d)): $EGG_1 \cap Y_2 \neq \emptyset$ and $YOLK_1 \cap Y_2 \neq \emptyset$;
5. Y_2 contains all the minimal information and some of the flexible ones (Figure 2.7(e)): $EGG_1 \cap Y_2 \neq \emptyset$ and $YOLK_1 \subset Y_2$;
6. Y_2 contains all the minimal information and all the flexible ones (Figure 2.7(f)): $EGG_1 \cap Y_2 \neq \emptyset$ and $YOLK_1 = Y_2$.

Each agent may be represented by a finite state diagram depicted in Figure 2.8. The state diagram is one of the contributions of this thesis. The states are representation of the relative situation between the received proposal and the knowledge of the agent; the states are:

1. *Call-away* occurs when p is a generalization[2] of the stubborn knowledge of i.
2. *Absolute disagreement* occurs when the stubborn knowledge of i is inconsistent with respect to p.

[2] A theory A is a *generalization* of a theory B when the models of A are a superset of the models of B.

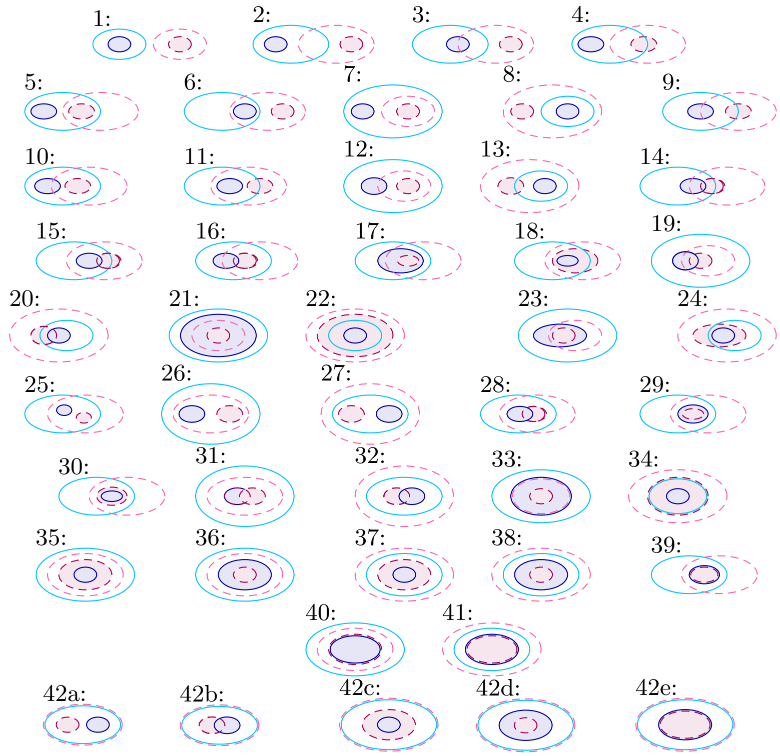


Figure 2.6. All the 46 possible Egg/Yolk configurations are illustrated here. The source type EGG_A and its prototype $YOLK_A$ are shown in dashed lines, whilst the target type EGG_B and its prototype $YOLK_B$ are shown in dotted lines. A continuous line indicates equality between a dotted and a dashed ellipse. The last five relations, in which $EGG_A = EGG_B$, are collapsed into one, since prototypes are superfluous if the types are truly identical [47].

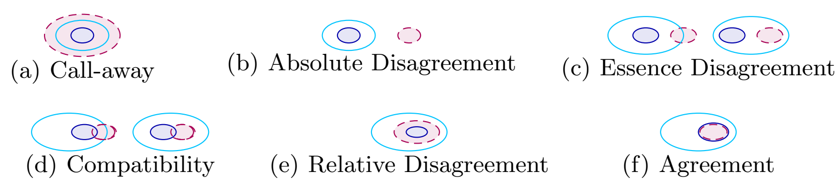


Figure 2.7. E/Y relations for the evaluation of a received offer p. The evaluation offer is represented by pink dashed line and the evaluating agent by the blue plain lines, the stubborn knowledge of i is the egg and her flexible knowledge is the yolk.

3. *Essence disagreement* occurs when the flexible knowledge of i is inconsistent with respect to p.
4. *Compatibility* occurs when p is consistent with the flexible knowledge of i but it is not a generalization or a restriction of i's viewpoint.
5. *Relative disagreement* occurs when p is a generalization of the flexible knowledge of i.

The enumeration of the negotiation situations above (call-away, absolute disagreement, etc.) identifies the tests of the order of the evaluation of the received offer presented above.

The transition from one state to another one depends upon the proposals made by the agent and it is discussed in detail in the Chapter 4.

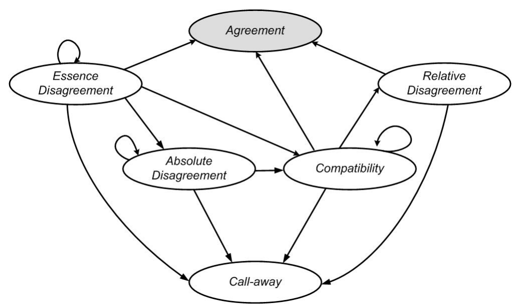


Figure 2.8. Finite state diagram of each negotiating agent.

The Meaning Negotiation process continues until the agents share a common viewpoint, thus they are in agreement, or they have no more proposal to perform.

The Meaning Negotiation stages are the following ones:

- *Init*: the first bidding agent makes a proposal;
- *Negotiate*: the agents propose their viewpoints in turns and evaluate whether they agree with the opponents;
- *Agreement*: all[3] the agents agree on a common viewpoint;
- *Disagreement*: the agents do not have a shared viewpoint.

I represent the Meaning Negotiation process as the state diagram depicted in Figure 2.9 in which the state are the above mentioned ones and the transitions depend upon the disagreement relation between agents.

[3] [42] consider more than two negotiating agents and formalize a partial positive outcome, in which a degree of sharing denotes the minimum number of agreeing agents needed to consider the MN as positive.

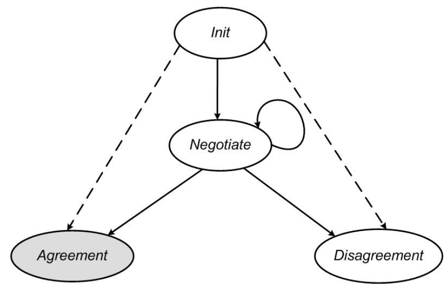


Figure 2.9. Finite state diagram of the MN.

3

Meaning Negotiation in a game-theoretic perspective

3.1 Introduction: Negotiation games

In this chapter I present the Meaning Negotiation process as games belonging to the Game Theory literature. I initially show how the Artificial Intelligence researchers have dealt with the problem of Meaning Negotiation in a game-theoretic point of view and then I give a formalisation of the MN by two games: Bargaining and English Auction. In general, the current Artificial Intelligence literature tackles the problem of Meaning Negotiation by modeling it dependending on the number of the players, whether two or more. In a two negotiating agents scenario, 1-1 Meaning Negotiation, the games used in modeling the negotiation are:

- **Bargaining Game**: two agents discuss how to share one dollar. The agents make in turn a request that is the part of one dollar they want. The Bargaining Game develops in two stages: the demand stage and the war of attrition one. In the first stage both agent make simultaneously a proposal and if the two proposal are *compatible* in the sense that their sum is less then one dollar, the game end in positive. Agents has the part of one dollar they asked for and moreover they receive half of the remaining part. If the first two proposals is not compatible, then the second stage begins. In the war of attrition stage each agent continues to make in turn a proposal until a pair of compatible ones is found. The Bargaining Game may be infinite. It is not a violation that agents make always the same proposals. To limit the length of the game, a timestamp and a maximal number of proposals are introduced as parameter of the game.
- **Pleadings**: The Pleadings game has been formalised by Gordon in [76] and it is largely used in literature to model legal reasoning in identifying the issue in a trial. The Pleadings game uses *conditional entailments* to specify agent reasoning rules and it is regulated by some simple guidelines:
  1. no player can contradict herself;
  2. if a player asserts that a rule is valid then she has to accept that all its applications are right;
  3. a player can support an argument only if it has been denied and it is an issue;
  4. a player can deny a claim only if it is not a direct consequence of his own claims;

5. a supporting argument can be rebutted by another one only if it is stronger and the claim remains an issue.

The Pleadings game admits two players: the plaintiff and the defendant. Both players move consistently to their knowledge given by a set of propositions coupled with the set of the assertions made by agents in the history of the game. Meaning Negotiation is viewed as a Pleadings Game on what issues agents share.

- **Divorce**: The Divorce Game involves two players, an husband and a wife, that litigate to according about the commons division. This game is similar to Bargaining game but they are different because players try to persuade opponents by making a request and an offer. In *the war of attrition stage* there are two negotiation processes that take place: a pretending and a conceding negotiations. Husband has a stubborn and a flexible theories of requests and has a flexible theory of conceding: these theories have to be disjoint. The same does the wife. Each negotiation process is a Meaning Negotiation about how to reach an agreement among parties. [186]

In a two negotiating agents scenario, 1-1 Meaning Negotiation, one agent is a buyer and the other is a seller; the distinction of the roles of the agents is only nominal because the actions they may perform are the same. During a negotiation process, both the buyer and the seller make proposals, or accept or reject the opponent's one.

Conversely, in a more than two negotiating agents scenario, the modelisation of the Meaning Negotiation depends also on the role of the involved agents. Having $n+1$ agents in the negotiation, the possible role distinctions are:

- 1-n: one seller and many buyers;
- n-1: many sellers and one buyer;
- n_1-n_2: many sellers and many buyers.

In the first case, the agents behave like in an auction. Before entering the auction, the seller establishes a maximal price for the item. The seller begins the game by making the initial request that is the *reservation price*. The auction develops by *beats*. A beat consists of:

1. the seller makes a request;
2. each buyer proposes a counteroffer or accepts the seller's proposal.

No more beat begins if the maximal price is reached or if the buying agents do not make new proposals. In auction scenario, a proposal is also called a *bid*. The end of the auction is established by the seller, i.e. by the auctioneer. In general, in an auction there is only one winner, i.e. only one agent buys the item in the auction.

There are many types of auction that differ how the agents make their bids, the number of proposals the players do and the order with respect to each agent makes a bid. The main auctions in Game Theory literature are:

- **English Auction**: it is the most commonly known type of auction. The auction begins by a proposal of the auctioneer that is the *reservation price* (which may be 0) of the good in negotiation. The agents alternate by making proposal and their bid have to be more then the current highest bid. All the agents can see

the bids being made, and are able to participate to the bid if they so desire. When no agent is willing to make a new bid, then the good is allocated to the agent that has made the current highest bid, and the price they pay for the good is the amount of this bid;
- **Dutch Auction**: the auction begins when the auctioneer starts out offering the good at some artificially high value (above the expected value of any bidder's valuation of it). The auctioneer continually lowers the offer price by some small value, until some agent makes a bid for the good which is equal to the current offer price. The good is allocated to the agent that made the offer;
- **First-price sealed-bid auction**: it is a *one-shot* auction. There is a single round in which bidders submit the auctioneer a bid for the hood. There no subsequent bidding round and the good is allocated to the agent that makes the highest offer for the good.
- **Vickrey auction**: it is the most unusual and perhaps the most counterintuitive of all the auction types. As the first-price sealed-bid, the Vickrey auction is one round and the winner is the agent that makes the highest current bid. The winner pays the second current highest offer for the good.

The second case, n-1, is similar to the first one. The sellers have to convince the buyer to accept the price they propose and the buyer make her one. In the Meaning Negotiation perspective, a buyer is not different from a seller because they have the same feasible action: accept an offer, reject an offer or make a proposal. Even if the agents generally have different strategies depending on their role, i.e. typically a buyer enhances instead the seller falls the last offer, the purpose of the seller and of the buyer is the same: to meet the opponent's request. Therefore, buyers and sellers make new proposals in the same way that is by *ceasing* their last one.

The third case, n_1-n_2, is called *fish market*. It is not possible to make a modelisation of the Meaning Negotiation of this multiple-agent system structure because there is no agent monitoring the process and no behavioural guidelines for the players. In the first two cases, the auctioneers, the seller in the first and the buyer in the second, are the agents who controls the Meaning Negotiation process and check whether an agreement is reached between the involved agents. As in the auction game, in the fish market each agent makes a proposal or accepts/rejects the opponents' one but there is no coordination among the agents. It may be the case that two or more agents make proposals simultaneously so each agent is a buyer, i.e. she makes an offer, and a seller, i.e. she evaluates the received offers, at the same time. The result is that a common proposal is difficult to find. In the worst case, where there are n agents involved in negotiation in total, this means there can be up to $n(n-1)/2$ negotiation threads. Clearly, from an analysis point of view, this makes such negotiation hard to handle.

Alternating offers Rubinstein protocols [154] consists in a continuous schema in which two players get in turn. When an agent's turn is effective, the player can respond in three different ways: by accepting the offer, by rejecting it or by placing a new offer. Such a protocol can be used to govern several games based upon mutual offers including pairwise bargaining.

In the following three sections I formalise the definition of agent and of subjective hierarchy I discussed in Section 2.2.1 (Section 3.2), and I present a formalisation of the Meaning Negotiation process by Game Theory for a bilateral scenario (Section 3.3) and for a more than two agents one (Section 3.4).

3.2 Terminology and Definitions

In this section I give a formal definition of agent and of subjective hierarchy I discussed in 2.2.1. An agent participating into a Meaning Negotiation process distinguishes from other agents in the language she uses to represent her knowledge about the world and, presumably, in her beliefs. Therefore, the agents may have different expression languages and different point of view about the subject under negotiation. Suppose a group of agents are speaking about the meaning of the word *fiera*. The correct use of the word *fiera* is linked to the language in which it has a meaning. Agents express themselves in their language and they use only the terms they know and they think as relevant with respect to the meaning negotiation they are involved in. Moreover, since the Meaning Negotiation is contextual, the set of the beliefs constituting the knowledge of the agents changes in different Meaning Negotiation processes. The same for the unquestionable knowledge of the agent; basic information about a concept changes when the context does. Suppose that the Meaning Negotiation is about the word *fiera* again: if the context of the term is " animals" then the unquestionable knowledge of the agent may be "a *fiera* is a wild beast with sharp teeth", otherwise if the context is "events" then the unquestionable knowledge may be "*fiera* is a trade event".

Definition 3.1 formalises the agent as en entity characterised by an expression language and a set of beliefs with some unquestionable information about the object in negotiation.

Definition 3.1. *An* agent*, indicated by* ag*, is defined as a triple* $(\mathcal{L}_{\text{ag}}, Ax_{\text{ag}}, Stub_{\text{ag}})$ *where:*

- $\mathcal{L}_{\text{ag}}$ *is the expression language of* ag*;*
- Ax_{ag} *is the axioms' set establishing her initial point of view about the world;*
- $Stub_{\text{ag}}$ *is a subset of* Ax_{ag} *and it represents the unquestionable knowledge of* ag*.*

By Definition 3.1, the agents are characterised by a behavioral nature representing their negotiation power. I assume that each agent has at least one axiom and that she has at least one element in her stubbornness set.

The limit case is represented by those agents with empty stubbornness set. Agents with no unquestionable knowledge have no negotiation power and she is always inclined to give up her beliefs in order to meet the opponents' ones. Such an agent is called of *absolute flexibility*. Conversely, an agent is in *absolute stubbornness* when all her axioms are stubborn ones. An absolutely stubborn agent has high negotiation power and she never give up her beliefs. If an agent is nor absolutely flexible nor absolutely stubborn she is *imperfectly committed*. The following proposition is a direct consequence of the definition of absolutely flexible agent.

Proposition 3.2. *When in a 1-1 MN process, at least one agent is of absolute flexibility the outcome of the process is the opponent's first proposal.*

Proof Consider two agents ag_1 and ag_2 and suppose that ag_1 is of absolute flexibility, and it is ag_2's turn to start. Whatsoever the most specific theory ag_2 is proposing, ag_1 will accept it, otherwise, there would be at least one incompatible axiom for ag_2, in ag_1's most specific theory. This is contradictory with the assumption that ag_1 is of absolute flexibility. □

The above proposition states that an absolutely flexible agent is not a powerful negotiating one because she has not unquestionable beliefs about the world and she always accepts the other's theory.

Agents express themselves in a formal language, that is a language built by well-formed formulae. In this paper I limit myself in studying models based on propositional logic or in first-order logic. Starting from a language, an axioms' set and a set of inference rules (Δ), an agent builds her own theory about the world. Given $\mathrm{ag} = (\mathcal{L}_{\mathrm{ag}}, Ax_{\mathrm{ag}}, Stub_{\mathrm{ag}})$ and a set of the inference rules Δ, T_{ag} is the set of theorems built by Ax_{ag} applying a finite number of inference rules in Δ. $T_{\mathrm{ag}} = \{\phi | (Ax_{\mathrm{ag}}) \vdash^* \phi\}$ is the theory about the world of the agent ag and ag is identified by it.

In Section 2.2.1 I discussed about the necessity of agents having a preference order between their beliefs in order to negotiate. The preference relation helps the agent in choosing the next proposal to perform in the Meaning Negotiation; typically human people first ask for the most preferred thing and if no positive concession is received then a new request for a less preferred thing is done. In negotiation, participants typically ask more then how they expect because it increases the probability of having the expected outcome. For instance, suppose that Alice wants to sell her red skirt and she hopes to gain almost 20$; Bob is interested in buying the red skirt and he asks to Alice the purchase price. Alice may behave in two different ways:

1. Alice request 20$ to Bob;
2. Alice request 30$ to Bob.

In the former case Alice has less chances of selling the skirt to Bob than in the latter case. Bob may be annoyed of Alice's behaviour of not lowering her start price, and he may think she is not friendly. Viceversa, in the latter case Alice seems to be condescending and picks at Bob in negotiating for the skirt. Moreover, if Bob offers 25$, Alice obviously accept and gains more than what she expected.

In Meaning Negotiation, the proposals of the agents are definitions of the contending term and in general, the preference relation between proposals is coherent with the degree of the exhaustiveness of the definition proposed. Usually, a more exhaustive definition is preferred to a less exhaustive one. The proposals the agents make in negotiation are logical theories and exhaustivity relation between proposals translate in *restriction* (or *generalisation*) relation between logical theories. A theory T_1 is a restriction of a theory T_2, and T_2 is a generalisation of T_1, if

$$T_2 \vdash \bigwedge_{\phi \in T_1} \phi$$

and

$$T_1 \nvdash \bigwedge_{\psi \in T_2} \psi$$

Suppose, $T_1 = p \wedge q$ and $T_2 = p$ then T_1 is a restriction of T_2.
The generalisation of a theory is the result of a weakening operation on its formulas. There are many ways in which a theory can be generalised. In this thesis, I assume that each agent participating into a meaning negotiation process has a *finite* number of "partial" point of views that are generalisations of her initial one, T_{ag}. At each step of the negotiation process, the agent takes a node of the subjective hierarchy as her *current viewpoint*. The nodes of the subjective hierarchy are acceptable world representations, i.e. acceptable outcomes of the negotiation.

Moreover, here I do not care about how the agents weaken the formulas of their beliefs. I assume that if an agent think that a theory can be generalised then she also knows how the generalisation is done.

Henceforth, I use the symbol $\prec$ for the preference relation and by $T_1 \prec T_2$ I mean that T_1 is a restriction of T_2.

As said in Section 2.2.1, the preference order between the beliefs of the agent, produces the graph I called *subjective hierarchy*. In Definition 3.3 the subjective hierarchy structure is formalised.

Definition 3.3. *Given T_{ag}, an agent theory, based on a set of axioms Ax_{ag}, the* subjective hierarchy *of* ag *is a finite graph* $\mathrm{TheoryTree_{ag}} = \langle \mathrm{V}, \mathrm{E} \rangle$ *where:*

i) $T^0_{\mathrm{ag}} = Ax^*_{\mathrm{ag}}$ *is the head;*
ii) $\mathrm{V} \subseteq \{T^i_{\mathrm{ag}}\}$ *where for every* T^i_{ag}, $T^i_{\mathrm{ag}} \succ T^0_{\mathrm{ag}}$*;*
iii) $\mathrm{E} \subseteq \{(T^i_{\mathrm{ag}}, T^j_{\mathrm{ag}})\}$*, where both* T^i_{ag} *and* T^j_{ag} *are in* V *and* $T^i_{\mathrm{ag}} \prec T^j_{\mathrm{ag}}$*;*
iv) there's only one leaf, $\emptyset$*, representing a theory of the stubbornness axioms, then* $T^{\perp}_{\mathrm{ag}} = (Stub_{\mathrm{ag}})^*$
v) The relation E *is antitransitive.*

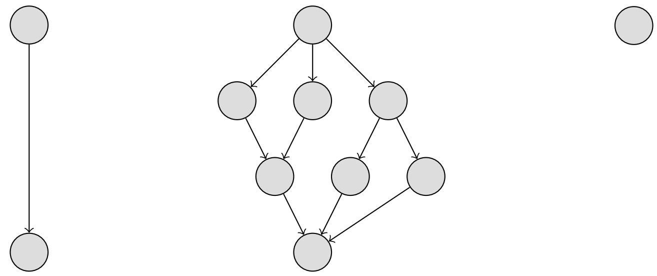
The last property of antitransitivity is settled because the represented relation is a partial order, therefore transitive. The transitive closure of the graph is the preference relation. This settling makes the model most compact. The structure of the subjective hierarchy depends on the negotiation power of the agent. Figure 3.1 shows the different structures. An absolutely flexible agent (Figure 3.1(a)) has two nodes: the root is her initial viewpoint and the leaf is the empty set. An absolutely stubborn agent (Figure 3.1(c)) has only one node that is both her initial and her stubbornness point of view. The imperfectly committed agent (Figure 3.1(b)) has many intermediate nodes that are her acceptable viewpoints, i.e. acceptable outcomes for the negotiation process.

A straightforward consequence of the definition of subjective hierarchy and of the relation $\prec$ is the following proposition.

Proposition 3.4. *A subjective hierarchy* $\mathrm{TheoryTree_{ag}} = \langle \mathrm{V}, \mathrm{E} \rangle$ *is a directed acyclic graph.*

Proof Straightforward consequence of the definition of subjective hierarchy. □

In general, apart for absolutely flexible agents, there are unquestionable axioms agents always defend. The negotiating agents choose the proposal to perform in the negotiation by keeping a node in their subjective hierarchy and the choose depends on the attitudes of the agents. As said in Section 2.3.2, the attitudes are the guidelines for behaving in multiple agent contexts. The agency of the



(a) Absolutely Flexible (b) Imperfectly Committed (c) Absolutely Stubborn

Figure 3.1. Subjective hierarchies of the absolutely flexible agent (a), of the imperfectly committed one (b), and of the absolutely stubborn one (c).

agents depends on their goals and on what they think about each other. The main attitudes, collaborative and competitive, call for community welfare, in the former case, and for personal advantage in the latter one. Different attitudes cause different visit ways of the subjective hierarchy.

Agents in a Meaning Negotiation MAS, have four feasible actions: propose, receive, accept or reject.

The receiving, accepting and rejecting actions are performed when the negotiation continues for at least another step, in the first case, when the received proposal is in some sense a *good* compromise for the agent, in the second case, and when the received proposal is not *acceptable* for the agent, in the last case.

The acceptability or the goodness of a proposal depends on the generalisation or restriction relation between the current point of view of the agent and her received proposal which is the current viewpoint of another agent in the system. The viewpoints of the agents relation are pairwise. Let ag_1 and ag_2 two negotiating agents, and T_{ag_1} and T_{ag_2} their current point of views; the relation between T_{ag_1} and T_{ag_2} are:

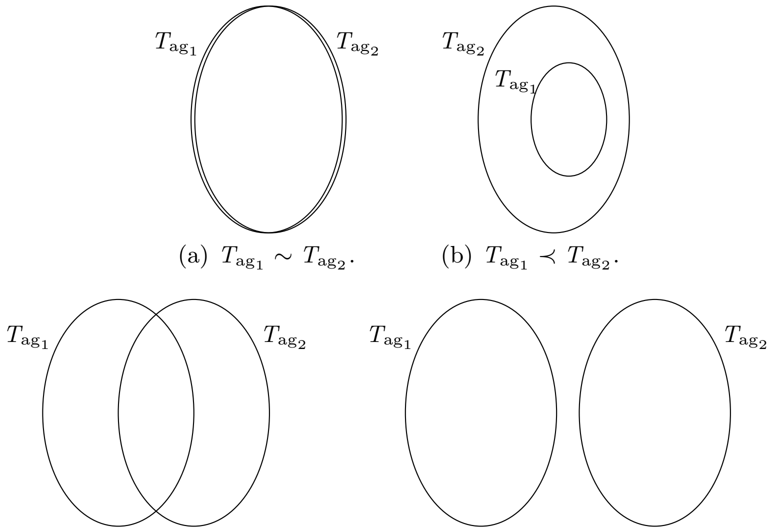
equivalence : if $T_{\mathrm{ag}_1} \vdash \bigwedge_{a \in T_{\mathrm{ag}_2}} a$ and $T_{\mathrm{ag}_2} \vdash \bigwedge_{a \in T_{\mathrm{ag}_1}} a$ and $T_{\mathrm{ag}_1} \wedge T_{\mathrm{ag}_2} \not\vdash \bot$ then theories are *equivalent* denoted with $T_{\mathrm{ag}_1} \sim T_{\mathrm{ag}_2}$;

restriction if $T_{\mathrm{ag}_1} \vdash \bigwedge_{a \in T_{\mathrm{ag}_2}} a$ and $T_2 \not\vdash \bigwedge_{a \in T_1} a$ and $T_{\mathrm{ag}_1} \wedge T_{\mathrm{ag}_2} \not\vdash \bot$ then T_{ag_1} is *limited* or *restricted* with respect to T_{ag_2}; we denote this with $T_{\mathrm{ag}_1} \prec T_{\mathrm{ag}_2}$;

compatibility if $T_{\mathrm{ag}_1} \not\vdash \bigwedge_{a \in T_{\mathrm{ag}_2}} a$ and $T_{\mathrm{ag}_2} \not\vdash \bigwedge_{a \in T_{\mathrm{ag}_1}} a$ and $T_{\mathrm{ag}_1} \wedge T_{\mathrm{ag}_2} \not\vdash \bot$ then theories are consistent but not comparable. In this case we say that the theories are *compatible* and denote it with $T_{\mathrm{ag}_1} \bowtie T_{\mathrm{ag}_2}$;

inconsistence if $T_{\mathrm{ag}_1} \wedge T_{\mathrm{ag}_2} \vdash \bot$ the theories are inconsistent; we denote this with $T_{\mathrm{ag}_1} \dashv\vdash T_{\mathrm{ag}_2}$.

In Figure 3.2 the above cases are represented. The theories of the agents' viewpoints are identified by their semantical models, i.e. by a set of interpretations satisfying them. The above relations are tested when agents received proposal. Because of the expression language in the definition of the agent, the test of the relation between theories have to use a translation function from the sending language to the receiver one. If ag_1 is the receiver and $\tau_{\mathrm{ag}_1,\mathrm{ag}_2}$ is the translation function



(a) $T_{ag_1} \sim T_{ag_2}$. (b) $T_{ag_1} \prec T_{ag_2}$.

(c) $T_{ag_1} \bowtie T_{ag_2}$. (d) $T_{ag_1} \dashv\vdash T_{ag_2}$.

Figure 3.2. Relations between viewpoints. Theories are equivalent when they have the same models (a). A restriction relation lays when one theory has less semantical models then the other (b). If the theories are consistent, i.e. they share models, they are compatible (c) else they are inconsistent (d).

from the ag_2's language to the ag_1's one, in the description of the relation above, $\tau_{\text{ag}_1,\text{ag}_2}(T_{\text{ag}_2})$ is instead of T_{ag_2}. A received proposal is good, i.e. acceptable, when it is not too restricted or not too general with respect to the agent's point of view. Therefore, the acceptability of an offer depends on its collocation in the subjective hierarchy. Definition 3.5 defines the acceptability of a received proposal.

Definition 3.5. *Let* $\text{ag}_1 = (\mathcal{L}\text{ag}_1, Ax_{\text{ag}_1}, Stub_{\text{ag}_1})$ *an agent and* $\text{TheoryTree}_{\text{ag}_1} = \langle \text{V}, \text{E} \rangle$ *her subjective hierarchy, and* T *a received proposal.* T *is* good*, or* acceptable*, for* ag_1 *iff*

- *T is equivalent to a node of the subjective hierarchy of* ag_1*,* $\text{TheoryTree}_{\text{ag}_1}$*; or*
- *T is a generalisation of a node of* $\text{TheoryTree}_{\text{ag}_1}$ *and it is not a generalisation of* $T^{\perp}_{\text{ag}_1}$*;*
- *T is a restriction of a node of* $\text{TheoryTree}_{\text{ag}_1}$ *and it is not a restriction of the source node of* $\text{TheoryTree}_{\text{ag}_1}$*,* $T^0_{\text{ag}_1}$*.*

In Figure 3.3, a graphical representation of a good offer with respect to a subjective hierarchy is shown. When the last made proposal is good for all the agents in the MAS receiving it, the Meaning Negotiation ends with a positive outcome, i.e. the shared theory. Otherwise, the Meaning Negotiation development depends on how an offer is not acceptable. In Figure 3.3, there are two red arrows of the mapping of T into the subjective hierarchy TheoryTree.

An agent cannot accept a too restricted offer because in a Meaning Negotiation context "restriction" means "more features". As said above, the agent characterised a concept definition with the features she considers relevant and which she

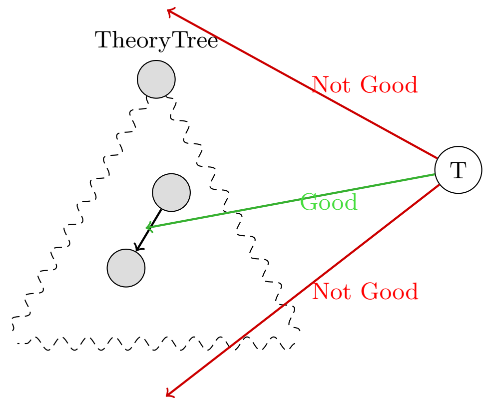


Figure 3.3. Acceptability of a received proposal. Dashed lines represent the conformation of the subjective hierarchy of the receiving agent. Gray nodes are admissible viewpoints of the agent and the white node is the received proposal T. T is good if it maps into the subjective hierarchy of the agent.

knows. A restricted definitions involve more terms then a less restricted one or add properties. Such a scenario is depicted in Figure 3.4(a). The Meaning Negotiation process continues for at least one step more in which the receiver hopes a generalisation of the sender's viewpoint.

A proposal is again not acceptable when it is too general, i.e. it does not include all the properties that the receiver considers as necessary. Accepting a too general proposal means that the receiver has no more to consider the beliefs she has in her stubbornness set. However it violates the definition of agent I gave in Definition 3.1. When the received offer is too general the Meaning Negotiation process ends with a negative outcome. Figure 3.4(b) shows the collocation of a too general proposal in the subjective hierarchy of the receiver.

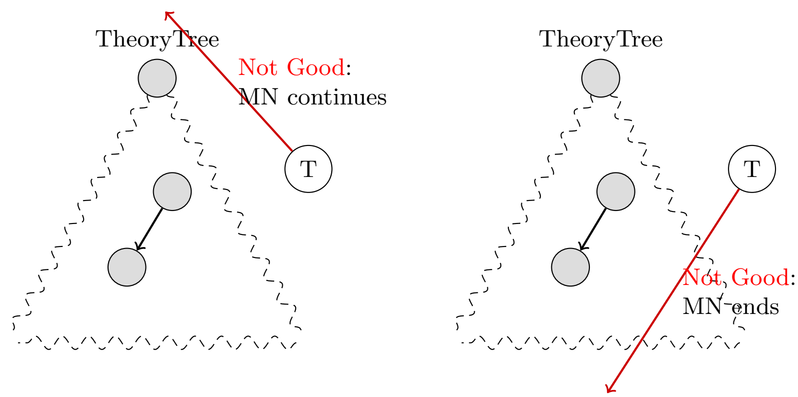
3.3 MN by Bargaining Game

3.3.1 Introduction

In this section I show a formalisation of 1-1 MN by the Bargaining Game. The scenario in which two agents negotiate in order to obtain an acceptable common view of a domain, is similar to the problem of finding how to split 1$ between two requesting players. I model MN by the Bargaining game in which the agents make proposal in turns until an agreement is found. In this section I first present the Bargaining Game (Section 3.3.2) and then I formalise the Meaning Negotiation in terms of a Bargaining Game (Section 3.3.3).

3.3.2 The Bargaining Game

"A two-person bargaining situation involves two individuals who have the opportunity to collaborate for mutual benefit in more than one way." [128].



(a) Too restricted offer. (b) Too general offer.

Figure 3.4. Different not good offers. The Meaning Negotiation proceeds in the first case (a) and ends in the second case (b).

In the Bargaining Game agents play in order to share one dollar. The negotiation process is by *bootstrap*, i.e. the players begin the bargaining by simultaneously proposing a share to each other. The goal of the players is to find a pair of shares that are *compatible*, i.e. the sum of the demands is less than one dollar. Therefore, if the agents i and j demand x and y respectively, they end the bargaining in a positive way if $x + y \leq 1$. When the initial proposals are not compatible, the players have to continue the bargaining by changing or reiterating the share they ask.

The game is two stage.

1. *Demand Stage*: In the first stage each agent demands her share x and thus offers to the opponent the remaining $1 - x$; if the demands are compatible the game ends positively, otherwise the second stage begins.
2. *The "war of attrition" Stage*: the agents make their demands in turns in order to find a pair of compatible demands.

The game develops by agents making proposals representing the part of one dollar they ask to exit the bargaining.

In [98], the author models the bargaining game with imperfect commitment. In this paper, the key assumption is that, with small probability, the players commit themselves to their initial demands before the war of attrition stage starts. The committed player is called *stubborn* and the not-committed one is called *flexible*. The commitment of an agent with respect to her initial position represents the *negotiation power* of the agent. "To cease or not to cease" are negotiation actions and the agent chooses whether to cease or not depending on her negotiation power. A stubborn agent commits herself to her initial demand and waits until her opponent accepts it; thus a stubborn agent perpetually makes the same proposal during the bargaining and accepts the opponent's one iff it is equivalent to her own.

The outcomes of a bargaining game are:

- *agreement*: if a pair of compatible proposals was performed by the agents, i.e. the two players agree on how the share of one dollar has to be;
- *disagreement*: otherwise.

The agreement outcome is reached by testing the compatibility relation between the proposal made by agents. Conversely, there is not a simple condition to say the bargaining ends negatively, thus in disagreement. The disagreement is the running condition of the bargaining and of the negotiation process because the involved agents continue in performing proposals until an agreement is found, so that a new proposal is made if the agents do not agree.

Perpetual disagreement is the limit case representing the never-ending negotiation; when the two players are stubborn there is no possibility to incur agreement. In [98] author asserts that a flexible agent gradually accepts the opponent's offer by choosing the timing acceptance randomly. He calls *potentially exhaustive time* the time needed for the flexible agent to accept the opponent's share. A stubborn agent has the same exhaustive time of her opponent because she never accepts until her opponent does.

At the beginning of the bargaining game, the agents do not know the negotiation power of the opponent. If the "war of attrition" stage begins, a player may *abduce* whether the opponent is committed to her initial demand or not. An agent can only perceive the negotiation power of her opponent through the negotiation proposal's sequence. Uncertainty about the opponent's negotiation power leads the bargaining in having multiple endings, positive or negative.

The necessary but not sufficient condition to find an equilibrium is that at least one of the two playing agent is flexible, as claimed in the following theorem.

Theorem 3.6 (Kambe, [98]). *If all agents playing in a Bargaining Game are stubborn, then the game has a perpetual disagreement.*

In the Theory of Games, the agents may change their negotiation power in an unique and irreversible fashion: flexible agents become stubborn. This happens when an agent has reached her minimum acceptable offer, under which the loss is perceived as excessive.

The main assumption in our framework is that all players are committed with respect to their initial proposals in different ways and with different degrees. Therefore, the commitment is a *preference* the agent has with respect to the set of her feasible demands. In the next section I formalise the Meaning Negotiation problem by the Bargaining Game.

3.3.3 The Bargaining Framework

In this section I give a formalisation of the steps of a pairwise Meaning Negotiation process with the Bargaining Game guidelines. I first discuss the multiple agent system configurations, i.e. players, actions and etc., and then show how the "demand" and "the war of attrition" stage develop.

The multiple agent system in a 1-1 Meaning Negotiation consists of two agents, named Alice = $(\mathcal{L}_{\mathrm{A}}, Ax_{\mathrm{A}}, Stub_{\mathrm{A}})$ and Bob = $(\mathcal{L}_{\mathrm{B}}, Ax_{\mathrm{B}}, Stub_{\mathrm{B}})$. Initially, I suppose that the agents express themselves in the same language, $\mathcal{L}_\text{A} = \mathcal{L}_\text{B}$ thus no translation function is needed and no misunderstandings occur.

The set of the feasible actions of the agents are: propose, receive, accept and reject. Agents in negotiation play in turns when entering in "the war of attrition" stage, thus if Alice sends a proposal to Bob, Bob makes a receive action and Alice makes a propose one.

Moreover, in this framework I do not take care of the agent attitudes and I only assume that the involved agents choose the proposal to put forward in some way.

The current proposal of each agent represents her current point of view, i.e. an admissible positive outcome of the process and a good definition of the item in negotiation. As said in the previous section, the agents change beliefs during the negotiation. Even if the initial set of beliefs is a parameter in agent definition and it is constant during the process, the agent changes the current beliefs' set. The initial knowledge of the agent can be called as *viewpoint* and the current set of beliefs as the *current angle*. A viewpoint has many angles and the agents negotiate them. Therefore the first proposal an agent makes is her viewpoint and the next ones are angles. Let T be an angle for the agent ag, then ag puts it forward by the logical formula: φ_T:

$$\varphi_T = \bigwedge_{\alpha \in T} \alpha$$

As direct consequence of the definition of subjective hierarchy, each node of the graph has a logical formula.

Henceforth, I use the symbol T_ag^{Cur} to denote the current angle of the agent ag and $\varphi_{T_\text{ag}^{Cur}}$ as its logical formula representation, the symbol, $\varphi_{T_\text{ag}^0}$ is the initial knowledge of the agents, i.e. her viewpoint.

Demand Stage

In the first stage of the Meaning Negotiation by Bargaining, the agents propose simultaneously their viewpoints. The simultaneity of the first stage of the negotiation is not problematic because the agents may propose in two different times and then synchronise them: the result is the same as the simultaneous proposing actions.

After proposing and thus receiving the opponent's viewpoint each agent knows whether they are in agreement or not.

The relation between the viewpoints is evaluated by both agents. Let ag_i and ag_j be the two players and ag_i the referring agent, each of the players perform the following tests in order:

1. "is my viewpoint the same as the opponent's one?" : $\vdash (\varphi_{T_{\text{ag}_i}^0} \leftrightarrow \varphi_{T_{\text{ag}_j}^0})$;
2. "is my viewpoint a restriction of the opponent's one?" : $\vdash (\varphi_{T_{\text{ag}_i}^0} \rightarrow \varphi_{T_{\text{ag}_j}^0})$;
3. "is my viewpoint a generalisation of the opponent's one?" : $\vdash (\varphi_{T_{\text{ag}_j}^0} \rightarrow \varphi_{T_{\text{ag}_i}^0})$;
4. "is my viewpoint only consistent with respect to the opponent's one?" : $(\varphi_{T_{\text{ag}_i}^0} \wedge \varphi_{T_{\text{ag}_j}^0}) \nvdash \bot$;

5. "is my viewpoint inconsistent with respect to the opponent's one?" : $(\varphi_{T^0_{\mathrm{ag}_i}} \wedge \varphi_{T^0_{\mathrm{ag}_j}}) \vdash \bot$.

The above evaluation tests have to be done in order and the positive answers of the questions state the relations between agents. The relations between the agents with respect to the above tests are:

1) agreement;
2) and 3) relative disagreement;
4) compatibility;
5) absolute disagreement.

The Demand stage and Meaning Negotiation ends with a positive outcome if the agents are in agreement relation, otherwise the next stage begins.

Figure 3.5 shows a simple graphical representation of the exchanging message of the agents in the demand stage.

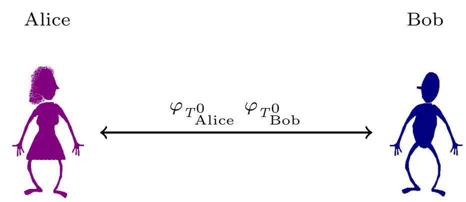


Figure 3.5. Demand Stage: Alice and Bob simultaneously propose their viewpoints.

The War of Attrition Stage

In the second stage of the Meaning Negotiation by Bargaining, the agents continue to propose until an agreement is found. Differently from the demand stage, in the war of attrition one it is needed an order of game between agents. The negotiation power of the agents makes an important role in the development and in the ending of the Meaning Negotiation process. In the case that both the agents are absolutely stubborn, the process cannot ends in positive because of the current not-agreement condition between and of the non-existence of new proposals. In all the other combinations of negotiation powers of the players, the Meaning Negotiation outcome depends on the relation between the stubbornness angles of the agents. Alice does not know which is the unquestionable knowledge of Bob and viceversa. Therefore, the eventual positive (or negative) outcome of the Meaning Negotiation is explored and searched by agents into their subjective hierarchies. If each agent reaches her stubbornness node and not an agreement is checked, then Meaning Negotiation ends negatively. The finiteness of the nodes of the subjective hierarchy leads to the finiteness of the Meaning Negotiation.

Figure 3.6 depicts the exchanging messages between agents during the war of attrition stage.

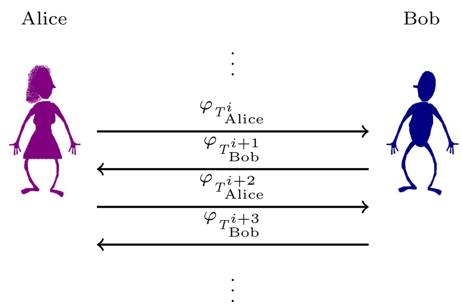


Figure 3.6. "The war of attrition" stage: Alice and Bob propose their viewpoints in turns.

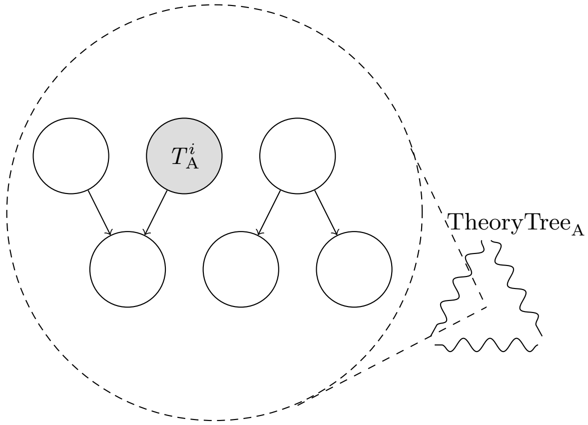
Let Alice be the next proposing agent. Alice knows her last offer, $\varphi_{T^i_{\mathrm{Alice}}}$, and the counterproposal of Bob, $\varphi_{T^{i+1}_{\mathrm{Bob}}}$. Alice has two ways in choosing the current angle and thus the next proposal to make:

- weakening her last offer and assume a less exhaustive definition as her new current angle (Figure 3.7(b));
- change her last offer with a different one with the same degree of exhaustiveness as her current angle (Figure 3.7(c)).

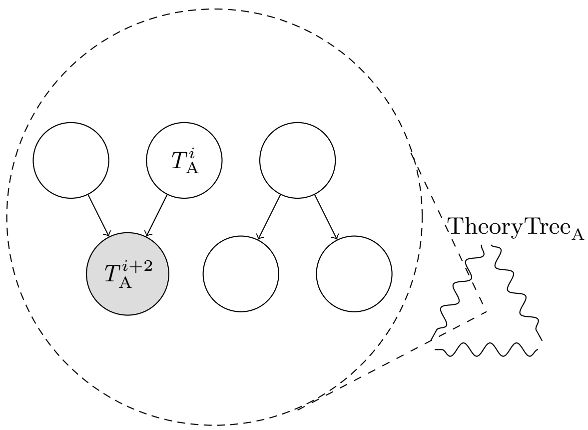
A weakening proposal is the result of a visit in depth from the current angle, instead the changing angle action corresponds to a step of visiting in breadth. As shown in Figure 3.7, the new current angle is related in some way to the last one and the choice of the best node to take as current angle depends on the attitudes of the agent and of her strategy. There are many available weakened and shifted angles for each current node. The agent chooses among the available nodes in dependence on the relation they are with respect to the last received offer and on her attitude. Table 3.1 shows how all the relations among the last proposal, the received offer and the new current angle and which is the visit way that causes it. Let me explain all the cases in Table 3.1.

$T^i_{\mathrm{A}} \prec T^{i+1}_{\mathrm{B}}$: by definition of $\prec$, $T^i_{\mathrm{A}} \prec T^{i+1}_{\mathrm{B}}$ iff $\phi_{T^i_{\mathrm{A}}} \rightarrow \phi_{T^{i+1}_{\mathrm{B}}}$.
- Suppose Alice makes a weakening, $\phi_{T^i_{\mathrm{A}}} \rightarrow \phi_{T^{i+2}_{\mathrm{A}}}$. Then
  1. if $\phi_{T^{i+2}_{\mathrm{A}}} \rightarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \prec T^{i+1}_{\mathrm{B}}$ (Figure 3.8(a));
  2. if $\phi_{T^{i+2}_{\mathrm{A}}} \leftrightarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \sim T^{i+1}_{\mathrm{B}}$(Figure 3.8(b));
  3. if $\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \succ T^{i+1}_{\mathrm{B}}$(Figure 3.8(c));
- Suppose Alice makes a change, $(\phi_{T^i_{\mathrm{A}}} \vee \phi_{T^{i+2}_{\mathrm{A}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \rightarrow \phi_{T^{i+2}_{\mathrm{A}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \leftarrow \phi_{T^{i+2}_{\mathrm{A}}})$. Then
  1. if $\phi_{T^{i+2}_{\mathrm{A}}} \rightarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \prec T^{i+1}_{\mathrm{B}}$ (Figure 3.8(d));
  2. if $(\phi_{T^{i+2}_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \rightarrow \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \bowtie T^{i+1}_{\mathrm{B}}$ (Figure 3.8(e));
  3. if $\neg(\phi_{T^{i+2}_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \dashv\vdash T^{i+1}_{\mathrm{B}}$ (Figure 3.8(f));

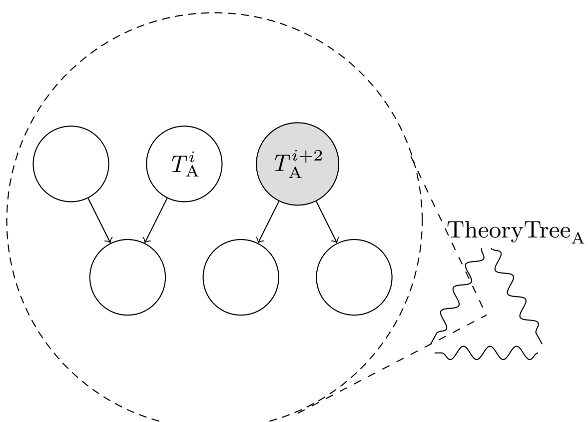
$T^i_{\mathrm{A}} \succ T^{i+1}_{\mathrm{B}}$: by definition of $\succ$, $T^i_{\mathrm{A}} \succ T^{i+1}_{\mathrm{B}}$ iff $\phi_{T^i_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}}$. Alice may perform a weakening action but the situation between the players does not change.



(a) The current angle.



(b) Weakening the knowledge.



(c) Changing the angle.

Figure 3.7. Choosing a new proposal. The figures show extracts from the subjective hierarchy of the agent Alice. The gray nodes represents current angles. The weakening proposal is a child node of the last one (from (a) to (b)). Changing angle means to choose a "brother" node in the subjective hierarchy (from (a) to (c)).

T^i_{A} ? T^{i+1}_{B}	T^{i+2}_{A} ? T^{i+1}_{B}	Weakening (W) or Changing (C)
	$\sim$	W
	$\succ$	W
$\prec$	$\succ$	C/W
	$\bowtie$	C
	$\dashv\vdash$	C
	$\succ$	C
$\succ$	$\bowtie$	C
	$\dashv\vdash$	C
	$\sim$	C
	$\succ$	C/W
$\bowtie$	$\prec$	C
	$\bowtie$	C/W
	$\dashv\vdash$	C/W
	$\sim$	C
	$\succ$	C
$\dashv\vdash$	$\prec$	C
	$\bowtie$	C
	$\dashv\vdash$	C

Table 3.1. Relations among the last proposal, the received offer and the new proposal.

Suppose Alice makes a changing action, $(\phi_{T^i_{\mathrm{A}}} \vee \phi_{T^{i+2}_{\mathrm{A}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \to \phi_{T^{i+2}_{\mathrm{A}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \leftarrow \phi_{T^{i+2}_{\mathrm{A}}})$. Then

1. if $\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \succ T^{i+1}_{\mathrm{B}}$ (Figure 3.9(a));
2. if $(\phi_{T^{i+2}_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \to \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \bowtie T^{i+1}_{\mathrm{B}}$ (Figure 3.9(b));
3. if $\neg(\phi_{T^{i+2}_{\mathrm{A}}} \vee \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \dashv\vdash T^{i+1}_{\mathrm{B}}$ (Figure 3.9(c));

$T^i_{\mathrm{A}} \bowtie T^{i+1}_{\mathrm{B}}$: by definition of $\bowtie$, $T^i_{\mathrm{A}} \bowtie T^{i+1}_{\mathrm{B}}$ iff $(\phi_{T^i_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \to \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}})$.

- Suppose Alice makes a weakening, $\phi_{T^i_{\mathrm{A}}} \to \phi_{T^{i+2}_{\mathrm{A}}}$. Then
  1. if $\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \succ T^{i+1}_{\mathrm{B}}$ (Figure 3.10(a));
  2. if $(\phi_{T^{i+2}_{\mathrm{A}}} \vee \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \to \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \bowtie T^{i+1}_{\mathrm{B}}$ (Figure 3.10(b));
  3. if $\neg(\phi_{T^{i+2}_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \dashv\vdash T^{i+1}_{\mathrm{B}}$ (Figure 3.10(c));
- Suppose Alice makes a change, $(\phi_{T^i_{\mathrm{A}}} \wedge \phi_{T^{i+2}_{\mathrm{A}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \to \phi_{T^{i+2}_{\mathrm{A}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \leftarrow \phi_{T^{i+2}_{\mathrm{A}}})$. Then
  1. if $\phi_{T^{i+2}_{\mathrm{A}}} \leftrightarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \sim T^{i+1}_{\mathrm{B}}$ (Figure 3.10(d));
  2. if $\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \succ T^{i+1}_{\mathrm{B}}$ (Figure 3.10(e));
  3. if $\phi_{T^{i+2}_{\mathrm{A}}} \to \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \prec T^{i+1}_{\mathrm{B}}$ (Figure 3.10(f));
  4. if $(\phi_{T^{i+2}_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \to \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \bowtie T^{i+1}_{\mathrm{B}}$ (Figure 3.10(g));
  5. if $\neg(\phi_{T^{i+2}_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \dashv\vdash T^{i+1}_{\mathrm{B}}$ (Figure 3.10(h));

$T^i_{\mathrm{A}} \dashv\vdash T^{i+1}_{\mathrm{B}}$: by definition of $\dashv\vdash$, $T^i_{\mathrm{A}} \dashv\vdash T\mathrm{B}^{i+1}$ iff $\neg(\phi_{T^i_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}})$. Whenever Alice makes a weakening action the absolute disagreement between Alice and Bob does not change because they do not share any generalisation of their viewpoints. Suppose Alice makes a changing action, $(\phi_{T^i_{\mathrm{A}}} \wedge \phi_{T^{i+2}_{\mathrm{A}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \rightarrow \phi_{T^{i+2}_{\mathrm{A}}}) \wedge \neg(\phi_{T^i_{\mathrm{A}}} \leftarrow \phi_{T^{i+2}_{\mathrm{A}}})$. Then

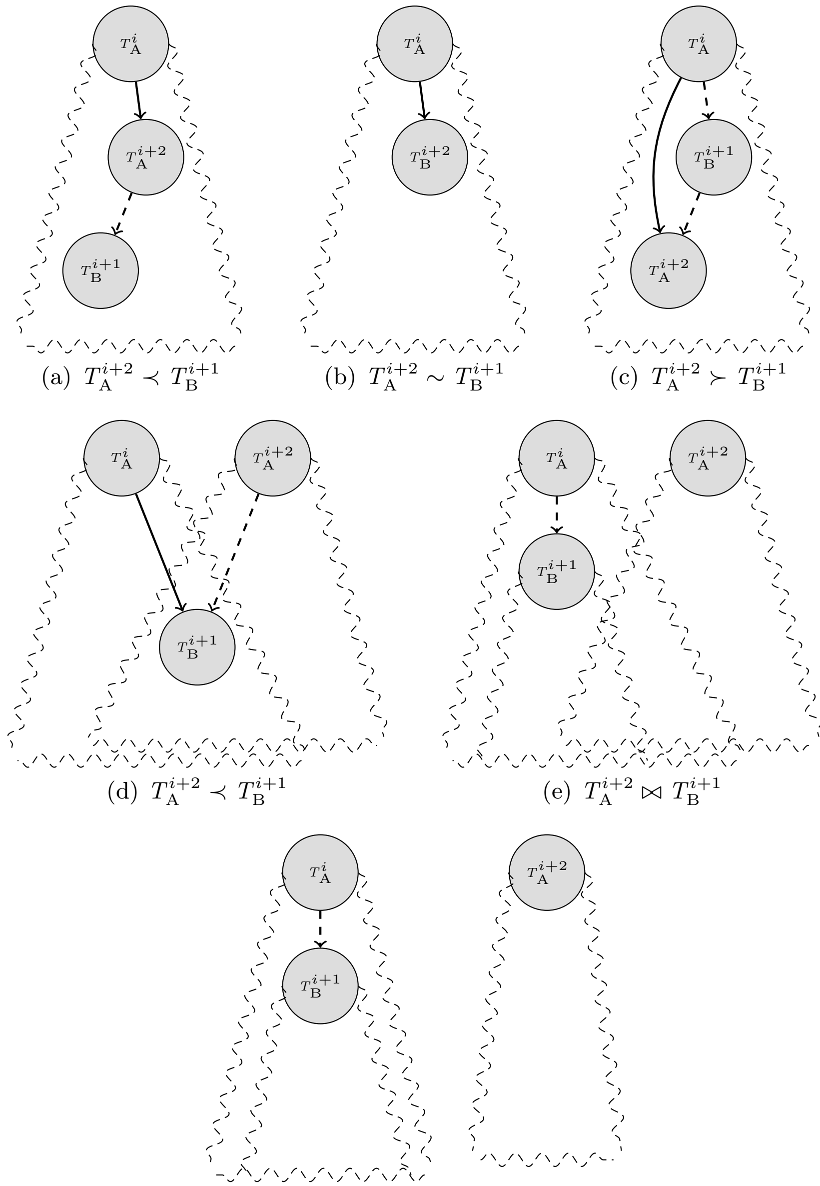
1. if $\phi_{T^{i+2}_{\mathrm{A}}} \leftrightarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \sim T^{i+1}_{\mathrm{B}}$ (Figure 3.11(a));
2. if $\phi_{T^{i+2}_{\mathrm{A}}} \rightarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \prec T^{i+1}_{\mathrm{B}}$ (Figure 3.11(b));
3. if $\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}}$ then $T^{i+2}_{\mathrm{A}} \succ T^{i+1}_{\mathrm{B}}$ (Figure 3.11(c));
4. if $(\phi_{T^{i+2}_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \rightarrow \phi_{T^{i+1}_{\mathrm{B}}}) \wedge \neg(\phi_{T^{i+2}_{\mathrm{A}}} \leftarrow \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \bowtie T^{i+1}_{\mathrm{B}}$ (Figure 3.11(d));
5. if $\neg(\phi_{T^{i+2}_{\mathrm{A}}} \wedge \phi_{T^{i+1}_{\mathrm{B}}})$ then $T^{i+2}_{\mathrm{A}} \dashv\vdash T^{i+1}_{\mathrm{B}}$ (Figure 3.11(e));.

Algorithm 1 implements the Meaning Negotiation by the Bargaining Game. The main phases of the algorithm are:

1. *initialisation*:
   the system keeps the initial viewpoints of the agents as their current angles ($T^{cur}_{\mathrm{ag}_1} = T^0_{\mathrm{ag}_1}$, $T^{cur}_{\mathrm{ag}_2} = T^0_{\mathrm{ag}_2}$) and the logical formulas for each of them ($\varphi_{T^{cur}_{\mathrm{ag}_1}} = \bigwedge_{\alpha \in T^{cur}_{\mathrm{ag}_1}} \alpha$, $\varphi_{T^{cur}_{\mathrm{ag}_2}} = \bigwedge_{\beta \in T^{cur}_{\mathrm{ag}_2}} \beta$). Two boolean variables are used to keep under control the stubbornness of the agents. At the beginning of the MN the agents are assumed to be not absolutely stubborn;
2. *demand stage*:
   each agent sends her viewpoint and receives the opponent's one; the system evaluates the exchanged messages to find if an agreement is reached. If it is the case, the MN ends with a positive outcome that is $T^0_{\mathrm{ag}_1}$ or $T^0_{\mathrm{ag}_2}$ indifferently;
3. *the war of attrition stage*:
   at the beginning of the war of attrition stage a proposing order between agents is established ($i = 1, j = 2$) and the stubbornness condition of the proposing agent is tested. The proposing agent chooses the next angle ($T = \mathrm{visit}(\mathrm{ag}_i, \mathrm{TheoryTree}_{\mathrm{ag}_i}, T^{cur}_{\mathrm{ag}_i})$). The new node T is reached by weakening, changing action or by renewing the last proposal. The strategy of the agent makes deterministic the choice of T. Having T as the new proposal, ag_i tests it is a generalisation of the ag_j's last offer and in this case, she backwards looks for a more restricted proposal among the parents of T in her subjective hierarchy $\mathrm{TheoryTree}_{\mathrm{ag}_i}$. This action is a *retraction* and it causes an optimisation in the outcome of the MN. At the end of a war of attrition turn, the proposing agent ag_i sends $T^{cur}_{\mathrm{ag}_i}$ to ag_j and a new turn begins with ag_j as proposing agent ($temp = j$, $j = i$, $i = temp$). The war of attrition stage ends when an agreement is found or when both agents are in stubbornness.

3.3.4 Theoretical Results

In this section, I present some results obtained by our formalisation. I show that the meaning negotiation algorithm is correct and complete by Theorem 3.8.
I can now derive a theoretical decidability result, regarding the problem defined for one pair of agents that negotiate propositional theories in subjective hierarchies.



(a) $T_A^{i+2} \prec T_B^{i+1}$ (b) $T_A^{i+2} \sim T_B^{i+1}$ (c) $T_A^{i+2} \succ T_B^{i+1}$

(d) $T_A^{i+2} \prec T_B^{i+1}$ (e) $T_A^{i+2} \bowtie T_B^{i+1}$

(f) $T_A^{i+2} \dashv\vdash T_B^{i+1}$

Figure 3.8. $T_A^i \prec T_B^{i+1}$

Algorithm 1: MN algorithm by Bargaining.

Input : Two agents and their subjective hierarchies, ag_1, ag_2, $\mathrm{TheoryTree}_{\mathrm{ag}_1}$ and $\mathrm{TheoryTree}_{\mathrm{ag}_2}$

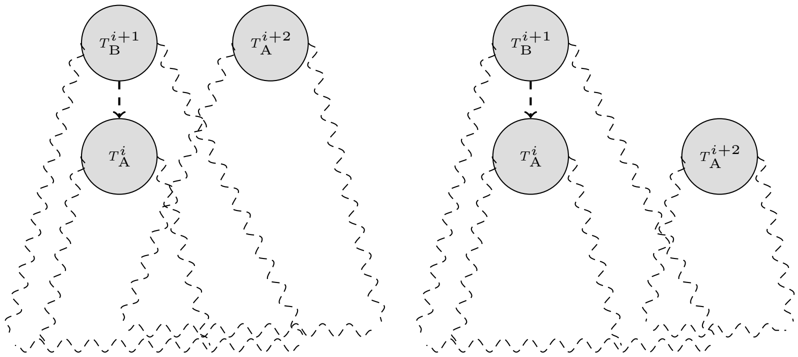
Output: A negotiated theory, if possible, otherwise $\bot$

`/* initialisation */`

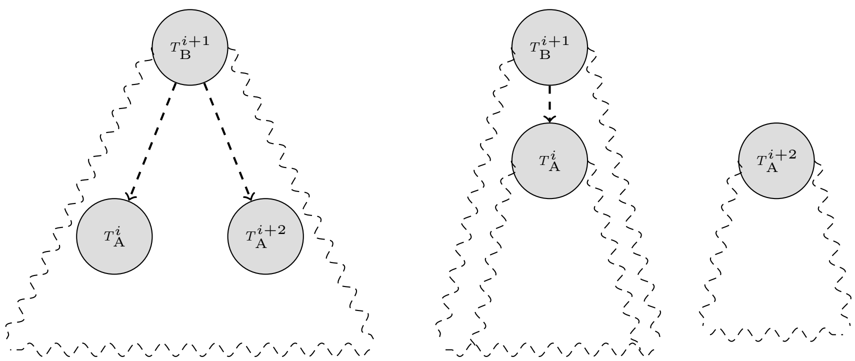
$stub_1 = stub_2 =$ `false`;
$T^{cur}_{\mathrm{ag}_1} = T^{0}_{\mathrm{ag}_1}$;
$T^{cur}_{\mathrm{ag}_2} = T^{0}_{\mathrm{ag}_2}$;
$\varphi_{T^{cur}_{\mathrm{ag}_1}} = \bigwedge_{\alpha \in T^{cur}_{\mathrm{ag}_1}} \alpha$;
$\varphi_{T^{cur}_{\mathrm{ag}_2}} = \bigwedge_{\beta \in T^{cur}_{\mathrm{ag}_2}} \beta$;

`/* Demand Stage */`

ag_1 proposes $\varphi_{T^{cur}_{\mathrm{ag}_1}}$ to ag_2, ag_2 receives $\varphi_{T^{cur}_{\mathrm{ag}_1}}$ from ag_1 ;
ag_2 proposes $\varphi_{T^{cur}_{\mathrm{ag}_2}}$ to ag_1, ag_1 receives $\varphi_{T^{cur}_{\mathrm{ag}_2}}$ from ag_2 ;
if $(\varphi_{T^{cur}_{\mathrm{ag}_i}} \leftrightarrow \varphi_{T^{cur}_{\mathrm{ag}_j}})$ **then**
    return $T^{cur}_{\mathrm{ag}_1}$ `// Agreement`
else
    `/* ``The War of Attrition'' stage */`
    $i = 1, j = 2$; `//` ag_1 `is the receiver and` ag_2 `is the sender`
    while not$(\varphi_{T^{cur}_{\mathrm{ag}_1}} \leftrightarrow \varphi_{T^{cur}_{\mathrm{ag}_2}})$ **or** $(\neg stub_1 \vee \neg stub_2)$ **do**
        if $(T^{cur}_{\mathrm{ag}_i} \sim T^{\bot}_{\mathrm{ag}_i})$ **then**
            `/*` ag_i `is in stubbornness set */`
            $stub_i =$ `true` ;
        end
        $T = \mathrm{visit}(\mathrm{ag}_i, \mathrm{TheoryTree}_{\mathrm{ag}_i}, T^{cur}_{\mathrm{ag}_i})$;
        $T^{cur}_{\mathrm{ag}_i} = T$;
        $\varphi_{T^{cur}_{\mathrm{ag}_i}} = \bigwedge_{\alpha \in T^{cur}_{\mathrm{ag}_1}} \alpha$;
        if $(\varphi_{T^{cur}_{\mathrm{ag}_j}} \rightarrow \varphi_{T^{cur}_{\mathrm{ag}_i}})$ **then**
            `/* find the more restrictive theory (retraction) */`
            ag_i finds the last parent of $T^{cur}_{\mathrm{ag}_i}$, let it $p(T^{cur}_{\mathrm{ag}_i})$, such that $(\varphi_{T^{cur}_{\mathrm{ag}_j}} \rightarrow \varphi_{p(T^{cur}_{\mathrm{ag}_i})})$;
            $T^{cur}_{\mathrm{ag}_i} = p(T^{cur}_{\mathrm{ag}_i})$;
            $\varphi_{T^{cur}_{\mathrm{ag}_i}} = \bigwedge_{\alpha \in T^{cur}_{\mathrm{ag}_i}} \alpha$;
        end
        ag_i proposes $\varphi_{T^{cur}_{\mathrm{ag}_i}}$ to ag_j, ag_j receives $\varphi_{T^{cur}_{\mathrm{ag}_i}}$ from ag_i ;
        $temp = j$;
        $j = i$;
        $i = temp$;
    end
end
if $(\varphi_{T^{cur}_{\mathrm{ag}_i}} \leftrightarrow \varphi_{T^{cur}_{\mathrm{ag}_j}})$ **then**
    return $T^{cur}_{\mathrm{ag}_i}$ `// Agreement`
else
    return $\bot$ `// Disagreement`
end



(a) $T_A^{i+2} \bowtie T_B^{i+1}$



(b) $T_A^{i+2} \succ T_B^{i+1}$ (c) $T_A^{i+2} \nVdash T_B^{i+1}$

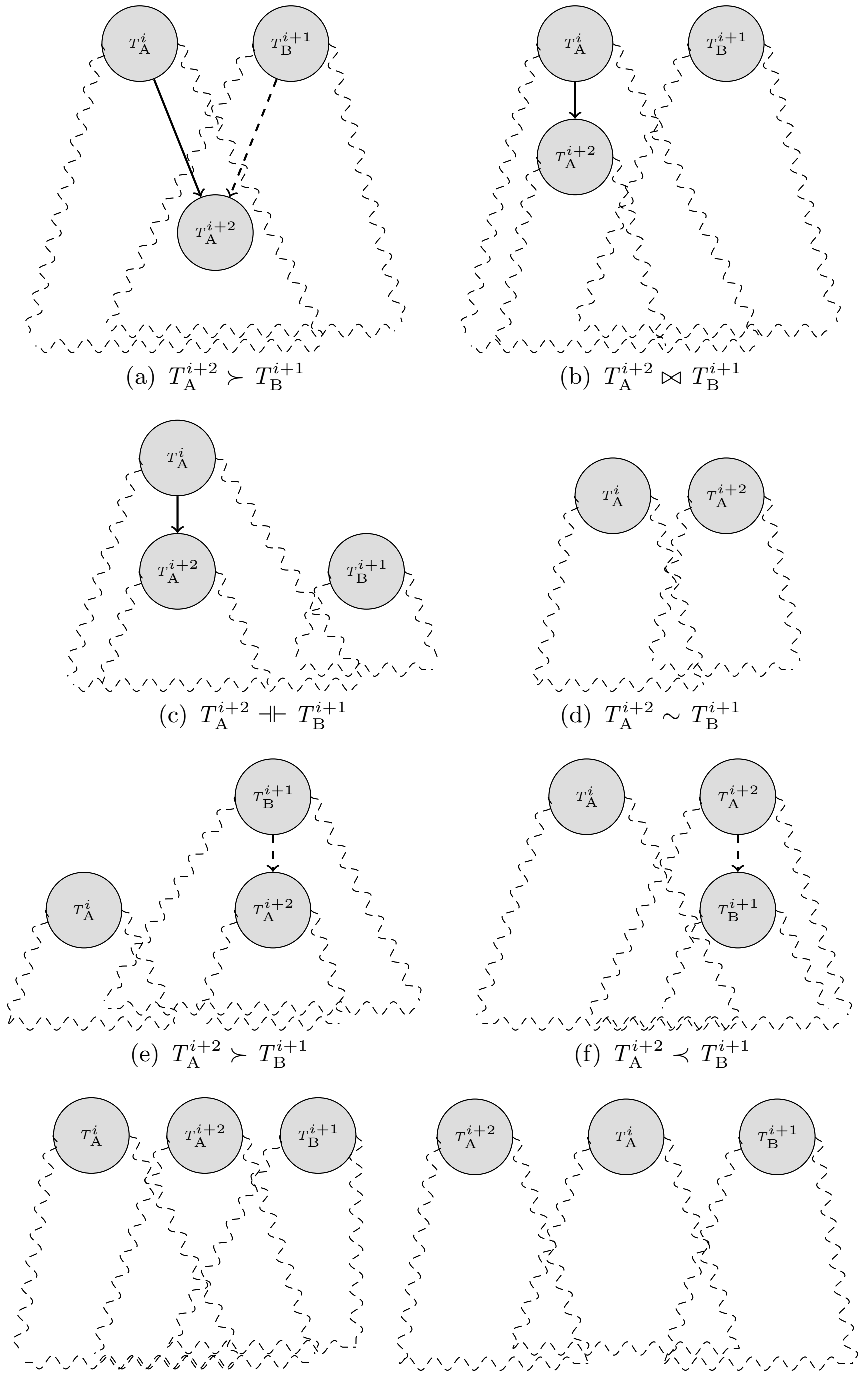
Figure 3.9. $T_A^{i} \succ T_B^{i+1}$

Given two agents ag_1 and ag_2 that possess one subjective hierarchy each, the problem of performing a negotiation process of the hierarchies between those agents is named *meaning negotiation problem.*

Theorem 3.7. *The meaning negotiation problem is decidable iff the theories of the agents are propositional.*

Proof

- ($\Rightarrow$) Suppose that Meaning Negotiation is fully decidable, i.e. there exists an algorithm that computes the shared theory between agents. The main test of the Meaning Negotiation problem is to check if the logical formula for the theory of agent ag_i is logically equivalent to the logical formula for the theory f agent ag_j, where $\mathrm{ag}_i, \mathrm{ag}_j \in \mathrm{Ag}$. This test translates in "is φ_{ag_i} in T_{ag_j}?". The membership of a formula to a propositional logical theory is decidable only for propositional theories. Therefore, all the theories of the agents are propositional.
- ($\Leftarrow$) Suppose that T_{ag_i} is propositional for all $\mathrm{ag}_i \in \mathrm{Ag}$, i.e. that there exists an algorithm computing the membership of a formula to their logical theories. The membership test is he main point of the Meaning Negotiation problem. In fact



(a) $T_A^{i+2} \succ T_B^{i+1}$

(b) $T_A^{i+2} \bowtie T_B^{i+1}$

(c) $T_A^{i+2} \nVdash T_B^{i+1}$

(d) $T_A^{i+2} \sim T_B^{i+1}$

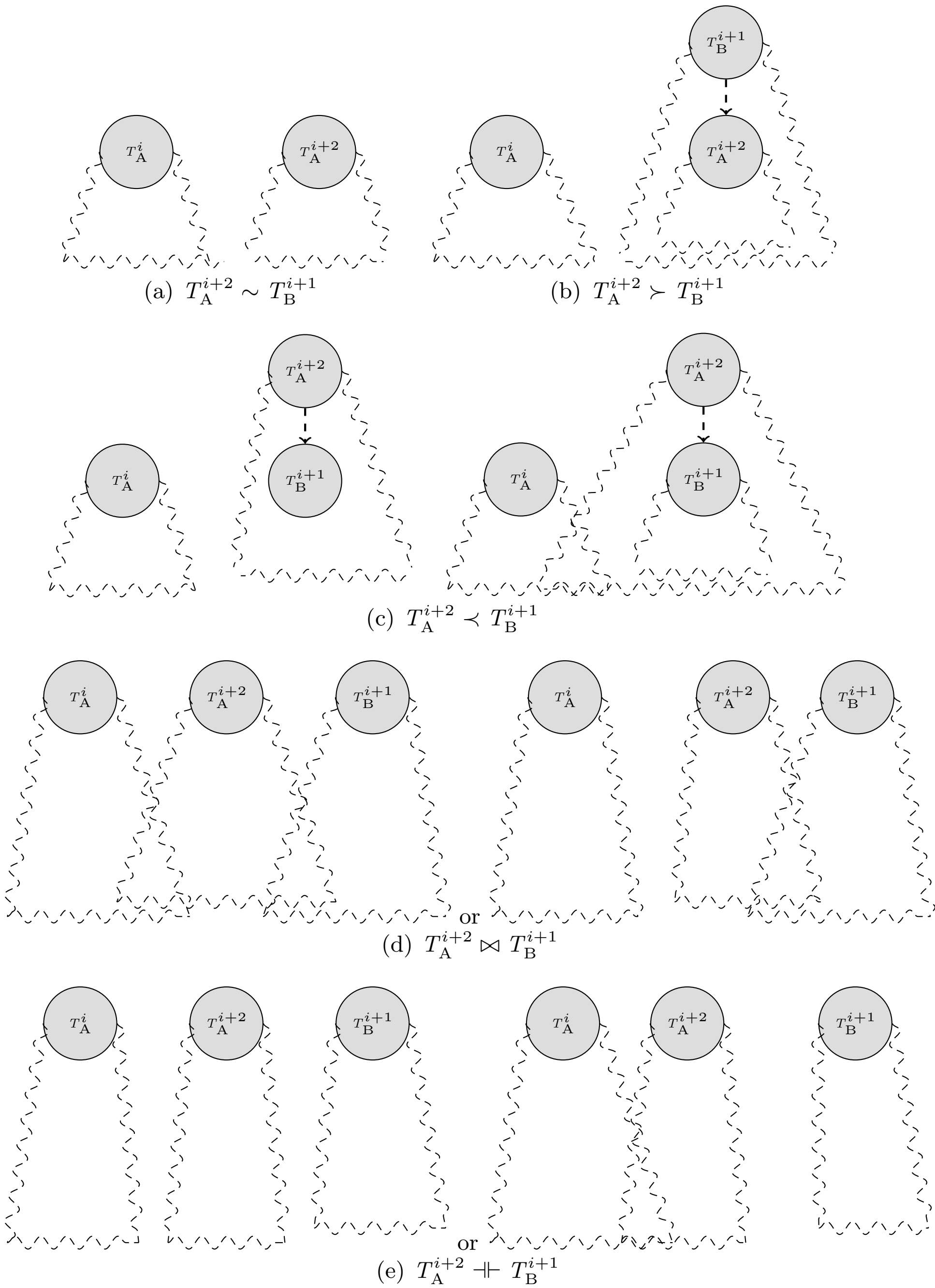
(e) $T_A^{i+2} \succ T_B^{i+1}$

(f) $T_A^{i+2} \prec T_B^{i+1}$

(g) $T_A^{i+2} \bowtie T_B^{i+1}$

(h) $T_A^{i+2} \nVdash T_B^{i+1}$

Figure 3.10. $T_A^i \bowtie T_B^{i+1}$



(a) $T^{i+2}_{\mathrm{A}} \sim T^{i+1}_{\mathrm{B}}$ (b) $T^{i+2}_{\mathrm{A}} \succ T^{i+1}_{\mathrm{B}}$

(c) $T^{i+2}_{\mathrm{A}} \prec T^{i+1}_{\mathrm{B}}$

(d) $T^{i+2}_{\mathrm{A}} \bowtie T^{i+1}_{\mathrm{B}}$

(e) $T^{i+2}_{\mathrm{A}} \dashv\vdash T^{i+1}_{\mathrm{B}}$

Figure 3.11. $T^i_{\mathrm{A}} \dashv\vdash T^{i+1}_{\mathrm{B}}$

the test $(\varphi_{\mathrm{ag}_i} \leftrightarrow \varphi_{\mathrm{ag}_j})$ is equivalent to test if $\varphi_{\mathrm{ag}_i} \in T_{\mathrm{ag}_j}$ and $\varphi_{\mathrm{ag}_j} \in T_{\mathrm{ag}_2}$. The two test are decidable because both T_{ag_i} and T_{ag_j} are decidable then Meaning Negotiation is decidable.

□

In particular, Algorithm 1 is able to process meaning negotiation problems. The following theorem proves that if there is a positive outcome then the algorithm finds it (completeness) and that if the algorithm produces a positive outcome then it is a shared viewpoint for the agents (correctness).

Theorem 3.8. *Algorithm 1 is correct and complete.*

Proof Suppose that there is not a possible positive outcome, that is the agents cannot share a point of view. In such a case, agent ag_i, after visiting all nodes of her $\mathrm{TheoryTree}_i$, reaches one leaf node that constitutes her current theory. The same happens for her opponent player. Each agent tests that the two theories are not compatible and that she cannot propose another theory because she is at a leaf node and has already visited all the nodes having an edge connecting them to the leaf one. By construction the agents go to step 10 and then the negotiation fails. Suppose that two theories exist, one per agent, that are equivalent. Suppose that the process starts with the proposal of ag_1; she continues to compare the theory she received with the theory she is currently assuming as current one, so to make a new proposal until the current theory of the opponent is compatible with her current one. When this situation is reached then also ag_2 thinks that the two theories are compatible. The process ends positively with agents sharing a theory about the world. □

The complexity of Algorithm 1 is obtained in Theorem 3.9.

Theorem 3.9. *Algorithm 1 solves the Meaning Negotiation Problem in* $\mathbf{O}(h \times \mathbf{C})$ *where* h *is the maximum number of nodes in the agents' hierarchies and* $\mathbf{C}$ *is the computational cost of the relationship test between theories of the agents.*

Proof Consider the case in which there is no possible shared theory. Since the stubbornness sets of the two agents are incompatible, I shall visit all the nodes of both subjective hierarchies in turn, in order to reach the conclusion that no common shared theory can be negotiated. Moreover, if such a common shared theory can be found the process necessarily terminates before. Therefore the case of incompatible stubbornness sets is the worst complexity case.

Suppose $\mathrm{ag}_1 = (\mathcal{L}\mathrm{ag}_1, Ax_{\mathrm{ag}_1}, Stub_{\mathrm{ag}_1})$ and $\mathrm{ag}_2 = (\mathcal{L}\mathrm{ag}_2, Ax_{\mathrm{ag}_2}, Stub_{\mathrm{ag}_2})$. Let be n_i the number of nodes ag_i can negotiate. Each subjective hierarchy $\mathrm{TheoryTree}_i$ of ag_i has h_i number of vertices. By construction, Algorithm 1 visits all the vertices. Then such algorithm makes $max\{h_1, h_2\}$ steps in the worst case and for each step it makes a test of the relationship between theories that costs $\mathbf{C}$. □

In particular, when the theories of the agents are propositional, the computational cost of the algorithm is $\mathbf{O}(h \times m \times 2^l)$ where h is the maximum number of nodes in the subjective hierarchies, m is the maximum number of logical formulas in each theories of agents, and l is the maximum number of occurring symbols.
An interesting special case occurs when the subjective hierarchies cannot reach a final agreement about the negotiated meaning. The following theorem establishes when this is the case.

Theorem 3.10. *If* $(Stub_{\mathrm{ag}_1})^* \not\sim (Stub_{\mathrm{ag}_2})^*$ *then the meaning negotiation process fails.*

Proof By construction, $(Stub_{\mathrm{ag}_1})^*$ is the unique leaf node of subjective hierarchy $\mathrm{TheoryTree}_{\mathrm{ag}_i}$ of the agent ag_i and it represents the most general theory ag_i can assume. If the most general theories of agents are not identical then no other less general ones are. □

There are other special cases in meaning negotiation process: when at least one agent is of absolute flexibility (see 3.1) and when both agents are of absolute stubbornness. The first case is enunciated in proposition 3.2. The last case is established by Theorem 3.11[1].

Theorem 3.11. *If both agents in a meaning negotiation process are absolutely stubborn then the complexity of the process is* $O(m \times l)$ *where* n *is the maximum number of theorems in agents' theory and* l *is the maximum number of symbols occurring in a theorem.*

Proof Suppose ag_1 and ag_2 are absolutely stubborn then $T_{\mathrm{ag}_i} = (Stub_{\mathrm{ag}_i})^*$ $\forall i \in \{1, 2\}$. Suppose the meaning negotiation process starts with ag_2 sending $ThCur_2 = T_{\mathrm{ag}_2}$ to ag_1. If $T_{\mathrm{ag}_1} \vdash \varphi(T_{\mathrm{ag}_2})'$ then agreement is reached otherwise the process fails. The process complexity depends on the complexity of theorem proving in propositional logic. Without loss of generality I can assume that the axioms are expressed in Clausal Normal Form, so I can use the resolution principle (see [44]) to prove the relevant theorems. Resolution principle implementations are linear in the number of symbols occurring in formulas and in the number of formulas. □

3.4 MN by English Auction

3.4.1 Introduction

In this section I show how I formalise 1-n MN by the English Auction Game. 1-n Meaning Negotiation takes place when there are more than two people that want to share something. In general, the first agent making a proposal is the one that evaluates the opponents' offers and that states when the involved agents agree. Therefore, the first *bidding* agent behaves like a referee in an English Auction scenario. In fact, as said above, the agents negotiate by ceasing, if possible, or by rebidding the precedent proposal if they strategically think it is the best action to perform.

In this section I first present the English Auction Game (Section 3.4.2) and then formalise the Meaning Negotiation in terms of a English Auction Game (Section 3.4.3).

[1] I assume here that the underlying theory is propositional logic. However analogous proofs can be exhibited for different logical models, so that the computed complexity is parametric in the underlying theory. For first-order logic I can derive a corresponding theorem, that is omitted and left to the reader.

3.4.2 The English Auction Game

English Auction is the most used game in the modelisation of the Meaning Negotiation in which more than two agents are involved. As said above, the game begins by the proposal of the auctioneer that is called *reservation price* and it is the minimum price the agents have to pay to win the auction. In the next step of the English Auction, each player makes her offer by incrementing the last bidden one, i.e. the auctioneer's proposal. There is not a fixed number of turns for agents' bidding, instead the game continues until no more bids are performed. The game ends with a winner that is the agent who bids the highest offer.

In a Meaning Negotiation perspective, the English Auction game is slightly different in the outcome. The goal of the negotiation is agents in sharing a viewpoint. Therefore the positive ending condition of the game is that all the agents make the same bid and the bidden proposal is the representation of their viewpoints.

There are Meaning Negotiation contexts in which it is sufficient a "major" part of the agents in agreeing about something to consider positive the negotiation. In general "major part" means that a number of agents, typically more then 50% , but it may mean that a part of the most trustworthy agents are in agreement. The latter case prevails when there are specialists about the negotiation subject into the multiple agent system and their opinion is more relevant then the opponents' ones. In my thesis, the trustworthiness of the agent is not considered specifically because it is represented as inbuilt the definition of an agent. When participating to a negotiation process, the agents assume a viewpoint and many admissible angles of it. A specialist knows more about the negotiation subject than a less expert agent and her negotiation behaviour will of making concessions as few as possible. Conversely, if a no expert agent knows that an agent the MAS is a specialist, then she trusts the specialist and probably makes concessions with respect to the proposals of the specialist. Therefore, the degree of knowledge of an agent translates into the trustworthiness with respect to herself, thus into her negotiation attitude.

In the former case, the minimum number of agreeing agents is a parameter of the game: suppose k is the chosen number for "major part", the meaning negotiation continues until at least k agents agree about a common angle. The minimum number of agreing agents is called *degree of sharing*. A Meaning Negotiation process for more than two agents has two positive ending conditions and two types of positive outcomes, if a positive outcome exists:

partially positive : when the degree of sharing is less than the number of the participants;

totally positive : when the degree of sharing is equal to the number of the negotiating agents.

Figure 3.12 shows a scenario in which four fictitious agents, Trisha, Harry, Craig and Oliver discuss on the effectiveness of an educational game. This is an extension of the example of Ravenscroft and McAlister ([146], Table 1 p.82). Each agent proposes her viewpoint about the topic of the discussion and agrees or not with the opponents' ones. They say "Good point!" to accept the received proposal. Trisha is the first asserting agent and behaves like an auctioneer for the debate. The agents close the dialogue in a totally positive way because all of them agree on what Oliver said in step 13. Conversely, suppose the dialogue ends at step 11, only Trisha and Harry agree on a viewpoint, so the negotiation ends in a partially positive way for them and negatively for the others.

(1) Trisha **I think**... a lot of learning games suck and that's why they're not used
(2) Harry **Why do you say that?**...
(3) Trisha **Let me explain**... a large number of games on the market have not caught up with the mainstream video industry with regard to narrative sophistication etc. When they are presented to an already media savvy kid... they don't play them
(4) Harry **I agree because**... I guess as million selling computer games don't even make any money till the third edition, it must be impossible for educational developers to keep up
(5) Trisha **I agree because**... the educational industry is outgunned by the "blow'em up" video game manufacturer, rather depressing...
(6) Craig **I disagree because**... I imagined educational game being played only in educational establishment and shoot em up being played at home. Therefore, the two should not cross.
(7) Trisha **Why do you say that?**... if an educational games was seen as fun, wouldn't it stand on equal footing with the shoot em ups?
(8) Harry **Let me explain**... the funding for comp games is massive compared to educational games, they make more money now than the film industry, but its not an immediate turn around. So for an educational game to compete is nigh on impossible.
(9) Oliver **Do we all agree?**... that educational games are poorly designed and people are not really interested in them?
(10) Harry **I disagree because**... although most are, you can probably learn more about ancient history from playing something like rise of nations than you would remember from a book
(11) Trisha **Good point.**
(12) Oliver **Let me explain**... the reason why the diffusion of educational games is poor lies on the lack of advertisement of them. It could be useful to produce signed gadgets and clothes for children.
(13) Craig **I agree because**... signed gadgets and clothes may become a new fashion for children.
(14) Harry **Good point**.
(15) Trisha **Good point**.

Figure 3.12. A critical discussion as reasoning game demonstrating constructive conflict, explanation and partial agreement (originally [146] Table 1 p. 82). The sentence "good point" is here considered to be a deliberative conclusion of the discussion by the contenders.

The role of the auctioneer is to monitor the game in order to understand when it ends and whether in a positive or a negative way. In general, the auctioneer is the first bidding agent but in a negotiation perspective she may play in two ways: active or passive. An active referee is a participant of the negotiation and the reservation price is her viewpoint. Moreover, an active referee makes herself proposals during the auction as all the other agents and she is considered in the agreement test. A passive auctioneer does not affects the negotiation, she only tests the process and makes only one bid, the first one for the reservation price.

3.4.3 The English Auction Framework

In this section I formalise the MN problem as an English Auction game. The framework I present models the MN process by assuming that there are at least three agents involved and that one of them is nominated the *auctioneer* (referee) namely the agent who controls and decides the process development. The existence of a referee is relevant but not a constraint to our model because, generally the first bidding agent is the one that regulates the game for every type of auction. The negotiation is performed by a dialogue among the agents involved: bids and accepting or rejecting proposals are send as messages to the agents.

The main assumption is that only the referee receives the proposals of the players. The auctioneer broadcasts her proposal and the participants make counteroffers and send them only to the auctioneer. The evaluation of the counterproposals is left to the referee. This way avoids that the agents evaluate and propose at the same time. The result is n, where n is the number of the agents involved, parallel sessions of Meaning Negotiation by Bargaining in which one of the player is the auctioneer and the other is one among the agents. Figure 3.13 depicts the configuration of the multiple agent system for my formalism. The agents negotiate one-to-one with the auctioneer who is involved in n bargaining negotiations. The

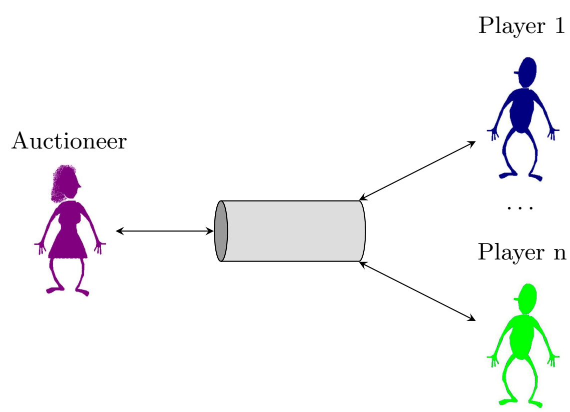


Figure 3.13. Meaning Negotiation by English Auction configuration.

auctioneer has to make the same proposal for each of the bargaining negotiations in order to synchronise all the 1-1 negotiations as a single 1-n one and find a common viewpoint, i.e. the same outcome for the 1-1 negotiations.

I formalise the MN by viewing it as a sequence of *beats*. Every beat is started by the auctioneer and participated by all the other agents in the game. Because the MN process works to build shared knowledge among a set of negotiating agents, I assume that the referee allows the *degree of sharing* she wants to obtain in front of the auction. The degree establishes the minimum number of agreeing agents the auctioneer admits to consider the MN positive: if n is the number of negotiating agents, the degree of sharing α is such that $0 < \alpha \leq n$. The case in which $\alpha = 1$ is clearly degenerated being possible an outcome in which the auctioneer is the only agreeing agent.

Suppose n is the number of the negotiating agents. A *beat* is a set of n pairs of (auctioneer proposal, agent counterproposal). As in the framework above (Section 3.3.3), the proposals and the counterproposals of the agents in Meaning Negotiation represent viewpoints and angles. The current proposal of each agent represents her current point of view, i.e. an admissible positive outcome of the process and a good definition of the item in negotiation. As said in the previous section, the agents change beliefs during the negotiation. Even if the initial set of beliefs is a parameter in agent definition and it is constant during the process, the agent changes the current beliefs set. The initial knowledge of the agent can be called a *viewpoint* and the current set of beliefs a the *current angle*. A viewpoint has many angles and the agents negotiate them. Therefore the first proposal an agent makes is her viewpoint and the next ones are angles. Let T be an angle for the agent ag, then ag puts it forward by its logical formula: φ_T:

$$\varphi_T = \bigwedge_{\alpha \in T} \alpha$$

As direct consequence of the definition of subjective hierarchy, each node of the graph has a logical formula.

Henceforth, I use the symbol T_{ag}^{Cur} to denote the current angle of the agent ag and $\varphi_{T_{\text{ag}}^{Cur}}$ as its logical formula representation, the symbol, $\varphi_{T_{\text{ag}}^{0}}$ is the initial knowledge of the agents, i.e. her viewpoint.

The negotiation develops by *beats* that are sessions of 1-1 negotiation between the auctioneer and a player. In the following subsections I describe a beat, and the behaviours of the auctioneer and of each agent.

Beat

A beat consists of a set of Meaning Negotiation by Bargaining rounds in which the auctioneer makes a proposal and receives the opponents' ones. Let ag_a the auctioneer and ag_i an agent involved in the negotiation, the steps of a beat are the following:

1. The auctioneer broadcasts her current angle as the logical formula $\phi_{T_{\text{ag}_a}^{cur}}$;
2. Each player ag_i receives the proposal of the auctioneer and evaluates it with respect to her own current angle in order to test if it is good;
3. Suppose ag_i thinks $T_{\text{ag}_a}^{cur}$ is not good, then ag_i makes a counteroffer and chooses it into her subjective hierarchy;
4. Each agent ag_i makes a counteroffer to the auctioneer;
5. The auctioneer ag_a receives the proposals from the agents;
6. ag_a controls the Meaning Negotiation situation by checking if a viewpoint exists that is shared by at least k agents where k is the degree of sharing.
7. If a shared viewpoint exists then the auctioneer ends the Meaning Negotiation with a positive outcome, i.e. the shared theory;
8. otherwise the negotiation continues and a new beat begins.

At the beginning of a beat every agent adopts an angle of her initial viewpoint that is a theory belonging to her subjective hierarchy defined in Definition 3.3.

At the end of each beat the referee controls the state of the MN process that is whether an agreement is reached or no possible shared point of view exists and thus the negotiation ends negatively. The auctioneer is able to state if the process is positively, whether partially or totally, or negatively ending or if a new beat has to start with a new proposal of the referee.

Bidding Agent

A negotiating agent behaves like a Bargaining player: she receives an offer and she may accept, reject it or she may make a counteroffer.

The acceptability and the rejection of a received offer depend upon its *goodness*. In all the situations in which the auctioneer proposal is not good, the agent chooses a new proposal to perform among the nodes of her subjective hierarchy by visiting it in some way. The choice depends on the attitude of the agent. As in MN by Bargaining, when choosing the next assertion, the agent can make a retraction in order to find the least general theory that is a good compromise between the received offer and the viewpoint of the bidding agent.

Auctioneer

The role of the auctioneer is of supervising the negotiation process to state if and how it ends. The actions of the referee for each beat is of three stages:

Proposal. The auctioneer makes a proposal and sends it to each agent, and receives the negotiating agents' proposals.

Test. The auctioneer tests if any ending conditions is reached with respect to the last proposals received by the negotiating agents.

Elaboration. The auctioneer has to perform a new proposal whenever the agreement has not been reached. She does so by visiting her subjective hierarchy in some way depending on her attitude.

The proposal the referee asserts in a beat is the same for each negotiating agent. The auctioneer chooses the next proposal to make in a way that is related to her attitude and to the trustworthiness with respect to the opponents. The referee makes assertions that support the agents she considers more reliable, more trustworthy, more friendly etc. than others, i.e. that she prefers in some way.

Only the referee knows the opponents' proposal and she is the only agent involved which is able to check if the Meaning Negotiation is positive or negative ending. A MN process is considered *positive* when the auctioneer asserts that a commonly accepted theory is found (*total* agreement) or that an acceptable number α of agreeing agents exist on that theory (*partial* agreement), as *negative* if there is not a common viewpoint shared by all the negotiating agents or by an acceptable number of them. I represent these possible MN outcomes as ending conditions the referee checks at the end of every beat.

Definition 3.12 (MN Ending Conditions). *Suppose that* $T^{cur}_{ag_a}$ *is the last theory the auctioneer advanced and* α *is the degree of sharing that she assumes. Then she may test the following MN ending conditions:*

Total T_{win} *is the least general theory with respect to* Th *bidden by a negotiating agent and it is good for all the other negotiating agents;*

Partial T_{win} *is the least general theory with respect to* Th *bidden by a negotiating agent* ag_{win} *such that it is good for at least* α *negotiating agents;*

Negative there is not a theory shared by at least α *negotiating agents and the auctioneer is stubborn.*

The MN process closes positively iff the total or partial ending conditions are eventually tested otherwise it closes negatively.

When at the end of a beat the auctioneer controls the MN state she checks the existence of a winning theory among those proposed by the agents and checks if there are other proposals she may perform. The referee is the only one able to decide and state how the MN ends because no other agent knows what the others proposed.

I provide an algorithm (Algorithm 2) that takes as input $n+1$ subjective hierarchies where $n \geq 2$ is the number of negotiating agents not nominated referee. At the beginning of the MN process the auctioneer ag_a, makes a proposal and waits until all the negotiating agents perform their own ones. The bids advanced by all the agents are logical formulae representing their viewpoints. Then if T is the theory an agent wants to bid, she sends $\varphi_T = \bigwedge_{\psi \in T} \psi$ in the auction.
If there are only two agents involved in the auction, a referee and a negotiated agent, the MN process automated by Algorithm 2 computes in the same way as Algorithm 1.

3.4.4 Theoretical Results

I now provide some theorems about the correctness (Theorem 3.13) and the completeness (Theorem 3.14) of Algorithm 2 (called henceforth MNEA). Assuming some restrictions to the representation of the agents viewpoints I finally show that the algorithm is polynomially decidable (Theorem 3.15).

The aim of this presentation is to prove that the proposed framework can be applied in practice. Nonetheless, some more investigation is needed to say the last word upon the presented formalism. In particular, I still do not have a proof that the obtained computational result is a lower bound, although I conjecture that the obtained upper bound result is also a lower bound. I start by showing that the MN algorithm I formalise is correct, namely the theory it outputs is the one at least α negotiating agents consider *good*, where α is the degree of sharing input.
First of all I claim soundness and completeness of the Algorithm MNEA.

Theorem 3.13. *If* T *is the theory that Algorithm MNEA outputs then* T *is the least general theory with respect to the one advanced by the auctioneer and which is shared by at least* α *agents where* α *is the degree of sharing assumed by the referee.*

Proof Let be $\mathrm{Ag} = \{ag_1, ag_2, \ldots, ag_n, ag_a\}$ the set of the agents involved in a MN process in which one of them is reserved to be a referee (ag_a), and T the theory MNEA outcomes. Suppose by contradiction that T is either not the least generalisation of an auctioneer theory or that T is not good for at least α agents, then:

$\mathbf{T} \not\preceq \mathbf{T_a}$: if T is not a generalisation of the auctioneer's theory then the algorithm has passed *Step 2.5* or *2.6* and it goes to *Step 11* stopping in negative outcome.

T is not shared by at least α agents : when the algorithm computes *Step 8* it fails and goes to *Step 9*. If no other proposal can be made by ag_a because she is in stubbornness then the algorithm performs *Step 5.1, 5.2* and goes to *Step 11* and it stops in negative outcome.

Therefore the claim is proven. □

The next theorem proves that the algorithm is able to outputs the right MN theory if it exists.

Theorem 3.14. *Let T be the theory which is the least generalisation among those the negotiating agents may admit. MNEA with the the $n+1$ subjective hierarchies $\{\mathcal{H}_1, \mathcal{H}_2, \ldots, \mathcal{H}_n, \mathcal{H}_a\}$ in input, computes the MN problem and outputs T.*

Proof To prove that the algorithm is complete I have to show that it preserve MN theory's properties in computing. The outcome of a MN process is a theory T which is:

1. $T_a \preceq T$, where T_a is the last theory the auctioneer advanced: this is guaranteed by *Steps 2.1-2.4*;
2. $\alpha \leq |\{\mathcal{H}_i : \exists S \in \mathcal{H}_i.T \preceq S \text{ where } i \in [1, n]\}|$: the number of the negotiating agents assuming T as *good* is at least α, namely the degree of sharing. This is guaranteed by *Steps 5-10*.

□

The complexity of the algorithm automating the MN problem depends on the representation of the agents' points of views. Henceforth I assume that establishing if a theory is good for an agent is a decidable problem.

Theorem 3.15. *If n is the number of the negotiating agents and h the maximum number of nodes among those of the subjective hierarchies of the negotiating agents, then MNEA computes the MN process in $\mathbf{O}(h^2 \times n \times \mathbf{C})$ where $\mathbf{C}$ is the computational cost of the relationship test among the theories advanced by agents during the MN.*

Proof The worst case occurs when no theory can be shared by the MN players. In this situation the auctioneer performs at most h proposals and for each proposal every negotiating agent tests if she considers good the received theory: no negotiating agent establishes that the proposal received is good and she does so by visiting all her subjective hierarchy's nodes (h) and by testing the relationship between the node she visited and the theory proposed by the auctioneer. Then, for each bid the auctioneer advances at most h bids to all the n agents, who check if it is good by relating it with respect to all the nodes in their subjective hierarchies (at most h nodes per graph). If the cost of the relationship test is $\mathbf{C}$, the MNEA algorithm computes this case in $h \times n \times h \times \mathbf{C}$ steps. □

If I assume that the agent knowledge bases are CPL or FOL formulae without identity, I can prove that Algorithm MNEA computes in polynomial time with respect to negotiating agents, number of theories involved, and number of axioms in the theories. This is claimed in the following theorem.

Theorem 3.16. *Let n be the number of the negotiating agents, h the maximum number of nodes among those of the subjective hierarchies of the negotiating agents. If m is the maximum number of the axioms in the agents knowledge bases and l the maximum number of symbols occurring in an axiom, then MNEA computes the MN process in* $\mathbf{O}(h^2 \times n \times m \times 2^l)$.

Proof Suppose that the relationship among the theories bidden by agents is computed by resolution principle. The implementation of the resolution principle are linear in the number of formulas and exponential in the number of occurring symbols. □

A nondeterministic version of the algorithm, based upon linear resolution can be easily built so that I can inherit the computational properties of this approach. Based on this approach I can prove that MN with English Auction is an NP problem[2].

Lemma 3.17. *The nondeterministic version of Algorithm MNEA computes the MN problem in polynomial time with respect to the number of symbols in the involved theories.*

Proof Consider a nondeterministic version of MNEA obtained by associating to the deterministic version of MNEA an oracle engine that computes in polynomial time the consistency of a set of clauses in CPL or FOL by linear resolution. Such an engine can be easily defined, as proved in several papers about Mechanical Theorem Proving. Since every deterministic algorithm that calls an oracle engine to compute in polynomial time the solution of the problem is nondeterministically polynomial, proved that the procedure ends in a nondeterminitic polynomial time as well, by Theorem 3.16. Therefore the claim is proved. □

A straightforward consequence of the above results is the following theorem. From Lemma 3.17 I can derive the following theorem, that poses practical modality of MNEA in nondeterministic version.

Theorem 3.18. *MN problem with at least three parties and subjective hierarchies in FOL is in NP.*

[2] I omit this part of the investigation and I leave it to future works

Algorithm 2: MN algorithm by English Auction (MNEA).

Input : n subjective hierarchies, ag_a the auctioneer, α the degree of sharing
Output: A negotiated theory, if possible

$m = 0$, $b_{win} = \bot$;
`// Initialisation` $count[] =$ array of (n+1) integers;
forall $i \in \mathrm{Ag} \cup \{\mathrm{ag}_a\}$ **do**
    $T_i^{cur} = T_i^0$, $\varphi_{T_i^{cur}} = \bigwedge_{\alpha \in T_i^{cur}}$;
    $stub_i =$ `false`;
end
while $((b_{win} = \bot)$ **or** $(\alpha \geq m))$ **or** $\bigvee_{i \in \mathrm{Ag} \cup \{\mathrm{ag}_a\}} \neg stub_i$ **do**
    ag_a broadcasts $\varphi_{T_{\mathrm{ag}_a}^{cur}}$;
    `// Beat beginning` **forall** $i \in \mathrm{Ag}$ **do**
        if $T_i^{cur} \sim T_i^{\bot}$ **then**
            $stub_i =$ `true`;
        end
        if $\neg(\varphi_{T_i^{cur}} \leftrightarrow \varphi_{T_{\mathrm{ag}_a}^{cur}})$ **then**
            $T_{\mathrm{ag}_i}^{cur} = \mathrm{visit}(i, \mathrm{TheoryTree}_i, T_i^{cur})$;
            $\varphi_{T_{\mathrm{ag}_i}^{cur}} = \bigwedge_{\alpha \in T_{\mathrm{ag}_i}^{cur}} \alpha$;
            if $(\varphi_{T_{\mathrm{ag}_a}^{cur}} \rightarrow \varphi_{T_i^{cur}})$ **then**
                `/* find the more restrictive theory (retraction) */`
                i finds the last parent of T_i^{cur}, let it $p(T_i^{cur})$, such that $(\varphi_{T_{\mathrm{ag}_a}^{cur}} \rightarrow \varphi_{p(T^{cur})})$;
                $T_i^{cur} = p(T_i^{cur})$;
                $\varphi_{T_i^{cur}} = \bigwedge_{\alpha \in T_i^{cur}} \alpha$;
            end
        end
        i proposes $\varphi_{T_i^{cur}}$ to ag_a;
    end
    ag_a receives the bids of the agents $bids = [\varphi_{T_{\mathrm{ag}_a}^{cur}}, \varphi_{T_{\mathrm{ag}_1}^{cur}}, \varphi_{T_{\mathrm{ag}_2}^{cur}} \ldots, \varphi_{T_{\mathrm{ag}_n}^{cur}}]$;
    for $i = 0$ *to* $n - 1$ **do**
        $count[i] = 0$;
        for $j = i + 1$ *to* n **do**
            if $bids[i] \leftrightarrow bids[j]$ **then**
                $count[i] + +$;
            end
        end
    end
    $m = max(count)$, $win = indexOf(m, count)$;
    if $T_{\mathrm{ag}_a}^{cur} \sim T_{\mathrm{ag}_a}^{\bot}$ **then**
        $stub_{\mathrm{ag}_a} =$ `true`;
    end
    $T_{\mathrm{ag}_a}^{cur} = \mathrm{visit}(\mathrm{ag}_a, \mathrm{TheoryTree}_{\mathrm{ag}_a}, T_{\mathrm{ag}_a}^{cur})$, $\varphi_{T_{\mathrm{ag}_a}^{cur}} = \bigwedge_{\phi \in T_{\mathrm{ag}_a}^{cur}} \phi$;
    `// Beat ending`
end
if $(bids[win] \neq \bot)$ **and** $(\alpha \leq m)$ **then**
    return $bids[win]$ `// Agreement`
end
else
    return $\bot$ `// Disagreement`
end

4

Meaning Negotiation as Inference

4.1 Introduction

In the previous chapter I give a formal representation of the MN process from a game-theoretic perspective. When involved in a MN, agents aim at sharing a common knowledge about a set of terms. They have formal representations of these terms by means of logical formulas. The contribution of this chapter is the formalisation of a deduction system, which I call *MND*, to reason about the MN process. In a 1-1 MN the two agents start the negotiation process with an initial proposal and concede to each other about the other's viewpoint until a common definition of the terms is obtained. Each of the two agents has a limit in negotiation, since some of her knowledge is unquestionable, from each agent's viewpoint, and, therefore, she will never concede about it. Consequently, after being flexible for a first phase of the negotiation process, when the agreement cannot be obtained, the agent becomes stubborn about her unquestionable knowledge. If this situation is symmetric, the disagreement condition becomes perpetual and the two agents keep on proposing the same incompatible definitions for the terms under negotiation. The system controls the procedure in what condition is reached. When the agreement condition is reached, the two agents agree about a common definition of the terms and the system ends the negotiation with positive outcome; when the agents reach a perpetual disagreement condition, the system ends the negotiation by stating that the agreement cannot be reached. In a 1-n MN the negotiation starts with the auctioneer proposal and it develops beat by beat. In each beat the negotiating agents make a counter-offer or accepts the auctioneer proposal. The negotiation continues until an acceptable number of agents agree with the auctioneer proposal. The minimum number of agreeing agents to consider positive the outcome of the negotiation is decided in front of the process.

MND allows us to express that agents communicate to each other not only the proposals, but also the disagreement conditions they have reached so far in order to give opponents some motivations about the non acceptability of their proposals. The process is governed by a set of rules that manage the provisional disagreement condition the agents have reached. More specifically, I first provide rules for deriving streams of dialog between two agents who discuss about the meaning of a set of terms, and then define a deduction system based upon these rules that derives a stream of dialog that ends with an agreement/disagreement condition.

MND contains three types of rules:

1. rules for building the next proposal from the current one;
2. rules formalising the negotiation assertion, i.e. how the agents communicate with each other, and they distinguish in rules for the second bidding agent and for the next ones;
3. rules to monitor the MN process: they test when and if the negotiation ends and if positively or not.

The absence of the perpetual disagreement is guaranteed by the system transition rules that test if the agents reached their stubbornness positions.

The rules differ also in the role the agents have (auctioneer or not). The auctioneer has to consider all the possible reactions of the other agents. The proposal the auctioneer performs increments the number of the negotiation situations in which agents may be. In fact, the proposal of the auctioneer may lead to an agreement with some agents and to an absolute disagreement with others or, in the most favorable situation, to a total agreement. In this way, the auctioneer's reasoning system is an extension of the negotiating agent rules in which all the combinations of negotiation conditions are considered. Moreover, the preconditions of the system transition rules contain the count of the agreeing agents.

In Section 4.2, I give our MN deduction system, where I formalise the knowledge and the language of negotiating agents. In Section 4.3.2 and the language and rules of the MN process, both for 1-1 MN and 1-n MN. In Section 4.4, I show how the MN develops.

4.2 A Formalisation of Negotiating Agents

I consider here a general MN process, so I abstract away from the particular terms whose meaning the agents are negotiating. I first consider the knowledge (Section 4.2.1) and language (Section 4.2.2) of negotiating agents.

4.2.1 The Knowledge of Negotiating Agents

When agents give the definition of a concept, they:

- give the necessary (*stubborn*) properties and the characterising (*flexible*) ones;
- give the properties that necessarily have not to hold and the ones that plausibly (flexibly) have not to hold; and
- give the formulas asserting what has not (stubbornly), or may not (flexibly), be used in the definition.

The notion of relevance of a formula is interesting at this stage of the definition, but instead of introducing a novel operator, I simply consider a formula as not relevant to an agent if she does not assert it. When i *asserts* a formula φ, she has a way to evaluate it: she thinks φ as positive or negative. If i does not assert φ

then either i does not know φ, i.e., she is not able to evaluate it or i does not think φ is relevant in defining the negotiated meaning.

So, I assume that *whenever i thinks α as not relevant for the negotiation, i never asserts α during the negotiation*.

Example 4.1. As a simple running example, consider the definition of the term "vehicle". Alice (stubbornly) thinks that it always has two, three, four or six wheels; a handlebar or a steering wheel; a motor, or two or four bicycle pedals, or a tow bar. Moreover, Alice (flexibly) thinks that a "vehicle" may be defined only as a car, then having four wheels, a steering wheel, and a motor; or only as a bicycle, then having two wheels, a handlebar and two bicycle pedals.

In other words, Alice has two acceptable ways to define a vehicle (namely, a car or a bicycle as particular "vehicles") but she has only one general description of a "vehicle". □

The necessary and the characterising properties of a concept definition are closely related to *EGG/YOLK* objects, introduced by [109] as a way to represent class membership based on typicality of the members: the egg is the set of the class members and the yolk is the set of the *typical* ones. For instance, the class of "employees" of a company A may be defined as "the set of people that receive money from the company in exchange for carrying out the instructions of a person who is an employee of that company", thus excluding, e.g., the head of the company (who has no boss), and the typical employee would include regular workers like secretaries and foremen. Another company B might have a different definition, e.g., including the head of the company, resulting in a mismatch. Nevertheless, if both companies provide some typical examples of "employees" it is possible that all of A's typical employees fit B's definition, and all of B's typical employees fit A's definition: $YOLK_B \leq EGG_A$ and $YOLK_A \leq EGG_B$, in the terminology of [109].

In this chapter, I use the same idea to express that negotiating agents have a *preference* over their knowledge: the properties an agent thinks as necessary are the typical ones, and the characterising properties are those that are not typical but plausible. I focus on the models of the knowledge of an agent. The stubborn properties of a concept definition are the most acceptable ones, therefore they thus have more elements satisfying them than the flexible properties have. Hence, I represent the elements satisfying the stubborn properties in the egg and those satisfying the flexible ones in the yolk. Differently from the original model, concept definitions are here restricted by stubborn properties to the largest acceptable set of models, hence represented by the egg, whilst the yolk is employed to denote the most restricted knowledge, that is, the one on which the agents are flexible.

The stubborn properties never change during the negotiation; therefore, the egg is fixed at the beginning of the MN. Instead, the flexible part of the definition of a concept is the core of the proposal of a negotiating agent. Each proposal differs from the further ones in two possible ways: it may give a definition of the negotiated object that is more descriptive than the next ones, or the given definition specifies properties that the next ones do not and vice versa. In the former case, we say that the agent carries out a *weakening action*, in the latter the agent carries out a *changing theory action*.

A general approach for dealing with agency in multiple agent system (MAS) is based on the representation of the choice of the action to perform by *attitudes*, which "are driving forces behind the actions of agents" [121]. In other words, attitudes are *the representation of the reasons that guide the agents in their behavior*. They are preferences between the criteria used to evaluate the feasible actions. The criteria, sometimes also called "contexts", are the features that result relevant in the MAS, e.g., legitimacy, social utility, and so on.

In general, the main criteria for evaluating an action are:

1. The MAS welfare: is the action positive for the agents in the MAS?
2. The personal advantage: is the action individually positive for the agent in choosing an action?

Therefore, the evaluation of actions is *contextualised*, i.e., each agent gives a value for each criterion: an action may increase the MAS welfare but be not personally advantageous.

By attitude, precisely, I mean the *preference order of the evaluation context*. Following the enumeration in the list above, the main attitudes in agency are:

- *collaborative*: the main goal of the agent is the welfare of the MAS: 1 is preferred to 2;
- *competitive*: the action performed by a competitive agent are advantageous or not damaging herself: 2 is preferred to 1.

In a Meaning Negotiation perspective, a collaborative agent aims at ending the process as soon as possible, whilst a competitive agent tends to stay as close as possible to her initial viewpoint. The collaborative and the competitive attitudes are dual.

Moreover, the behavior of an agent may change over time. A collaborative agent may become competitive and vice versa. The change of an attitude is generally connected to conditions of the environment (the multiple agent system) and the satisfaction of the agent goals. Agents are generally thought to have goals, wishes, intentions and they may choose to accomplish one goal because it is the simplest, but events that change the world can sometimes facilitate the occurring of more successful goals. Maintaining or changing the attitude is an individual choice and depends on the design of the agent. An agent that never changes her behavior has a *static* attitude, otherwise it is *dynamic* (see [128]).

However, none of weakening or changing theory actions can be carried out with respect to a proposal if the proposal describes the necessary properties of the object in the MN. We say that in such a situation the agents always make a *stubbornness action* that is equivalent to *no more change*.

4.2.2 The Language of Negotiating Agents

Each agent i is represented by her language $\mathcal{L}_i$, which is composed of two disjoint sublanguages:

- a *stubbornness* language containing the properties i deems as necessary in defining the negotiated meaning and

- a *flexible* language containing the properties i deems as not necessary in the MN.

Consider an abstract set of terms and let Ag be the set of the negotiating agents.

Definition 4.2. *Let* Ag *be the set of the* negotiating agents. *The* signature Σ_i *of an agent* $i \in \mathrm{Ag}$ *is the pair* $\langle \mathcal{P}_i, \alpha_i \rangle$ *where*

- $\mathcal{P}_i$ *is the set of the predicate symbols;*
- α_i *is the arity function for predicate symbols* $\alpha_i : \mathcal{P}_i \to \mathbb{N}$.

The language $\mathcal{L}_i$ *of* $i \in \mathrm{Ag}$ *comprises of* Σ_i*-formulas defined as follows:*

- *If* $P \in \mathcal{P}_i$, $\alpha_i(P) = n$ *and* $t_1, \ldots, t_n$ *are terms then* $P(t_1, \ldots, t_n)$ *is a* Σ_i*-formula.*
- *If* φ *and* ψ *are* Σ_i*-formulas then* $\neg\varphi$, $\varphi \wedge \psi$, $\varphi \vee \psi$, *and* $\varphi \to \psi$ *are* Σ_i*-formulas.*

The elements in $\mathcal{L}_i$ are Σ_i-formulas defined inductively in Definition 4.3.

Definition 4.3 ($\mathcal{L}_i$). *Given the signature* Σ_i*:*

1. *if* $P \in \mathcal{P}_i$, *if* $\alpha_i(P) = n$ *and if* $t_1, \ldots, t_n$ *are* Σ_i *terms then* $P(t_1, \ldots, t_n)$ *is a* Σ_i*-formula;*
2. *if* φ *and* ψ *are* Σ_i*-formula then* $\varphi \wedge \psi$, $\varphi \vee \psi$, $\neg\varphi$,$\varphi \to \psi$ *are* Σ_i*-formulas;*

Definition 4.4 (Stubbornness and Flexibility of an agent). *Let* $\mathcal{L}_i$ *be the set of the agent* i *formulas built from the signature* Σ_i*. The agent* i considers *the formulas in two ways,* stubborn *or* flexible*. The language* $\mathcal{L}_i$ *is divided in two sets:*

$\mathcal{L}_{\mathcal{S}_i}$ *is the set of stubborn formulas;*
$\mathcal{L}_{\mathcal{F}_i}$ *is the set of flexible formulas.*

The above languages are disjoint and $\mathcal{L}_i = \mathcal{L}_{\mathcal{S}_i} \cup \mathcal{L}_{\mathcal{F}_i}$*.I define*

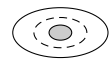
$$\mathrm{stub}_i = \bigwedge_{\varphi \in \mathcal{L}_{\mathcal{S}_i}} \varphi$$

and

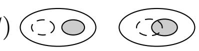
$$\mathrm{flex}_i = \bigwedge_{\varphi \in \mathcal{L}_{\mathcal{F}_i}} \varphi$$

During a negotiation process, the viewpoint of each agent is presented in a specific *angle*. In other words, a viewpoint is a hierarchy of theories, related by the partial order relation of weakening, and an element of this hierarchy is an angle. Each agent presents angles in sequence during the negotiation. Thus I call *current angle formula* (CAF) the angle presented at the current stage of the negotiation. A flexible formula flex_i^k expresses the k^{th} *angle* discussed in the MN and it changes during the process. I assume here that for each CAF flex_i^k there is a stubborn formula in $\mathcal{L}_{\mathcal{S}_i}$ that is a generalisation of it. In general, during a negotiation of the meaning of a term, the agents relax their viewpoint in order to meet the opponent's one, and they do this only if the relaxing formula is not too general. Then, for each assertion in the MN, the agents have a maximal generalisation of it and this is a

$$\frac{\text{flex}_i^k \to \text{flex}_i^{k+1} \quad \neg(\text{stub}_i \leftrightarrow \text{flex}_i^k)}{\text{flex}_i^{k+1}}\ (W)$$



$$\frac{\text{flex}_i^k \quad \neg(\text{stub}_i \leftrightarrow \text{flex}_i^k) \quad \neg(\text{flex}_i^k \to \text{flex}_i^{k+1})}{\text{flex}_i^{k+1}}\ (C)$$



$$\frac{\varphi \quad \text{stub}_i \leftrightarrow \varphi}{\varphi}\ (S)$$

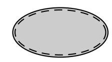


Table 4.1. Rules for making new proposals and the corresponding EGG/YOLKs. The plain lines identify the current angle and the stubborn knowledge of the agent, and the dashed line represents the new angle.

formula in the stubbornness set. For instance, if the object of the negotiation is the meaning of *pen*, an agent is flexible on the ink color of the object but not on the fact that the object contains ink; then, the *red ink* predicate is a flexible one and the *contains ink* predicate is a stubborn one.

flex_i^k changes during the MN by applying to it one of the rules for making new proposals given in Table 4.1: weakening (W), changing theory (C) or stubbornness (S). The EGG/YOLK representations show with dashed lines the collocation of the new proposal (in the stubbornness situation the new proposal is the same as the last one).

Let flex_i^k be the last proposal of an agent i during a MN. There are two ways for i to make a new proposal flex_i^{k+1}. The weakening rule (W) states that i can propose flex_i^{k+1} if flex_i^{k+1} is entailed by flex_i^k (i.e., $\text{flex}_i^k \to \text{flex}_i^{k+1}$) and flex_i^k is not the most general formula the agent can negotiate (corresponding to her stubbornness viewpoint, i.e., $\text{flex}_i^k \leftrightarrow \text{stub}_i$). Note that if i weakens, say, flex_i^0 to the new CAF flex_i^1, then i may be no more able to satisfy flex_i^0.

The rule (C) states that i can just change angle. Suppose that flex_i^k is the last proposal of an agent i during a MN. There are two ways for i to make a new proposal flex_i^{k+1}. In the first case, expressed by the weakening rule (W), i proposes flex_i^{k+1} if flex_i^{k+1} is entailed by flex_i^k (i.e., $\text{flex}_i^k \to \text{flex}_i^{k+1}$) and flex_i^k is not the most general formula the agent can negotiate (corresponding to her stubbornness viewpoint, i.e., $\text{flex}_i^k \leftrightarrow \text{stub}_i$). In the second case, expressed by the rule (C), i just changes theory. Although I do not consider MN strategies in detail here, in general, an agent chooses whether to perform a weakening or a changing theory action by applying the corresponding rule, but there are situations in which one action is better than the other. For instance, when an agent checks the compatibility situation it seems better to weaken the theory rather than changing it so to try to entail the opponent's viewpoint, while in essence disagreement situations it seems better to change the theory rather than weakening it so to try to meet the opponent's viewpoint.

If agent i is in stubbornness does she continue the negotiation or does she have to exit it? I assume that the agent exits the MN only if all the agents in the negotiation are stubborn. But an agent does not know the opponent's stubbornness viewpoint, so the exit condition is recognized only by the system. However, the stubborn agent always makes the same proposal during the MN, as expressed by the rule (S). If $\text{flex}_i^k \leftrightarrow \text{stub}_i$ then $\text{flex}_i^{k_1} = \text{flex}_i^{k_1+1}$ for all $k_1 > k$.

Let us now go deeply inside the negotiation process constraints. If an agent i makes a weakening of flex_i^0 and has flex_i^1 as the CAF, then i is no more able to satisfy flex_i^0. As I show below, the process of negotiation, means relaxing of individual hierarchies. In particular, based upon the reasoning above, flex_i^k is the k^{th} angle of agent i.

I introduce a set of Σ_i-structures as agents change angles during the negotiation process and these viewpoints have to be satisfied in a different structure. I thus define the semantical structure of a signature, which is built by a domain set and an interpretation function mapping predicate symbols into tuples of elements of the domain. I use a parameter k to denote the k^{th} structure of the k^{th} angle.

Definition 4.5. *Given a signature* $\Sigma_i = \langle \mathcal{P}_i, \alpha_i \rangle$, *a* Σ_i-structure $\mathcal{A}_i$ *is a pair* $\langle \mathcal{D}_i, \mathcal{I}_i \rangle$ *where the* domain $\mathcal{D}_i$ *is a finite non-empty set and the* interpretation function $\mathcal{I}_i$ *is such that* $\mathcal{I}_i(P) \subseteq \mathcal{D}_i^n$ *for all* $P \in \mathcal{P}_i$ *for which* $\alpha(P) = n$.

I define the set of Σ_i*-structures* $\mathcal{A}_i^k$ *as* $\mathcal{S}_i = \{\mathcal{A}_i^k \mid \mathcal{A}_i^k = \langle \mathcal{D}_i^k, \mathcal{I}_i^k \rangle\}$ *where* $\mathcal{D}_i^k \subseteq \mathcal{D}_i$ *is the domain set with respect to agent* i *and, for all pairs* $(\mathcal{I}_i^k, \mathcal{I}_i^{k+1})$, *if the* $(k+1)^{\text{th}}$ *rule that agent* i *applied is:*

- (W), *then* $\mathcal{I}_i^k(P) \subseteq \mathcal{I}_i^{k+1}(P)$ *for all* $P \in \mathcal{P}_i$;
- (C), *then* $\mathcal{I}_i^k(P) \neq \mathcal{I}_i^{k+1}(P)$ *and* $\mathcal{I}_i^k(P) \nsubseteq \mathcal{I}_i^{k+1}(P)$, *for all* $P \in \mathcal{P}_i$;
- (S), *then* $\mathcal{I}_i^k(P) = \mathcal{I}_i^{k+1}(P)$, *for all* $P \in \mathcal{P}_i$.

If φ *and* ψ *are* Σ_i*-formulas then:*

- $\mathcal{A}_i^k \models P(t_1, \ldots, t_n)$ *iff* $(\mathcal{I}_i(t_1), \ldots, \mathcal{I}_i(t_n)) \in \mathcal{I}_i(P)$, *where* $P \in \mathcal{P}_i$ *and* $t_1, \ldots, t_n$ *are terms;*
- $\mathcal{A}_i^k \models \neg\varphi$ *iff* $\mathcal{A}_i^k \not\models \varphi$;
- $\mathcal{A}_i^k \models \varphi \wedge \psi$ *iff* $\mathcal{A}_i^k \models \varphi$ *and* $\mathcal{A}_i^k \models \psi$;
- $\mathcal{A}_i^k \models \varphi \vee \psi$ *iff* $\mathcal{A}_i^k \models \varphi$ *or* $\mathcal{A}_i^k \models \psi$;
- $\mathcal{A}_i^k \models \varphi \rightarrow \psi$ *iff* $\mathcal{A}_i^k \models \psi$ *or* $\mathcal{A}_i^k \models \neg\varphi$.

Example 4.6. Suppose Alice defines "vehicle" as in Example 4.1. Then

$$\begin{aligned}\text{stub}_A = {} & (\mathit{has2wheels} \vee \mathit{has3wheels} \vee \mathit{has4wheels} \vee \mathit{has6wheels}) \wedge \\ & (\mathit{hasHandlebar} \vee \mathit{hasSteeringWheel}) \wedge \\ & (\mathit{hasMotor} \vee \mathit{has2bicyclePedals} \vee \mathit{has4bicyclePedals} \vee \mathit{hasTowBar})\end{aligned}$$

is the stubbornness part of Alice's knowledge whose interpretation is $\mathcal{I}(\text{stub}_A) = \{\mathsf{bicycle}, \mathsf{tandem}, \mathsf{motorbike}, \mathsf{scooter}, \mathsf{truck}, \mathsf{car}, \mathsf{trailer}, \mathsf{chariot}\}$. Let

$$\text{flex}_A^k = \mathit{has4wheels} \wedge \mathit{hasSteeringWheel} \wedge (\mathit{hasMotor} \vee \mathit{has2bicyclePedals})$$

be the CAF of Alice that it is not equivalent to her stubbornness knowledge and its interpretation is $\mathcal{I}(\text{flex}_A^k) = \{\mathsf{car}, \mathsf{truck}\} \subset \mathcal{I}(\text{stub}_A)$. Suppose Alice changes her CAF by means of a weakening action (W); then:

$$\text{flex}_A^{k+1} = (\textit{has4wheels} \vee \textit{has2wheels}) \wedge (\textit{hasSteeringWheel} \vee \textit{hasHandlebar}) \wedge (\textit{hasMotor} \vee \textit{has2bicyclePedals})$$

The interpretation of flex_A^{k+1} is $\mathcal{I}(\text{flex}_A^{k+1}) = \{\mathsf{motorbike}, \mathsf{scooter}, \mathsf{car}, \mathsf{truck}\} \subset \mathcal{I}(\text{flex}_A^{k})$. Otherwise, suppose Alice changes her CAF by means of a changing theory action (C); then:

$$\text{flex}_A^{k+1} = \textit{has6wheels} \wedge \textit{hasSteeringWheel} \wedge (\textit{hasMotor} \vee \textit{hasTowBar})$$

The interpretation of flex_A^{k+1} is $\mathcal{I}(\text{flex}_A^{k+1}) = \{\mathsf{truck}, \mathsf{trailer}\}$ and $\mathcal{I}(\text{flex}_A^{k+1}) \nsubseteq \mathcal{I}(\text{flex}_A^{k})$. □

In the following section I formalise the MN process.

4.3 The MN Process

Here, I formalise the MN process by giving definition of negotiation language (Section 4.3.1) and negotiation rules (Section 4.3.2).

I now formalise the MN process for two agents. During the MN, agents make proposals and say if they are in agreement or not with respect to the proposals made by the opponent. Proposals are negotiation formulas like $j : \varphi$, where I assume that the opponent i is able to recognise the name label j in $j : \varphi$ and remove it in order to evaluate φ.

In general, negotiating agents may not share the same language but have different signatures. Hence, when i evaluates an assertion by j, she first has to *translate* the symbols occurring in it to symbols belonging to her signature. Such a translation depends, of course, on the particular terms that are being considered for the negotiation, so I assume abstractly that for each pair of agents (i, j) there is the *translation function* $\tau_{i,j}$ such that:

$$\tau_{i,j} : \Sigma_j \rightarrow \Sigma_i \, .$$

When j asserts φ (i.e., $j : \varphi$), i is not able to find which part of φ is in the stubbornness set of j, since she only knows that $\varphi = \text{stub}_j \wedge \psi^k$ where stub_j is the conjunction of all the formulas in $\mathcal{L}_{\mathcal{S}_j}$ and ψ^k is the k^{th} angle of j.

In the following, I describe the main conditions an agent has to test in order to evaluate the opponent proposal and to identify the negotiation condition she is in. I suppose that j is the first proponent (bidding) agent and that i is the agent evaluating j's proposal. Figures 2.6 shows the EGG/YOLK representations in which i is identified by the plain line and j by the dashed line for each condition i tests; the numbering is that of [109]. Let φ be the proposal of j; then, the main conditions i has to test are (where, as usual, consistency means the impossibility to derive $\bot$):

- ($\mathbf{stub_i} \rightarrow \boldsymbol{\tau_{i,j}}(\varphi)$): are the agents in a *call-away* situation, i.e., is the proposal of j a generalisation of the stubbornness set of i? If it is the case, then the MN process ends negatively. The corresponding EGG/YOLK representation is shown in Table 4.2.

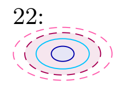


Table 4.2. The EGG/YOLK representation of the opponent's offer from agent i's viewpoint identified by the blue lines, for call-away.

- $\neg(\mathrm{stub}_{\mathbf{i}} \wedge \tau_{\mathbf{i},\mathbf{j}}(\varphi))$: is the proposal of j consistent with respect to i's stubbornness set? If it is not, then the agents are in absolute disagreement (Table 4.3).

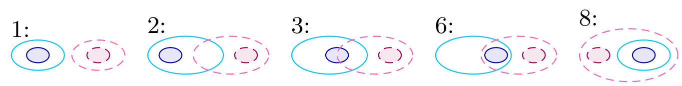


Table 4.3. The EGG/YOLK representation of the opponent's offer from agent i's viewpoint identified by the blue lines, for absolute disagreement.

- $\neg(\mathrm{flex}_{\mathbf{i}}^{\mathbf{k}} \wedge \tau_{\mathbf{i},\mathbf{j}}(\varphi)) \wedge (\mathrm{stub}_{\mathbf{i}} \vee \tau_{\mathbf{i},\mathbf{j}}(\varphi))$: i and j are not in absolute disagreement; is i's CAF consistent with respect to j's proposal? If it is not, then the agents are in essence disagreement (Table 4.4).

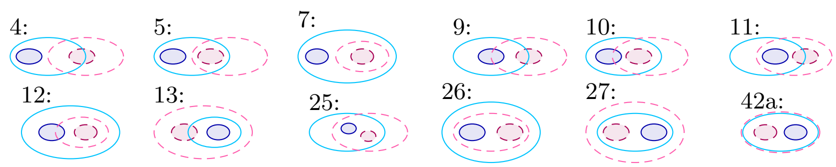


Table 4.4. The EGG/YOLK representation of the opponent's offer from agent i's viewpoint identified by the blue lines, for essence disagreement.

- $(\mathrm{flex}_{\mathbf{i}}^{\mathbf{k}} \rightarrow \tau_{\mathbf{i},\mathbf{j}}(\varphi)) \wedge \neg(\tau_{\mathbf{i},\mathbf{j}}(\varphi) \rightarrow \mathrm{flex}_{\mathbf{i}}^{\mathbf{k}})$: i and j are not in essence nor in absolute disagreement; is j's proposal a generalisation of i's CAF? If it is and if i's CAF is not equivalent to j's proposal, then the agents are in relative disagreement (Table 4.5).

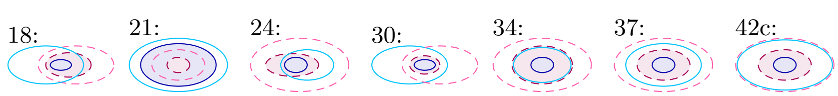


Table 4.5. The EGG/YOLK representation of the opponent's offer from agent i's viewpoint identified by the blue lines, for relative disagreement.

- $(\mathrm{flex}_{\mathbf{i}}^{\mathbf{k}} \vee \tau_{\mathbf{i},\mathbf{j}}(\varphi)) \wedge \neg(\mathrm{flex}_{\mathbf{i}}^{\mathbf{k}} \rightarrow \tau_{\mathbf{i},\mathbf{j}}(\varphi)) \wedge \neg(\tau_{\mathbf{i},\mathbf{j}}(\varphi) \rightarrow \mathrm{flex}_{\mathbf{i}}^{\mathbf{k}})$: i and j are not in absolute nor in relative disagreement; is i's CAF consistent with respect to j's proposal? If it is and if i's CAF is not a weakening of j's proposal, then the agents are in the compatibility relation (Table 4.6).

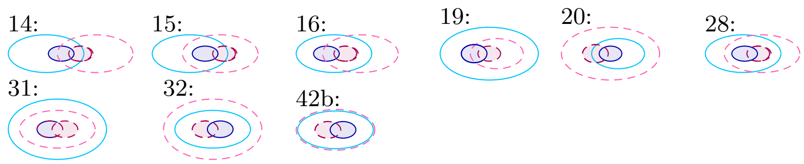


Table 4.6. The EGG/YOLK representation of the opponent's offer from agent i's viewpoint identified by the blue lines, for compatibility.

- $(\text{flex}_\mathbf{i}^\mathbf{k} \leftrightarrow \tau_{\mathbf{i},\mathbf{j}}(\varphi))$: the proposal of j is equivalent to i's CAF. The agents are in agreement (Table 4.7).

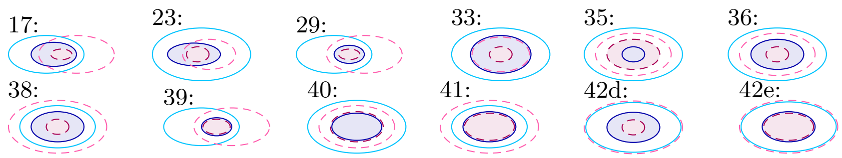


Table 4.7. The EGG/YOLK representation of the opponent's offer from agent i's viewpoint identified by the blue lines, for agreement.

From the above conditions it is impossible to derive $\bot$.

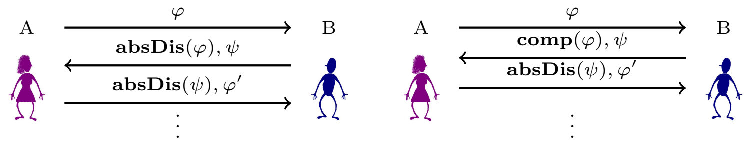
After evaluating the received proposal, agents inform the opponent about the negotiation situation they think to be in. To this end, I extend the formulas in the agent language:

Definition 4.7 ($\mathcal{L}_i$ extension). *If φ is a received proposal in the negotiation process, then it is a formula asserted by somebody as $j : \varphi$. I extend the language $\mathcal{L}_i$ with the formulas* $\mathbf{absDis}(j:\varphi)$, $\mathbf{essDis}(j:\varphi)$, $\mathbf{relDis}(j:\varphi)$, $\mathbf{comp}(j:\varphi)$, *and* $\mathbf{agree}(j:\varphi)$. *For $\mathcal{A}_i^k = \langle \mathcal{D}_i^k, \mathcal{I}_i^k \rangle$ a Σ_i-structure, the semantics of these additional formulas is:*

- $\mathcal{A}_i^k \models \mathbf{absDis}(j:\varphi)$ *iff* $\mathcal{A}_i^k \models \neg(\text{stub}_i \wedge \tau_{i,j}(\varphi))$*;*
- $\mathcal{A}_i^k \models \mathbf{essDis}(j:\varphi)$ *iff* $\mathcal{A}_i^k \models (\text{stub}_i \vee \tau_{i,j}(\varphi)) \wedge \neg(\text{flex}_i^k \wedge \tau_{i,j}(\varphi))$*;*
- $\mathcal{A}_i^k \models \mathbf{relDis}(j:\varphi)$ *iff* $\mathcal{A}_i^k \models (\text{flex}_i^k \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \text{flex}_i^k)$*;*
- $\mathcal{A}_i^k \models \mathbf{comp}(j:\varphi)$ *iff* $\mathcal{A}_i^k \models (\text{flex}_i^k \vee \tau_{i,j}(\varphi)) \wedge \neg(\text{flex}_i^k \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \text{flex}_i^k)$*;*
- $\mathcal{A}_i^k \models \mathbf{agree}(j:\varphi)$ *iff* $\mathcal{A}_i^k \models (\text{flex}_i^k \leftrightarrow \tau_{i,j}(\varphi))$.

I did not define a sentence $\mathbf{callAway}(j:\varphi)$ as the call-away condition interrupts the MN. It is also important to remark that in our system I restrict the evaluation of agent proposals to formulas in the basic agent language, so no assertion can be made by agents using extended (and nested) formulas like $\mathbf{agree}(\mathbf{comp}(j:\varphi))$. This restriction avoids nested MN processes.

In the two following subsections, I define the negotiation language and the deductive rules for the MN process.



(a) A start. (b) A violation.

Figure 4.1. Two MN scenarios.

4.3.1 MN language

The negotiation language, $\mathcal{L}$, is built by the assertions of the agents during the negotiation, i.e., labeled formulas $i : \varphi$ meaning that agent $i \in \mathrm{Ag}$ asserts the formula $\varphi \in \mathcal{L}_i$. That is, $i : \varphi$ represents a proposal the agent i makes in the negotiation and typically represents her CAF.

Definition 4.8 (Σ-formula). *The* signature *of the* MN language $\mathcal{L}$ *is* $\Sigma = \langle \mathcal{P}, \{\alpha_i\}_{i \in \mathrm{Ag}} \rangle$ *where* $\mathcal{P} = \bigcup_{i \in \mathrm{Ag}} \mathcal{P}_i$ *and* $\alpha_i : \mathcal{P}_i \to \mathbb{N}$ *is the arity function for predicate symbols. Let* φ *be a* $\mathcal{L}_i$ *formula for some* $i \in \mathrm{Ag}$*; then* $\mathcal{L}$ *comprises of* Σ-formulas *defined as follows:*

- *$i : \varphi$ is a Σ-formula;*
- *if φ_1 and φ_2 are Σ-formulas then $\varphi_1 \cap \varphi_2$ is a Σ-formula.*

Let $\mathcal{N}^k = (\{\mathcal{A}_i^k\}_{i \in \mathrm{Ag}, k \in \mathbb{N}}, \mathcal{F})$ be a Σ-structure where $\{\mathcal{A}_i^k\}_{i \in \mathrm{Ag}, k \in \mathbb{N}}$ is the domain set and $\mathcal{F}$ is an evaluation function that maps name labels into Ag. *Then:*

- *$\mathcal{N}^k \models i : \varphi$ iff $\mathcal{A}_{\mathcal{F}(i)}^k \models \varphi$;*
- *$\mathcal{N}^k \models \varphi_1 \cap \varphi_2$ iff $\mathcal{N}^k \models \varphi_1$ and $\mathcal{N}^k \models \varphi_2$.*

4.3.2 MN Rules

In this section I provide the deductive rules for the MN process. I distinguish between pairwise MN and one-to-many MN because the in the latter case the agents behave differently when they are the auctioneer. Moreover, in a 1-n MN the supervisor system ends the negotiation when all or a good part of the agents share a common angle.

MN Rules: 1-1 MN

I now give the transition rules the agents use to negotiate depending on the mutual negotiation position they test and on their flexibility; these rules are coupled with those in Table 4.1. There are different rules for the second proposing agent and the following ones. Consider the scenario in Figure 4.1(a): Alice (A) makes the proposal φ and Bob (B) evaluates it, where B's reasoning is based upon two tests:

1. The relation between his CAF and φ. B's CAF may be in agreement ($\varphi \leftrightarrow \mathrm{flex}_B^k$) or not with φ and B recognizes it by testing the condition listed above.

$$\frac{j:\varphi \quad \neg(\text{stub}_i \wedge \tau_{i,j}(\varphi))}{i:\textbf{absDis}(j:\varphi)\cap i:\text{flex}_i^1}\ (AD)$$

$$\frac{j:\varphi \quad \neg(\text{flex}_i^0 \wedge \tau_{i,j}(\varphi)) \wedge (\text{stub}_i \vee \tau_{i,j}(\varphi)}{i:\textbf{essDis}(j:\varphi)\cap i:\text{flex}_i^1}\ (ED)$$

$$\frac{j:\varphi \quad (\text{flex}_i^0 \wedge \tau_{i,j}(\varphi)) \vee (\neg\tau_{i,j}(\varphi) \wedge \text{flex}_i^0)}{i:\text{flex}_i^0}\ (I)$$

$$\frac{j:\varphi \quad (\text{flex}_i^0 \leftrightarrow \tau_{i,j}(\varphi)) \vee (\text{flex}_i^1) \leftrightarrow \tau_{i,j}(\varphi))}{i:\textbf{agree}(j:\varphi)\cap i:\tau_{i,j}(\varphi)}\ (Ag)$$

$$\frac{j:\varphi \quad (\text{flex}_i^0 \vee \tau_{i,j}(\varphi)) \wedge \neg(\text{flex}_i^0 \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \text{flex}_i^0)}{i:\textbf{comp}(j:\varphi)\cap i:\text{flex}_i^1}\ (Co)$$

Table 4.8. Rules for the second proposing agent.

2. His stubbornness condition, i.e., if his CAF is stub_B ($\text{flex}_B^k \leftrightarrow \text{stub}_B$) or not. Whenever B is stubborn, he performs the same counterproposal, otherwise he may relax his CAF by the (W) rule of Table 4.1 ($\text{flex}_B^k \rightarrow \text{flex}_B^{k+1}$) or change his theory by the (C) rule of Table 4.1 ($\text{flex}_B^k \vee \text{flex}_B^{k+1}$).

At the end of his evaluation, B replies to A with a counterproposal ψ. When A evaluates ψ she has to consider the relation between her CAF and ψ, her stubbornness condition ($\text{stub}_A \leftrightarrow \text{flex}_A^k$) and B's evaluation. The evaluation of the opponent agent helps agents in choosing the new proposal. The choice of the action, weakening or changing theory, and of the next proposal depends on the agent's attitude: a *collaborative agent* chooses the proposal that improves the negotiation relation with the opponent and a *competitive agent* chooses the proposal that changes the least the relation with the opponent. For instance, if B says to A that when A proposes φ they are in essence disagreement, and B makes the proposal ψ, A will propose φ_1 or φ_2, both inferred from φ by applying (W) or (C). When A is collaborative, she will propose φ_1 because she knows that they will be in agreement. Conversely, A will propose φ_2, if A is competitive, because she knows that they will remain in essence disagreement.

Suppose B says to A that when A proposes φ they are in relative disagreement ($\psi \rightarrow \varphi$) and B makes the proposal ψ, then A knows that they are in agreement when she proposes ψ.

To support the interaction sketched above, I define the system *MND* to consist of the standard introduction and elimination rules for the connectives of $\mathcal{L}_i$ and $\mathcal{L}$, and of two sets of rules: one set for the second proposing agent (Table 4.8) and another set for the following proposing agents (Table 4.9). For the sake of space, I omit the assumption of non call-away conditions in negotiation rules and explain only some of the rules by example.

Assume that A begins a MN by proposing flex_A^0 to B. B evaluates $\tau_{B,A}(\text{flex}_A^0)$ with respect to his initial angle flex_B^0 and suppose B thinks that $\tau_{B,A}(\text{flex}_A^0)$ is too

$$\frac{j:\mathbf{absDis}(i:\text{flex}_i^k)\cap j:\psi \quad \neg(\text{stub}_i \wedge \tau_{i,j}(\psi))}{i:\mathbf{absDis}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{AD\text{-}AD})$$

$$\frac{j:\mathbf{absDis}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{stub}_i \vee \tau_{i,j}(\psi)) \wedge \neg(\text{flex}_i^{k+1} \wedge \tau_{i,j}(\psi))}{i:\mathbf{essDis}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{AD\text{-}ED})$$

$$\frac{j:\mathbf{absDis}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{flex}_i^{k+1} \vee \tau_{i,j}(\psi)) \wedge \neg(\text{flex}_i^{k+1} \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \text{flex}_i^{k+1})}{i:\mathbf{comp}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{AD\text{-}Co})$$

$$\frac{j:\mathbf{absDis}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{flex}_i^{k+1} \rightarrow \tau_{i,j}(\psi)) \wedge \neg(\tau_{i,j}(\psi) \rightarrow \text{flex}_i^{k+1})}{i:\mathbf{relDis}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{AD\text{-}RD})$$

$$\frac{j:\mathbf{absDis}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{flex}_i^{k+1} \leftrightarrow \tau_{i,j}(\psi))}{i:\mathbf{agree}(j:\psi)\cap i:\tau_{i,j}(\psi)}\ (\mathit{AD\text{-}Ag})$$

$$\frac{j:\mathbf{essDis}(i:\text{flex}_i^k)\cap j:\psi \quad \neg(\text{stub}_i \wedge \tau_{i,j}(\psi))}{i:\mathbf{absDis}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{ED\text{-}AD})$$

$$\frac{j:\mathbf{essDis}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{stub}_i \vee \tau_{i,j}(\psi)) \wedge \neg(\text{flex}_i^{k+1} \wedge \tau_{i,j}(\psi))}{i:\mathbf{essDis}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{ED\text{-}ED})$$

$$\frac{j:\mathbf{essDis}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{flex}_j^{k+1} \vee \tau_{i,j}(\psi)) \wedge \neg(\text{flex}_i^{k+1} \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \text{flex}_i^{k+1})}{i:\mathbf{comp}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{ED\text{-}Co})$$

$$\frac{j:\mathbf{essDis}(i:\text{flex}_i^k)\cap j:\psi \quad (\neg\text{flex}_i^{k+1} \vee \tau_{i,j}(\psi)) \wedge \neg(\tau_{i,j}(\psi) \rightarrow \text{flex}_i^{k+1})}{i:\mathbf{relDis}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{ED\text{-}RD})$$

$$\frac{j:\mathbf{essDis}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{stub}_i \vee \tau_{i,j}(\psi)) \wedge \neg(\text{flex}_i^{k+1} \vee \tau_{i,j}(\psi))}{i:\mathbf{agree}(j:\psi)\cap i:\tau_{i,j}(\psi)}\ (\mathit{ED\text{-}Ag})$$

$$\frac{j:\mathbf{comp}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{stub}_i \vee \tau_{i,j}(\psi)) \wedge \neg(\text{flex}_i^{k+1} \wedge \tau_{i,j}(\psi))}{i:\mathbf{essDis}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{Co\text{-}ED})$$

$$\frac{j:\mathbf{comp}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{flex}_j^{k+1} \vee \tau_{i,j}(\psi)) \wedge \neg(\text{flex}_i^{k+1} \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \text{flex}_i^{k+1})}{i:\mathbf{comp}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{Co\text{-}Co})$$

$$\frac{j:\mathbf{comp}(i:\text{flex}_i^k)\cap j:\psi \quad (\neg\text{flex}_i^{k+1} \vee \tau_{i,j}(\psi)) \wedge \neg(\tau_{i,j}(\psi) \rightarrow \text{flex}_i^{k+1})}{i:\mathbf{relDis}(j:\psi)\cap i:\text{flex}_i^{k+1}}\ (\mathit{Co\text{-}RD})$$

$$\frac{j:\mathbf{comp}(i:\text{flex}_i^k)\cap j:\psi \quad (\text{flex}_i^{k+1} \leftrightarrow \tau_{i,j}(\psi))}{i:\mathbf{agree}(j:\psi)\cap i:\tau_{i,j}(\psi)}\ (\mathit{Co\text{-}Ag})$$

$$\frac{j:\mathbf{relDis}(i:\varphi)\cap j:\psi}{i:\mathbf{agree}(j:\psi)\cap i:\tau_{i,j}(\psi)}\ (\mathit{RD\text{-}Ag})$$

Table 4.9. Rules for the following proposing agents.

$$\frac{*(i,j) \quad i:\varphi \quad j:\mathbf{na}(i:\varphi) \quad j:\psi \quad \mathrm{stub}_i \leftrightarrow \varphi \quad \mathrm{stub}_j \leftrightarrow \psi}{\mathit{Disagreement}(i,j)}\ (D)$$

$$\frac{*(i,j) \quad i:\varphi \quad j:\mathbf{agree}(i:\varphi)}{\mathit{Agreement}(i,j)}\ (A)$$

$$\frac{*(i,j) \quad i:\varphi \quad j:\mathbf{na}(i:\varphi) \quad j:\psi}{\mathit{Negotiate}(i,j)}\ (N)$$

Table 4.10. 1-1 MN system transition rules.

strict, i.e., $\tau_{B,A}(\mathrm{flex}^0_A) \to \mathrm{flex}^0_B$. Thus, B cannot accept $\tau_{B,A}(\mathrm{flex}^0_A)$ and re-initiates the MN by the rule (I) and proposes flex^0_B by $B : \mathrm{flex}^0_B$. Otherwise, suppose B thinks that $\tau_{B,A}(\mathrm{flex}^0_A)$ is entailed by his initial angle flex^0_B and that $\tau_{B,A}(\mathrm{flex}^0_A)$ is not too general, i.e., it is not entailed by stub_B. In this case, B knows that A cannot accept flex^0_B because it is too strict with respect to her viewpoint, thus if B accepts $\tau_{B,A}(\mathrm{flex}^0_A)$ by (Ag) and says $B : \mathbf{agree}(A : \mathrm{flex}^0_A)$. This is the reason why there is no rule (RD) in Table 4.8. Consider the case in which B thinks that the proposal of A, flex^0_A, is consistent to his initial angle flex^0_B by (Co). B says to A that they are in the compatibility relation by $B : \mathbf{comp}(A : \mathrm{flex}^0_A)$ and makes a new proposal $B : \mathrm{flex}^1_B$ such that $\mathrm{flex}^0_B \to \mathrm{flex}^1_B$ (rule (W)). Now A thinks that $\tau_{A,B}(\mathrm{flex}^1_B)$ is an acceptable angle of her initial viewpoint, i.e. $\mathrm{flex}^1_A \leftrightarrow \tau_{A,B}(\mathrm{flex}^1_B)$. Thus A agrees with B and says $A : \mathbf{agree}(B : \mathrm{flex}^1_B)$ by $(Co\text{-}Ag)$. It may be the case that agents make proposals that become inconsistent with the received one. This inconsistency is tested by the opponent agent, not by the bidding one, because in *MND* agents choose the new proposal only with respect to their angles and not with respect to the opponent's one.

Consider now the scenario in Figure 4.1(b). B evaluates the proposal of A, tests the compatibility relation, and makes the counterproposal. A evaluates it and finds they are inconsistent. In situations like this, agents perform proposals that violate the MN relation among agents; I call such a proposal a *violation* and the rule causing it a *violation rule*. In Table 4.9, the violation rules are $(ED\text{-}AD)$ and $(ED\text{-}Co)$.

The MN develops by agents making proposals and asserting if they are in agreement or not. The entire process is controlled by a supervisor, an external viewpoint, which tests if the MN ends and if the outcome is positive or negative. Table 4.10 shows the transition rules for the system, which are a translation of the system transition graph in Figure 2.9. I use $j : \mathbf{na}(i : \varphi)$ to say that agent j thinks she is not in agreement with $i : \varphi$ and $*(i, j)$ to say *whatever the system state is* different from the final ones (*Agreement* and *Disagreement*), i.e., whether the system is in *Init* or *Negotiate*.[1] The MN begins when agents make proposals

[1] An agent is *absolutely stubborn* when she only has unquestionable knowledge. If all the involved agents are absolutely stubborn then the finite state diagram is different from Figure 2.9 because the state *Negotiate* does not exist and there are only the dashed edges. However, the formalisation above works as well.

in turns ($i : \varphi$, $j : \psi$) and they are not in agreement ($j : \mathbf{na}(i : \varphi)$) by ($N$). The MN ends with a positive outcome (φ) when each agent agrees on a proposal ($j : \mathbf{agree}(i : \varphi)$), otherwise the MN ends with a negative outcome if there are no more proposals to perform ($\mathrm{stub}_i \leftrightarrow \varphi$ and $\mathrm{stub}_j \leftrightarrow \psi$) and agents do not agree on a common acceptable angle ($j : \mathbf{na}(i : \varphi)$).

Example 4.9. Let Alice and Bob be two agents negotiating the definition of the term “vehicle”. Suppose that the initial viewpoint of Alice is

$$\mathrm{flex}_A^0 = \mathit{has2wheels} \wedge \mathit{hasSteeringWheel} \wedge (\mathit{hasMotor} \vee \mathit{has2bicyclePedals})$$

and her stubbornness knowledge is as in Example 4.6. Suppose that Bob's initial viewpoint is

$$\mathrm{flex}_B^0 = \mathit{has2wheels} \wedge \mathit{hasHandlebar} \wedge \mathit{has2bicyclePedals}$$

and his stubbornness knowledge is

$$\begin{aligned}\mathrm{stub}_B = {} & (\mathit{has2wheels} \vee \mathit{has3wheels} \vee \mathit{has4wheels}) \wedge \\ & (\mathit{hasHandlebar} \vee \mathit{hasSteeringWheel}) \wedge \\ & (\mathit{hasMotor} \vee \mathit{has2bicyclePedals} \vee \mathit{has4bicyclePedals})\end{aligned}$$

Alice is the first bidding agent and she proposes flex_A^0 to Bob, who receives the proposal and evaluates it. Bob tests that they are in compatibility because $(\mathrm{flex}_B^0 \vee \tau_{B,A}(\mathrm{flex}_A^0)) \wedge \neg(\mathrm{flex}_B^0 \rightarrow \tau_{B,A}(\mathrm{flex}_A^0)) \wedge \neg(\tau_{B,A}(\mathrm{flex}_A^0) \rightarrow \mathrm{flex}_B^0)$. Bob chooses the new CAF by a weakening action (W) in

$$\begin{aligned}\mathrm{flex}_B^1 = {} & (\mathit{has2wheels} \vee \mathit{has4wheels}) \wedge \\ & (\mathit{hasHandlebar} \vee \mathit{hasSteeringWheel}) \wedge \mathit{has2bicyclePedals}\end{aligned}$$

Bob uses the (Co) rule and sends his CAF to Alice:

$$\frac{A : \mathrm{flex}_A^0 \quad (\mathrm{flex}_B^1 \vee \tau_{B,A}(\mathrm{flex}_A^0)) \wedge \neg(\mathrm{flex}_B^1 \rightarrow \tau_{B,A}(\mathrm{flex}_A^0)) \wedge \neg(\tau_{B,A}(\mathrm{flex}_A^0) \rightarrow \mathrm{flex}_B^1)}{B : \mathbf{comp}(A : \mathrm{flex}_A^0) \cap B : \mathrm{flex}_B^1}\ (Co)$$

The system continues the MN by:

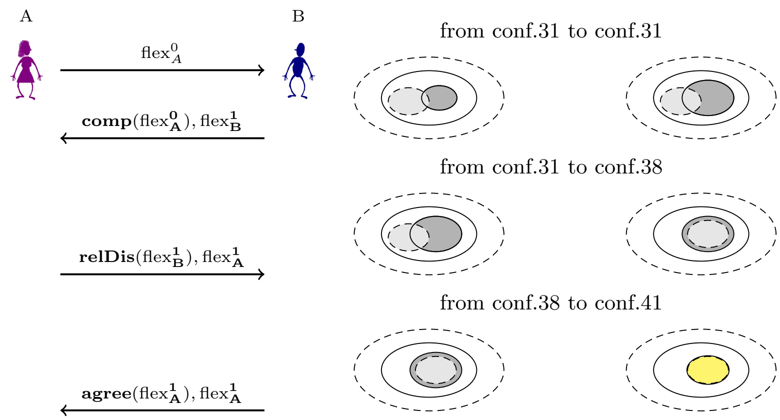
$$\frac{*(A,B) \quad A : \mathrm{flex}_A^0 \quad B : \mathbf{comp}(A : \mathrm{flex}_A^0) \quad B : \mathrm{flex}_B^1}{\mathit{Negotiate}(A,B)}\ (N)$$

Alice receives flex_B^1 and she has to make a weakening or a changing theory action because Bob did not say they were in agreement nor in relative disagreement. Alice performs a changing theory action by the rule (C) and her CAF is

$$\mathrm{flex}_A^1 = \mathit{has2wheels} \wedge (\mathit{hasHandlebar} \vee \mathit{hasSteeringWheel}) \wedge \mathit{has2bicyclePedals}$$

Alice thinks they are in relative disagreement since $(\mathrm{flex}_A^1 \rightarrow \tau_{A,B}(\mathrm{flex}_B^1)) \wedge \neg(\tau_{A,B}(\mathrm{flex}_B^1) \rightarrow \mathrm{flex}_A^1)$, and she uses the rule (Co-RD) to inform Bob that they are in relative disagreement:

$$\frac{B : \mathbf{comp}(A : \mathrm{flex}_A^0) \cap B : \mathrm{flex}_B^1 \quad (\mathrm{flex}_A^1 \rightarrow \tau_{A,B}(\mathrm{flex}_B^1)) \wedge \neg(\tau_{A,B}(\mathrm{flex}_B^1) \rightarrow \mathrm{flex}_A^1)}{A : \mathbf{relDis}(B : \mathrm{flex}_B^1) \cap A : \mathrm{flex}_A^1}\ (Co\text{-}RD)$$



(a) Message passing (b) EGG/YOLK configurations changing

Figure 4.2. The MN scenario of Example 4.9: the message passing flow (a) and the changes of the EGG/YOLKs of the agents (b).

The system continues the MN by:

$$\frac{*(B,A) \quad B:\text{flex}^1_B \quad A:\textbf{relDis}(B:\text{flex}^1_B) \quad A:\text{flex}^1_A}{\textit{Negotiate}(B,A)}\ (N)$$

Bob receives flex^1_A and he accepts it because Alice said they are in relative disagreement.

$$\frac{A:\textbf{relDis}(B:\text{flex}^1_B) \cap A:\text{flex}^1_A}{B:\textbf{agree}(A:\text{flex}^1_A) \cap B:\tau_{B,A}(\text{flex}^1_A)}\ (\textit{RD-Ag})$$

The system closes the MN by:

$$\frac{*(A,B) \quad A:\text{flex}^1_A \quad B:\textbf{agree}(A:\text{flex}^1_A)}{\textit{Agreement}(A,B)}\ (A)$$

with a positive outcome, flex^1_A.

Fig. 4.7 shows the message flow between Alice and Bob (Fig. 4.7(a)), and the changes of their EGG/YOLK configurations (Fig. 4.7(b)). □

The classification of the agreement conditions provided above is complete, in the sense that there is no other possible configuration of EGG/YOLKs, as shown in [109]. Based on the completeness of that analysis, I can show the following results.

Theorem 4.10. *MND is consistent.*

Proof Consider two agents represented in the *MND* system with sets $\mathcal{L}_{\mathcal{S}_1}$ and $\mathcal{L}_{\mathcal{S}_2}$ of stubbornness formulas and sets $\mathcal{L}_{\mathcal{F}_1}$ and $\mathcal{L}_{\mathcal{F}_2}$ of flexible formulas. To prove that *MND* is consistent, I show that if a Σ_i formula ξ is inferred using the *MND* rules, or, in other terms, is deduced as a theorem in the system, then ξ represents a proposal that is acceptable by both agents. In other words, I aim at proving that when the rules yield ξ then ξ generalises both $\mathcal{L}_{\mathcal{F}_1}$ and $\mathcal{L}_{\mathcal{F}_2}$ and is generalised by both $\mathcal{L}_{\mathcal{S}_1}$ and $\mathcal{L}_{\mathcal{S}_2}$. To prove this claim, I need specifically to show that:

- The rules for making new proposals yield a relation that is acceptable from the viewpoint of the agent who made the proposal before and infer a new proposal again still acceptable. In other terms, if an agent makes a proposal that is generalised by the set of stubbornness formulas $\mathcal{L}_{\mathcal{S}_i}$, and is a generalisation of the set of flexible formulas $\mathcal{L}_{\mathcal{F}_i}$, for one agent, the rules infer a new proposal that is in the same relationships with $\mathcal{L}_{\mathcal{S}_i}$ and $\mathcal{L}_{\mathcal{F}_i}$.
- The rules for the second proposing agent infer the relation between the agents at that step of the negotiation.
- The rules for the following proposing agent do the same as the rules for the second proposing agent, taking into account that this step takes place after the step of the second proposing agent.
- The system transition rules close the negotiation only when the proposal is acceptable by both agents, namely generalises both $\mathcal{L}_{\mathcal{F}_i}$ and is generalised by both $\mathcal{L}_{\mathcal{S}_i}$ sets.

Let us now consider a formula ξ that is acceptable by the two agents, and let us consider the rules that produce transitions in the system. In particular, if ξ is inferred by means of one of the rules (AD), (ED), (I), (Co), (Ag) for the second proposing agent, or by means of one of the rules given in Figure 4.9 for the following proposing agent, then the possible results of the step described above are given by the application of the system transition rules. Evidently, if ξ is inferred, then the rule (D) does not apply. If (N) applies, and one more inference is performed, then the rules (W), (C), (S) allow us to infer a different formula. Suppose now, by contradiction, that the new formula ξ is not acceptable by one of the agents (in the sense that either is not a generalisation of her set of flexible formulas or it is not generalised by the set of stubbornness formulas. As a consequence, one agent has called herself away, as I stated above. This, however, is impossible, by construction of the rules for the second and following proposals. Conversely, if the transition rule (D) applies and, therefore, the agents have incompatible viewpoints, then ξ is not inferred through the system, because it is not a generalisation of both flexible sets of formulas and generalises by both stubbornness sets of formulas. Clearly, by means of the full set of rules, it is not possible to do so when the agents have compatible viewpoints. □

Theorem 4.11. *MND is adequate to represent the MN of two agents.*

Proof We consider two agents that have compatible viewpoints, namely such that there exists a possible common angle. Their stubbornness sets and their flexible sets of formulas are in one of the EGG/YOLK configurations that do not correspond to one of the call-away or absolute disagreement relations. Suppose now that the *MND* system infers a Σ_i formula ξ. Then, ξ is a common angle. Conversely, consider two agents with incompatible viewpoints. The relation established is either call-away or absolute disagreement. The result is that no formula can be inferred through the system, which is consistent by Theorem 4.10. Hence, overall, the system is adequate. □

An interesting result can be obtained for negotiation processes that are built on finite signature theories. For MN processes that are built on finite signature theories, I obtain the following decidability result:

Corollary 4.12. *MN is decidable for theories with finite signature under the assumption of competitive agents.*

Proof Consider an MN between competitive agents on a language with finite signature. The number of possible proposals the agents can exchange during a negotiation process is formed by the possible formulas that can be built on the signature, which is finite. Since the rules of *MND* are finite and the new possible proposals are finite, and the number of applications of each rule is limited to the number of proposals the other negotiator can perform, then the number of steps that will be performed, in any algorithmic solution to the problem, is finite as well. □

In the following section I extend the MND for 1-n MN in which one agent is reserved to be a referee.

MN Rules: 1-n MN

When the Meaning Negotiation involves more than two agents, it may be viewed as an English Auction Game. The agents behave differently if they are an auctioneer or not. The referee is the agent who receives all the proposals of the others and find which one is shared by the agents. The auctioneer is a player himself; he makes a proposal at each new bid. The auctioneer replicates the same proposal to each of the negotiating agents. As a 1-1 MN player, the auctioneer evaluates the each received proposal by testing the validity of the conditions listed above: he checks the relation between each received proposal and his stubbornness knowledge and his flexible one. An auctioneer differs from the other negotiating agents in the number of the evaluations he has to do. Moreover, when the auctioneer infers the next proposal to perform by the weakening or the changing rules, the proposal may be related in more ways than that of the proposal made by other agents. In fact, in 1-1 MN it is not possible to reach the absolute disagreement by a relative disagreement situation because, when an agent, say i, informs her opponent, say j, that they are in relative disagreement then j knows that i proposed one of i CAF that is a restriction of her CAF and j accepts it. Instead, in 1-n MN, the previous situations may raise: the auctioneer may not accepts the proposal of one of the negotiating agent who said that they are in relative disagreement, because the proposal is not shared by the other agents. The set of deductive rules for the auctioneer is an extension of those in Table 4.9 and the added rules are those in Table 4.11. In particular, all the added rules are violations and they represents the changing of the negotiation situation from relative disagreement or agreement to all the other possible situation, absolute disagreement, essence disagreement and compatibility.

Moreover, the system transition rules are different from the 1-1 MN ones (Table 4.10) because different are the agreement and disagreement conditions. The 1-n MN ends in:

- *disagreement* when all the agents involved are in stubbornness and no agreement is found yet;
- *agreement* when all the agents or an acceptable part of them, i.e. α agents where α is degree of sharing, agree about a common angle;

$$\frac{j:\mathbf{comp}(i:\mathrm{flex}_i^k)\cap j:\psi \quad \neg(\mathrm{stub}_i \wedge \tau_{i,j}(\psi))}{i:\mathbf{absDis}(j:\psi)\cap i:\mathrm{flex}_i^{k+1}}\ (\mathit{Co\text{-}AD})$$

$$\frac{j:\mathbf{relDis}(i:\mathrm{flex}_i^k)\cap j:\psi \quad (\mathrm{stub}_i \vee \tau_{i,j}(\psi))\wedge\neg(\mathrm{flex}_i^{k+1}\wedge \tau_{i,j}(\psi))}{i:\mathbf{essDis}(j:\psi)\cap i:\mathrm{flex}_i^{k+1}}\ (\mathit{RD\text{-}ED})$$

$$\frac{j:\mathbf{relDis}(i:\mathrm{flex}_i^k)\cap j:\psi \quad (\mathrm{flex}_i^{k+1} \vee \tau_{i,j}(\psi))\wedge\neg(\mathrm{flex}_i^{k+1}\rightarrow \tau_{i,j}(\varphi))\wedge\neg(\tau_{i,j}(\varphi)\rightarrow \mathrm{flex}_i^{k+1})}{i:\mathbf{comp}(j:\psi)\cap i:\mathrm{flex}_i^{k+1}}\ (\mathit{RD\text{-}Co})$$

$$\frac{j:\mathbf{relDis}(i:\mathrm{flex}_i^k)\cap j:\psi \quad (\mathrm{flex}_i^{k+1} \rightarrow \tau_{i,j}(\psi))\wedge\neg(\tau_{i,j}(\psi)\rightarrow \mathrm{flex}_i^{k+1})}{i:\mathbf{relDis}(j:\psi)\cap i:\mathrm{flex}_i^{k+1}}\ (\mathit{RD\text{-}RD})$$

$$\frac{j:\mathbf{agree}(i:\mathrm{flex}_i^k)\cap j:\psi \quad \neg(\mathrm{stub}_i \wedge \tau_{i,j}(\psi))}{i:\mathbf{absDis}(j:\psi)\cap i:\mathrm{flex}_i^{k+1}}\ (\mathit{Ag\text{-}AD})$$

$$\frac{j:\mathbf{agree}(i:\mathrm{flex}_i^k)\cap j:\psi \quad (\mathrm{stub}_i \vee \tau_{i,j}(\psi))\wedge\neg(\mathrm{flex}_i^{k+1}\wedge \tau_{i,j}(\psi))}{i:\mathbf{essDis}(j:\psi)\cap i:\mathrm{flex}_i^{k+1}}\ (\mathit{Ag\text{-}ED})$$

$$\frac{j:\mathbf{agree}(i:\mathrm{flex}_i^k)\cap j:\psi \quad (\mathrm{flex}_i^{k+1} \vee \tau_{i,j}(\psi))\wedge\neg(\mathrm{flex}_i^{k+1}\rightarrow \tau_{i,j}(\varphi))\wedge\neg(\tau_{i,j}(\varphi)\rightarrow \mathrm{flex}_i^{k+1})}{i:\mathbf{comp}(j:\psi)\cap i:\mathrm{flex}_i^{k+1}}\ (\mathit{Ag\text{-}Co})$$

$$\frac{j:\mathbf{agree}(i:\mathrm{flex}_i^k)\cap j:\psi \quad (\mathrm{flex}_i^{k+1} \rightarrow \tau_{i,j}(\psi))\wedge\neg(\tau_{i,j}(\psi)\rightarrow \mathrm{flex}_i^{k+1})}{i:\mathbf{relDis}(j:\psi)\cap i:\mathrm{flex}_i^{k+1}}\ (\mathit{Ag\text{-}RD})$$

$$\frac{j:\mathbf{agree}(i:\mathrm{flex}_i^k)\cap j:\psi \quad (\mathrm{flex}_i^{k+1} \leftrightarrow \tau_{i,j}(\psi))}{i:\mathbf{agree}(j:\psi)\cap i:\tau_{i,j}(\psi)}\ (\mathit{Ag\text{-}Ag})$$

Table 4.11. Extension of the rules in Table 4.9 for the auctioneer. All these rules are violations.

$$\frac{\begin{array}{llll} *(a,i_1,\ldots,i_n) & a:\varphi & \text{for all } i\in \mathrm{Ag}_1.i:\mathbf{agree}(a:\varphi) & \text{for all } j\in \mathrm{Ag}_2.j:\mathbf{na}(a:\varphi) \\ & \mid \mathrm{Ag}_1\mid \leq \alpha & \text{for all } i\in \mathrm{Ag}.i:\psi \text{ and } \mathrm{stub}_i\leftrightarrow\psi & \end{array}}{\mathit{Disagreement}(a,i_1,\ldots,i_n)}\ (D)$$

$$\frac{\begin{array}{lll} *(a,i_1,\ldots,i_n) & a:\varphi & \text{for all } i\in \mathrm{Ag}_1.i:\mathbf{agree}(a:\varphi) \\ \text{for all } j\in \mathrm{Ag}_2.j:\mathbf{na}(a:\varphi) & \mid \mathrm{Ag}_1\mid \geq \alpha & \end{array}}{\mathit{Agreement}(a,i_1,\ldots,i_n)}\ (A)$$

$$\frac{*(a,i_1,\ldots,i_n) \quad a:\varphi \quad \text{for all } i\in \mathrm{Ag}_1.i:\mathbf{agree}(a:\varphi) \quad \text{for all } j\in \mathrm{Ag}_2.j:\mathbf{na}(a:\varphi) \quad \mid \mathrm{Ag}_1\mid \leq \alpha}{\mathit{Negotiate}(a,i_1,\ldots,i_n)}\ (N)$$

Table 4.12. 1-n MN system transition rules.

in all the other cases the MN continues. The system transition rules for 1-n MN are in Table 4.12.

4.4 MN Process Development

Agents in MN make bid flex such that for each agent i:

$$\text{flex}_i = \text{stub}_i \wedge \varphi$$

where stub_i is the stubbornness knowledge formula and φ is the flexible part of flex_i. Whenever an agent receive the opponent proposal, she does not know which is its flexible part and which the stubbornness one. She only knows which is the relation of the receive proposal with respect to her own stubbornness and flexible knowledge.

Only the supervisor system knows the stubbornness knowledge of all the agents. As said above, the stubbornness knowledge is unquestionable and it never changes during the negotiation. Therefore the MN process can be represented as a path of a graph in which nodes are the E/Y configurations and edges are the result of the usage of a bidding rule (Table 4.8 and Table 4.9).

Suppose that the agents have inconsistent stubbornness knowledge; whatever is the deductive rules they use they remain related as in configuration number 1 and it is described by a logical formula involving the stubbornness formulas of the agents (see Table 4.13).

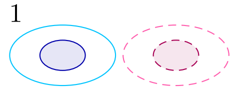
Configuration	Formula
1 	$\neg(\text{stub}_1 \wedge \text{stub}_2)$

Table 4.13. Configurations for inconsistent stubbornness knowledge.

In the following subsections I describe all the MN situations with respect to the relations of the stubbornness knowledge of the agents.

4.4.1 Equivalent Stubbornness Knowledge

Suppose that the agents have equivalent stubbornness sets. Then

$$(\text{stub}_i \leftrightarrow \text{stub}_j)$$

The equivalence relation between stubbornness theories is represented in Region Connection Calculus with 5 relations (RCC5) by EQ.

In Table 4.14 I show the possible yolks' configurations and I give a statement representing the configuration, i.e. the negotiation state.

Configuration	Formula
	Continued on next page

Table 4.14 – continued from previous page

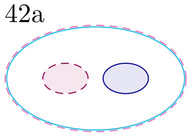
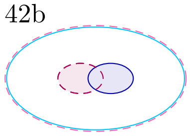
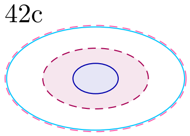
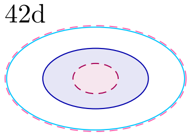
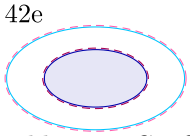
Configuration	Formula
42a 	$(\text{stub}_i \leftrightarrow \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge(\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
42b 	$(\text{stub}_i \leftrightarrow \text{stub}_j) \wedge (\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge(\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
42c 	$(\text{stub}_i \leftrightarrow \text{stub}_j) \wedge (\text{flex}_i \leftarrow \text{flex}_j) \wedge$ $\wedge(\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
42d 	$(\text{stub}_i \leftrightarrow \text{stub}_j) \wedge (\text{flex}_i \rightarrow \text{flex}_j) \wedge$ $\wedge(\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
42e 	$(\text{stub}_i \leftrightarrow \text{stub}_j) \wedge (\text{flex}_i \leftrightarrow \text{flex}_j) \wedge$ $\wedge(\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$

Table 4.14: Configurations for equivalent stubbornness sets.

Figure 4.3 depicts the graph of the possible negotiation relations of the agents during the negotiation. The nodes are the E/Y configurations and the edges are coloured by the agent who makes the next bid. The yellow nodes identifies the positive outcome of the negotiation.

All the rules the agents use when their stubbornness knowledge are equivalent are legitimate. In the following subsection I show how deductive rules of MND are used and their effects in the E/Y configurations when the stubbornness knowledge of agents are equivalent.

Example

Suppose Alice and Bob are related as in configuration 42a. Alice, A, is the first bidding agent and she proposes flex_A^0 to Bob, B. Bob receives the proposal and evaluates it. Bob tests that they are in absolute disagreement. Bob generalises his initial viewpoint flex_B^0 by:

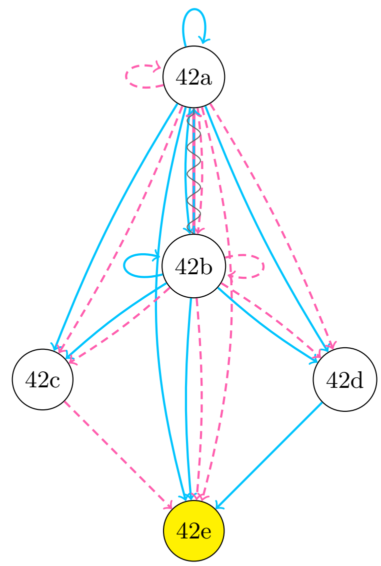


Figure 4.3. Transition graph for equivalent stubbornness knowledge. Nodes are coloured: the yellow node is the configuration of the positive outcome of the negotiation process.

$$\frac{\mathrm{flex}_B^0 \rightarrow \mathrm{flex}_B^1 \quad \neg(\mathrm{stub}_B \leftrightarrow \mathrm{flex}_B^0)}{\mathrm{flex}_B^1}\ (W)$$

and he checks the provisional negotiation situation by:

$$\frac{A:\mathrm{flex}_A^0 \quad \neg(\mathrm{flex}_B^1 \wedge \tau_{B,A}(\mathrm{flex}_A^0)) \wedge (\mathrm{stub}_B \wedge \tau_{B,A}(\mathrm{flex}_A^0))}{B:\mathbf{essDis}(A:\mathrm{flex}_A^0) \cap B:\mathrm{flex}_B^1}\ (ED)$$

Bob says to Alice that they are in essence disagreement and makes a proposal flex_B^1.

The system continues the MN by:

$$\frac{*(A,B) \quad A:\mathrm{flex}_A^0 \quad B:\mathbf{essDis}(A:\mathrm{flex}_A^0) \quad B:\mathrm{flex}_B^1}{\mathit{Negotiate}(A,B)}\ (N)$$

Alice receives flex_B^1 and she makes a weakening or a changing action because Bob said they are not in agreement nor in relative disagreement. Suppose Alice generalises her CAF by:

$$\frac{\mathrm{flex}_A^0 \rightarrow \mathrm{flex}_A^1 \quad \neg(\mathrm{stub}_A \leftrightarrow \mathrm{flex}_A^0)}{\mathrm{flex}_A^1}\ (W)$$

Alice tests the negotiation relation by:

$$\frac{B:\mathbf{essDis}(A:\mathrm{flex}_A^0) \cap B:\mathrm{flex}_B^1 \quad (\mathrm{flex}_A^1 \wedge \tau_{A,B}(\mathrm{flex}_B^1)) \wedge \neg(\mathrm{flex}_A^1 \rightarrow \tau_{A,B}(\mathrm{flex}_B^1)) \wedge \neg(\tau_{A,B}(\mathrm{flex}_B^1) \rightarrow \mathrm{flex}_A^1)}{A:\mathbf{comp}(B:\mathrm{flex}_B^1) \cap A:\mathrm{flex}_A^1}\ (ED\text{-}Co)$$

Alice says to Bob that they are in compatibility and makes a proposal flex_A^1.

The system continues the MN by:

$$\frac{*(B,A) \quad B:\mathrm{flex}_B^1 \quad A:\mathbf{comp}(B:\mathrm{flex}_B^1) \quad A:\mathrm{flex}_A^1}{\mathit{Negotiate}(B,A)}\ (N)$$

Bob receives flex_A^1 and he makes a weakening or a changing action because Alice said they are not in agreement nor in relative disagreement. Suppose Bob changes her CAF by:

$$\frac{\mathrm{flex}_B^1 \quad \neg(\mathrm{stub}_B \leftrightarrow \mathrm{flex}_B^1) \quad \neg(flex1_B \to \mathrm{flex}_B^2)}{\mathrm{flex}_B^2}\ (C)$$

Bob tests the negotiation relation by:

$$\frac{A:\mathbf{comp}(B:\mathrm{flex}_B^1) \cap A:\mathrm{flex}_A^1 \quad (\mathrm{flex}_A^2 \wedge \tau_{B,A}(\mathrm{flex}_A^1)) \wedge \neg(\mathrm{flex}_A^2 \to \tau_{B,A}(\mathrm{flex}_A^1)) \wedge \neg(\mathrm{flex}_A^2 \leftarrow \tau_{B,A}(\mathrm{flex}_A^1))}{B:\mathbf{comp}(A:\mathrm{flex}_A^1) \cap B:\mathrm{flex}_B^2}\ (Co\text{-}Co)$$

Bob says to Alice that they are in compatibility and makes a proposal flex_B^2.

The system continues the MN by:

$$\frac{*(A,B) \quad A:\mathrm{flex}_A^1 \quad B:\mathbf{comp}(A:\mathrm{flex}_A^1) \quad B:\mathrm{flex}_B^2}{\mathit{Negotiate}(A,B)}\ (N)$$

Alice receives flex_B^2 and she makes a weakening or a changing action because Bob said they are not in agreement nor in relative disagreement. Suppose Alice changes her CAF by:

$$\frac{\mathrm{flex}_A^2 \quad \neg(\mathrm{stub}_A \leftrightarrow \mathrm{flex}_A^2) \quad \neg(\mathrm{flex}_A^2 \to \mathrm{flex}_A^3)}{\mathrm{flex}_A^3}\ (C)$$

Alice tests the negotiation relation by:

$$\frac{B:\mathbf{comp}(A:\mathrm{flex}_A^2) \cap B:\mathrm{flex}_B^2 \quad (\mathrm{flex}_A^3 \leftrightarrow \tau_{A,B}(\mathrm{flex}_B^3))}{A:\mathbf{agree}(B:\mathrm{flex}_A^2) \cap A:\tau_{A,B}(\mathrm{flex}_B^2)}\ (Co\text{-}Ag)$$

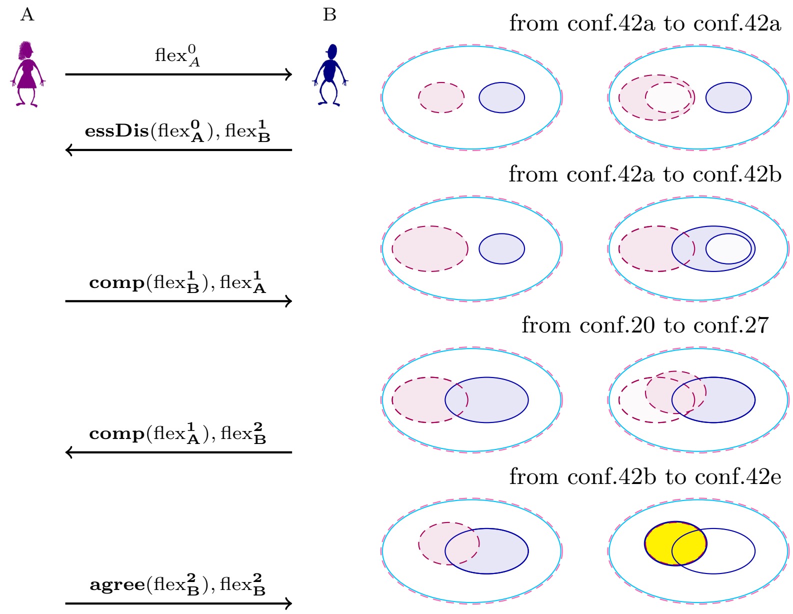
Alice says to Bob that they are in agreement and that they have a common angle that is flex_B^2.

The system closes the MN by:

$$\frac{*(B,A) \quad B:\mathrm{flex}_B^2 \quad A:\mathbf{agree}(B:\mathrm{flex}_B^2)}{\mathit{Agreement}(B,A)}\ (A)$$

with a positive outcome, flex_B^2.

In Figure 4.4 I show the message passing flow between Alice and Bob (Figure 4.4(a)), and the changes of the E/Y configurations (Figure 4.4(b)). The MN results in a path, showed in Figure 4.5, from node 8 to node 41 of the graph in Figure 4.3.



(a) Message passing (b) E/Y configuration changing

Figure 4.4. A MN scenario between Alice and Bob with equivalent stubbornness knowledge: the message passing flow (a) and the changes of their CAFs (b).

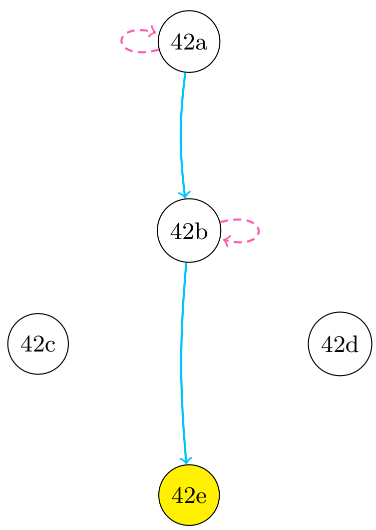


Figure 4.5. The MN path of the Alice and Bob message passing in Figure 4.4.

4.4.2 Generalised Stubbornness Knowledge

Suppose that one agent's stubbornness set is a *generalisation* of the theory of the opponent, i.e. they are consistent and one is a restriction of the other. Then

$$(\mathrm{stub}_i \leftarrow \mathrm{stub}_j)$$

The generalisation (weakening, relaxing, etc.) relation between stubbornness theories is represented in RCC5 as the partial proper part relation between *eggs*. I assumed that the stubbornness part of the agent theory never changes, then the models satisfying it are fixed at the beginning of the negotiation process.

On the other hand, the flexible sets are relaxed or changed during the negotiation process so that the models satisfying them change during the negotiation. The *flexible models* are the yolks of the RCC theory.

In Table 4.15 I show the possible yolks' configurations and I give a statement representing the configuration, i.e. the negotiation state.

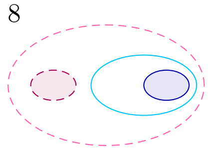
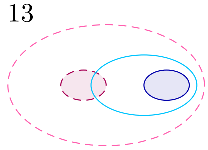
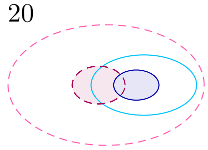
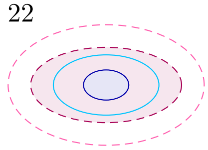
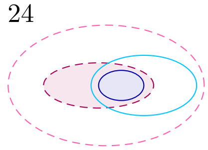
Configuration	**Formula**
8 	$(\mathrm{stub}_i \leftarrow \mathrm{stub}_j) \wedge \neg(\mathrm{flex}_i \wedge \mathrm{flex}_j) \wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge \neg(\mathrm{flex}_j \wedge \mathrm{stub}_i)$
13 	$(\mathrm{stub}_i \leftarrow \mathrm{stub}_j) \wedge \neg(\mathrm{flex}_i \wedge \mathrm{flex}_j) \wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \wedge \mathrm{stub}_i)$
20 	$(\mathrm{stub}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_i \wedge \mathrm{flex}_j) \wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \wedge \mathrm{stub}_i)$
22 	$(\mathrm{stub}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_i \leftarrow \mathrm{flex}_j) \wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \rightarrow \mathrm{stub}_i)$
24 	$(\mathrm{stub}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_i \leftarrow \mathrm{flex}_j) \wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \wedge \mathrm{stub}_i)$

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Table 4.15 – continued from previous page

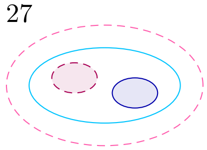
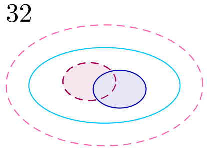
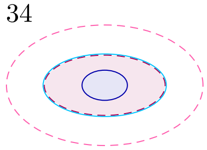
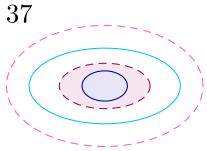
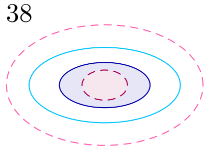
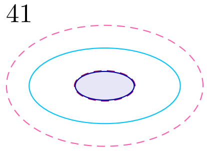
Configuration	Formula
27 	$(\text{stub}_i \leftarrow \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
32 	$(\text{stub}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_i \wedge \text{flex}_j) \wedge$ $(\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
34 	$(\text{stub}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_i \leftarrow \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \leftrightarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
37 	$(\text{stub}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_i \leftarrow \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
38 	$(\text{stub}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_i \rightarrow \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \leftrightarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
41 	$(\text{stub}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_i \leftrightarrow \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \leftrightarrow \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$

Table 4.15: Configurations for generalised/restricted stubbornness sets. The stubbornness knowledge of the agent i, identified by blue lines, is generalised by the stubbornness knowledge of the agent j, identified by pink lines.

Figure 4.6 depicts the graph of the possible negotiation relations of the agents during the negotiation. The nodes are the E/Y configurations and the edges are coloured by the agent who makes the next bid. The yellow nodes identifies the positive outcome of the negotiation.

All the rules the agent i, identified by blue lines, use are legitimate. The violation rules are used only by the agent j, identified by pink lines.

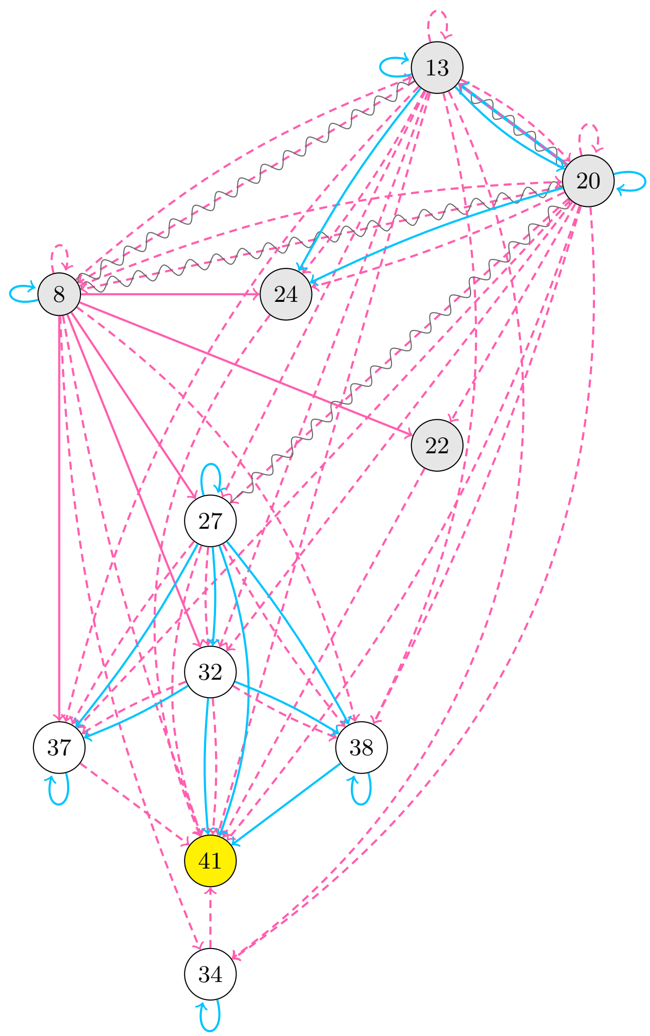


Figure 4.6. Transition graph for generalised (or restricted) stubbornness knowledge: the stubbornness knowledge of agent i, identified by blue lines, is a restriction of the stubbornness knowledge of agent j, identified by pink lines. The nodes are coloured: in gray nodes the negotiability condition is not true, in white nodes the negotiability condition is valid, and the yellow node is the configuration of the positive outcome of the negotiation process.

In the following subsection I show how deductive rules of MND are used and their effects in the E/Y configurations when the stubbornness knowledge of agents are a generalisation/restriction relation.

Example

Suppose Alice and Bob are related as in configuration 8. Alice, A, is the first bidding agent and she proposes flex_A^0 to Bob, B. Bob receives the proposal and evaluates it. Bob tests that they are in absolute disagreement. Bob generalises his initial viewpoint flex_B^0 by:

$$\frac{\text{flex}_B^0 \rightarrow \text{flex}_B^1 \quad \neg(\text{stub}_B \leftrightarrow \text{flex}_B^0)}{\text{flex}_B^1} \ (W)$$

and he checks the provisional negotiation situation by:

$$\frac{A : \text{flex}_A^0 \quad \neg(\text{flex}_B^1 \wedge \tau_{B,A}(\text{flex}_A^0)) \wedge (\text{stub}_B \wedge \tau_{B,A}(\text{flex}_A^0)}{B : \mathbf{essDis}(A : \text{flex}_A^0) \cap B : \text{flex}_B^1} \ (ED)$$

Bob says to Alice that they are in essence disagreement and makes a proposal flex_B^1.

The system continues the MN by:

$$\frac{*(A, B) \quad A : \text{flex}_A^0 \quad B : \mathbf{essDis}(A : \text{flex}_A^0) \quad B : \text{flex}_B^1}{\mathit{Negotiate}(A, B)} \ (N)$$

Alice receives flex_B^1 and she makes a weakening or a changing action because Bob said they are not in agreement nor in relative disagreement. Suppose Alice changes her CAF by:

$$\frac{\text{flex}_A^0 \quad \neg(\text{stub}_A \leftrightarrow \text{flex}_A^0)}{\text{flex}_A^1} \ (C)$$

Alice tests the negotiation relation by:

$$\frac{B : \mathbf{essDis}(A : \text{flex}_A^0) \cap B : \text{flex}_B^1 \quad (\text{flex}_A^1 \wedge \tau_{A,B}(\text{flex}_B^1)) \wedge \neg(\text{flex}_A^1 \rightarrow \tau_{A,B}(\text{flex}_B^1)) \wedge \neg(\text{flex}_A^1 \leftarrow \tau_{A,B}(\text{flex}_B^1))}{A : \mathbf{comp}(B : \text{flex}_B^1) \cap A : \text{flex}_A^1} \ (ED\text{-}Co)$$

Alice says to Bob that they are in compatibility and makes a proposal flex_A^1.

The system continues the MN by:

$$\frac{*(B, A) \quad B : \text{flex}_B^1 \quad A : \mathbf{comp}(B : \text{flex}_B^1) \quad A : \text{flex}_A^1}{\mathit{Negotiate}(B, A)} \ (N)$$

Bob receives flex_A^1 and he makes a weakening or a changing action because Alice said they are not in agreement nor in relative disagreement. Suppose Bob changes his CAF by:

$$\frac{\text{flex}_B^1 \quad \neg(\text{stub}_B \leftrightarrow \text{flex}_B^1) \quad \neg(\text{flex}_B^1) \rightarrow \text{flex}_B^2}{\text{flex}_B^2} \ (C)$$

Bob tests the negotiation relation and makes a violation by:

$$\frac{A:\mathbf{comp}(B:\text{flex}_B^1)\cap A:\text{flex}_A^1 \quad (\text{stub}_B\wedge\tau_{B,A}(\text{flex}_A^1))\wedge\neg(\text{flex}_B^2\wedge\tau_{B,A}(\text{flex}_A^1))}{B:\mathbf{essDis}(A:\text{flex}_A^1)\cap B:\text{flex}_B^2}\ (\textit{Co-ED})$$

Bob says to Alice that they are in essence disagreement and makes a proposal flex_B^2.

The system continues the MN by:

$$\frac{*(A,B)\quad A:\text{flex}_A^1\quad B:\mathbf{essDis}(A:\text{flex}_A^1)\quad B:\text{flex}_B^2}{\textit{Negotiate}(A,B)}\ (N)$$

Alice receives flex_B^2 and she makes a weakening or a changing action because Bob said they are not in agreement nor in relative disagreement. Suppose Alice changes her CAF by:

$$\frac{\text{flex}_A^1\quad\neg(\text{stub}_A\leftrightarrow\text{flex}_A^1)\quad\neg(\text{flex}_A^1\rightarrow\text{flex}_A^2)}{\text{flex}_A^2}\ (C)$$

Alice tests the negotiation relation by:

$$\frac{B:\mathbf{essDis}(A:\text{flex}_A^1)\cap B:\text{flex}_B^2\quad(\text{flex}_A^2\wedge\tau_{A,B}(\text{flex}_B^2))\wedge\neg(\text{flex}_A^2\rightarrow\tau_{A,B}(\text{flex}_B^2))\wedge\neg(\text{flex}_A^2\leftarrow\tau_{A,B}(\text{flex}_B^2))}{A:\mathbf{comp}(B:\text{flex}_B^2)\cap A:\text{flex}_A^2}\ (\textit{ED-Co})$$

Alice says to Bob that they are in compatibility and makes a proposal flex_A^2.

$$\frac{*(B,A)\quad B:\text{flex}_B^2\quad A:\mathbf{comp}(B:\text{flex}_B^2)\quad A:\text{flex}_A^2}{\textit{Negotiate}(B,A)}\ (N)$$

Bob receives flex_A^2 and he makes a weakening or a changing action because Alice said they are not in agreement nor in relative disagreement. Suppose Bob changes his CAF by:

$$\frac{\text{flex}_B^2\quad\neg(\text{stub}_B\leftrightarrow\text{flex}_B^2)\quad\neg(\text{flex}_B^2\rightarrow\text{flex}_B^3)}{\text{flex}_B^3}\ (C)$$

Bob tests the negotiation relation by:

$$\frac{A:\mathbf{comp}(B:\text{flex}_B^2)\cap A:\text{flex}_A^2\quad(\text{flex}_B^3\leftrightarrow\tau_{B,A}(\text{flex}_A^2))}{B:\mathbf{agree}(A:\text{flex}_A^2)\cap B:\tau_{B,A}(\text{flex}_A^2)}\ (\textit{Co-Ag})$$

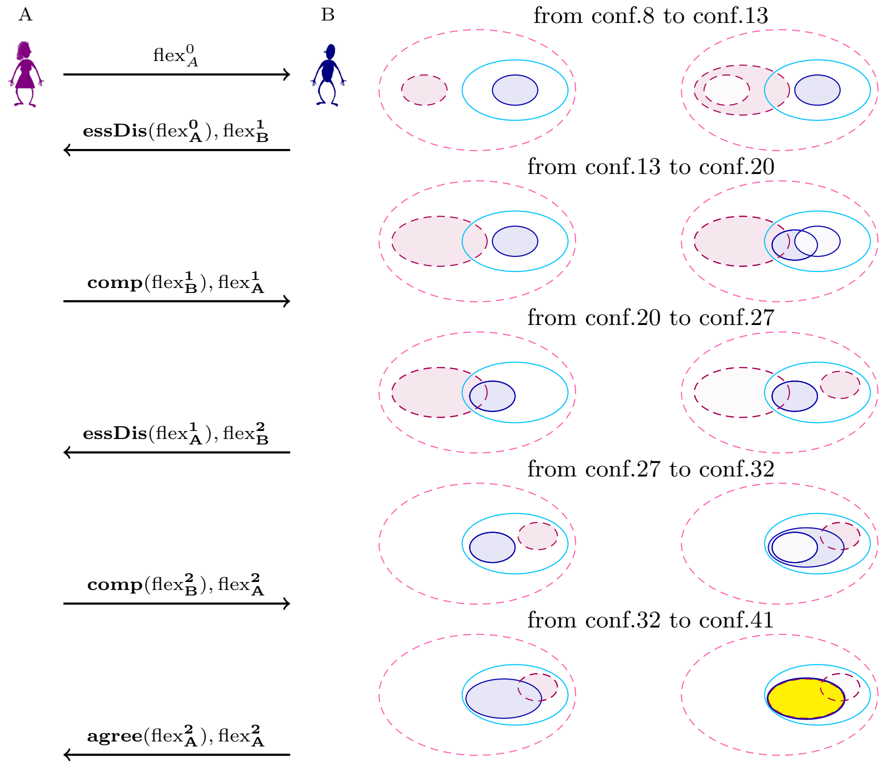
Bob says to Alice that they are in agreement and that they have a common angle that is flex_A^2.

The system closes the MN by:

$$\frac{*(A,B)\quad A:\text{flex}_A^2\quad B:\mathbf{agree}(A:\text{flex}_A^2)}{\textit{Agreement}(A,B)}\ (A)$$

with a positive outcome, flex_A^2.

In Figure 4.7 I show the message passing flow between Alice and Bob (Figure 4.7(a)), and the changes of the E/Y configurations (Figure 4.7(b)). The MN results in a path, showed in Figure 4.8, from node 8 to node 41 of the graph in Figure 4.6.



(a) Message passing (b) E/Y configuration changing

Figure 4.7. A MN scenario between Alice and Bob with stubbornness knowledge of Alice is a restriction of the stubbornness knowledge of Bob: the message passing flow (a) and the changes of their CAFs (b).

4.4.3 Consistent Stubbornness Knowledge

Suppose that the agents' stubbornness knowledge are *compatible*, i.e. they are consistent and no one is a restriction or a generalisation of the other. Then

$$(\text{stub}_i \wedge \text{stub}_j)$$

The compatibility relation between stubbornness theories is represented in RCC5 as the partial overlapping relation between *eggs*. We assumed that the stubbornness part of the agent theory never changes, then the models satisfying it are fixed at the beginning of the negotiation process.

On the other hand, the flexible sets are relaxed or changed during the negotiation process so than the models satisfying them change during the negotiation. The *flexible models* are the yolks of the RCC theory.

In Table 4.16 I show the possible yolks' configurations and I give a statement representing the configuration, i.e. the negotiation state.

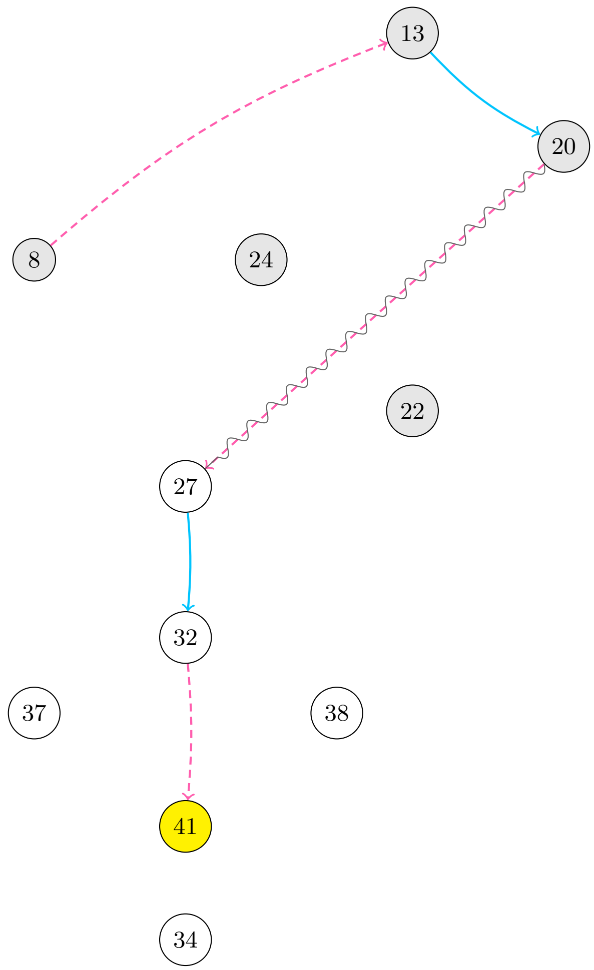


Figure 4.8. The MN path of the Alice and Bob message passing in Figure 4.7.

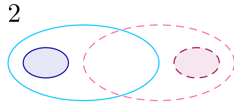
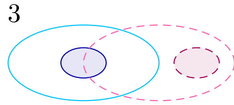
Configuration	Formula
2 	$(\text{stub}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge \neg(\text{flex}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_j \wedge \text{stub}_i)$
3 	$(\text{stub}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge(\text{flex}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_j \wedge \text{stub}_i)$

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Table 4.16 – continued from previous page

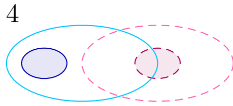
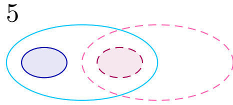
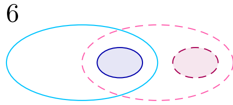
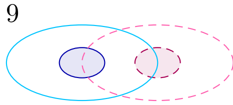
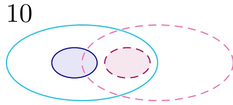
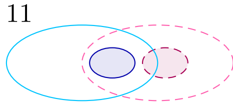
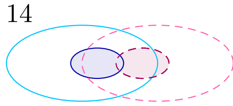
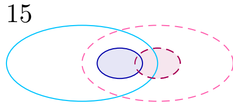
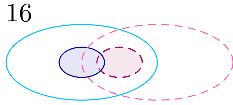
Configuration	**Formula**
4 	$(\text{stub}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge \neg(\text{flex}_i \wedge \text{stub}_j) \wedge (\text{flex}_j \wedge \text{stub}_i)$
5 	$(\text{stub}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge \neg(\text{flex}_i \wedge \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
6 	$(\text{stub}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \leftarrow \text{stub}_j) \wedge \neg(\text{flex}_j \wedge \text{stub}_i)$
9 	$(\text{stub}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \wedge \text{stub}_j) \wedge (\text{flex}_j \wedge \text{stub}_i)$
10 	$(\text{stub}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \wedge \text{stub}_i)$
11 	$(\text{stub}_i \wedge \text{stub}_j) \wedge \neg(\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \wedge \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$
14 	$(\text{stub}_i \wedge \text{stub}_j) \wedge (\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \wedge \text{stub}_j) \wedge (\text{flex}_j \wedge \text{stub}_i)$
15 	$(\text{stub}_i \wedge \text{stub}_j) \wedge (\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \leftarrow \text{stub}_j) \wedge (\text{flex}_j \wedge \text{stub}_i)$
16 	$(\text{stub}_i \wedge \text{stub}_j) \wedge (\text{flex}_i \wedge \text{flex}_j) \wedge$ $\wedge (\text{flex}_i \wedge \text{stub}_j) \wedge (\text{flex}_j \leftarrow \text{stub}_i)$

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Table 4.16 – continued from previous page

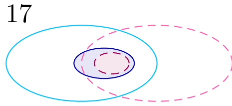
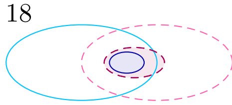
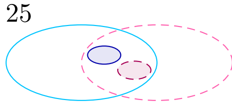
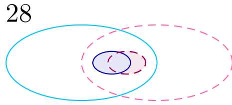
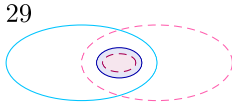
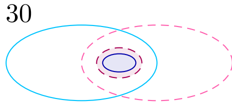
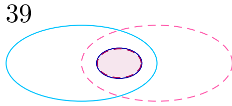
Configuration	Formula
17 	$(\mathrm{stub}_i \wedge \mathrm{stub}_j) \wedge (\mathrm{flex}_i \leftarrow \mathrm{flex}_j)\wedge$ $\wedge(\mathrm{flex}_i \wedge \mathrm{stub}_j) \wedge (\mathrm{flex}_j \leftarrow \mathrm{stub}_i)$
18 	$(\mathrm{stub}_i \wedge \mathrm{stub}_j) \wedge (\mathrm{flex}_i \leftarrow \mathrm{flex}_j)\wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \wedge \mathrm{stub}_i)$
25 	$(\mathrm{stub}_i \wedge \mathrm{stub}_j) \wedge \neg(\mathrm{flex}_i \wedge \mathrm{flex}_j)\wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \leftarrow \mathrm{stub}_i)$
28 	$(\mathrm{stub}_i \wedge \mathrm{stub}_j) \wedge (\mathrm{flex}_i \wedge \mathrm{flex}_j)\wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \leftarrow \mathrm{stub}_i)$
29 	$(\mathrm{stub}_i \wedge \mathrm{stub}_j) \wedge (\mathrm{flex}_i \rightarrow \mathrm{flex}_j)\wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \leftarrow \mathrm{stub}_i)$
30 	$(\mathrm{stub}_i \wedge \mathrm{stub}_j) \wedge (\mathrm{flex}_i \leftarrow \mathrm{flex}_j)\wedge$ $(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \leftarrow \mathrm{stub}_i)$
39 	$(\mathrm{stub}_i \wedge \mathrm{stub}_j) \wedge (\mathrm{flex}_i \leftrightarrow \mathrm{flex}_j)\wedge$ $\wedge(\mathrm{flex}_i \leftarrow \mathrm{stub}_j) \wedge (\mathrm{flex}_j \leftarrow \mathrm{stub}_i)$

Table 4.16: Configurations for consistent stubbornness sets. The stubbornness knowledge of the agent i, identified by blue plain lines, is only consistent by the stubbornness knowledge of the agent j, identified by pink dashed lines.

Figure 4.9 depicts the graph of the possible negotiation relations of the agents during the negotiation. The nodes are the E/Y configurations and the edges are coloured by the agent who makes the next bid. The yellow nodes identifies the positive outcome of the negotiation.

Both agents may make legitimate or violation actions, thus they may use or not the violation rules in Table 4.9. In the following subsection I show how deductive rules of MND are used and their effects in the E/Y configurations when the stub-

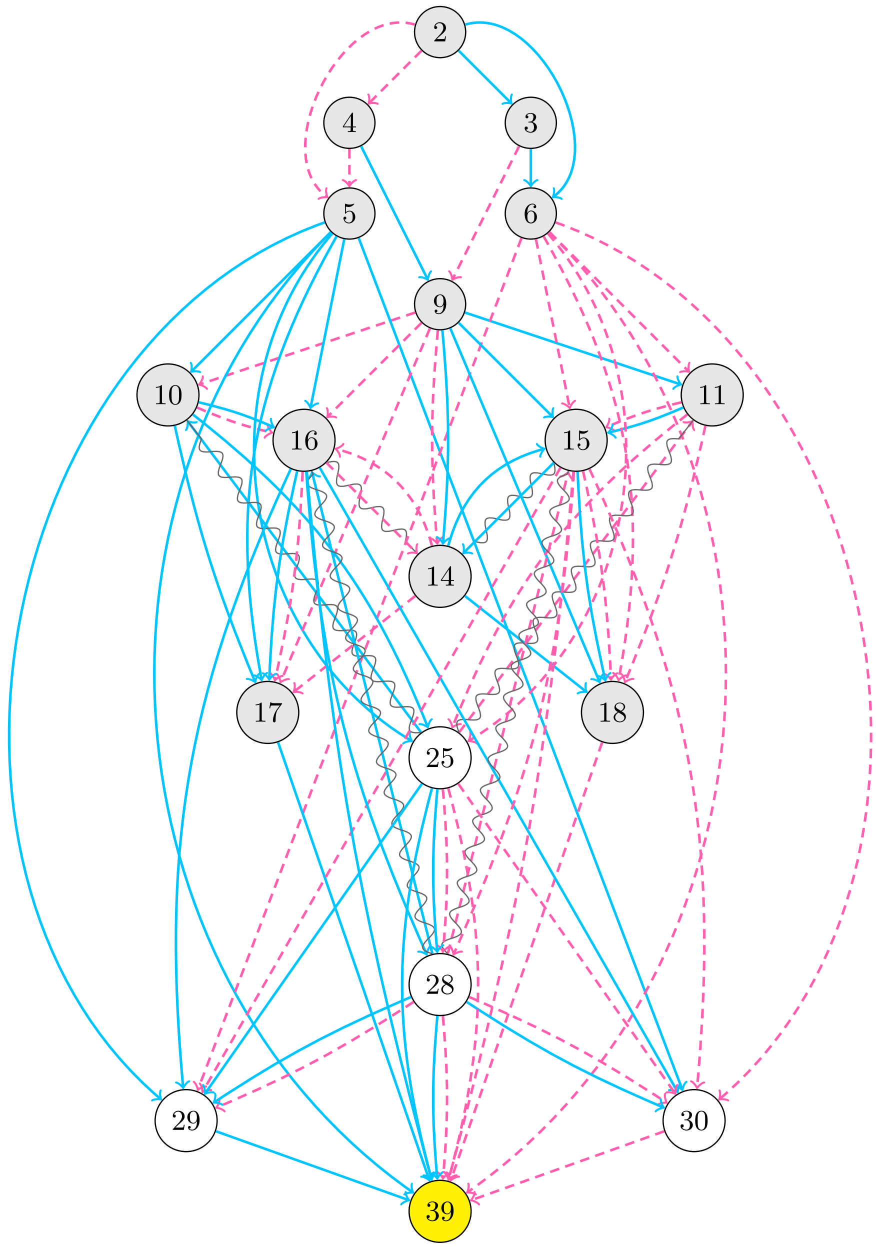


Figure 4.9. Transition graph for consistent and not generalised/restricted stubbornness knowledge: the stubbornness knowledge of agent i, identified by blue lines, is not a restriction of the stubbornness knowledge of agent j, identified by pink lines, and viceversa but they have shared semantical structures. The nodes are coloured: in gray nodes the negotiability condition is not true, in white nodes the negotiability condition is valid, and the yellow node is the configuration of the positive outcome of the negotiation process.

bornness knowledge of agents are consistent and no generalisation or restriction relation exist between them.

Example

Suppose Alice and Bob are related as in configuration 2. Alice, A, is the first bidding agent and she proposes flex_A^0 to Bob, B. Bob receives the proposal and evaluates it. Bob tests that they are in absolute disagreement. Bob generalises his initial viewpoint flex_B^0 by:

$$\frac{\text{flex}_B^0 \rightarrow \text{flex}_B^1 \quad \neg(\text{stub}_B \leftrightarrow \text{flex}_B^0)}{\text{flex}_B^1}\ (W)$$

and he checks the provisional negotiation situation by:

$$\frac{A : \text{flex}_A^0 \quad \neg(\text{stub}_B \wedge \tau_{B,A}(\text{flex}_A^0))}{B : \textbf{absDis}(A : \text{flex}_A^0) \cap B : \text{flex}_B^1}\ (AD)$$

Bob says to Alice that they are in absolute disagreement and makes a proposal flex_B^1.

The system continues the MN by:

$$\frac{*(A, B) \quad A : \text{flex}_A^0 \quad B : \textbf{absDis}(A : \text{flex}_A^0) \quad B : \text{flex}_B^1}{\mathit{Negotiate}(A, B)}\ (N)$$

Alice receives flex_B^1 and she makes a weakening or a changing action because Bob said they are not in agreement nor in relative disagreement. Suppose Alice changes her CAF by:

$$\frac{\text{flex}_A^0 \quad \neg(\text{stub}_A \leftrightarrow \text{flex}_A^0) \quad \neg(\text{flex}_A^0 \rightarrow \text{flex}_A^1)}{\text{flex}_A^1}\ (C)$$

Alice tests the negotiation relation by:

$$\frac{B : \textbf{absDis}(A : \text{flex}_A^0) \cap B : \text{flex}_B^1 \quad (\text{stub}_A \wedge \tau_{A,B}(\text{flex}_B^1)) \wedge \neg(\text{flex}_A^1 \wedge \tau_{A,B}(\text{flex}_B^1))}{A : \textbf{essDis}(B : \text{flex}_B^1) \cap A : \text{flex}_A^1}\ (AD\text{-}ED)$$

Alice says to Bob that they are in essence disagreement and makes a proposal flex_A^1.

The system continues the MN by:

$$\frac{*(B, A) \quad B : \text{flex}_B^1 \quad A : \textbf{essDis}(B : \text{flex}_B^1) \quad A : \text{flex}_A^1}{\mathit{Negotiate}(B, A)}\ (N)$$

Bob receives flex_A^1 and he makes a weakening or a changing action because Alice said they are not in agreement nor in relative disagreement. Suppose Bob changes her CAF by:

$$\frac{\text{flex}^1_B \quad \neg(\text{stub}_B \leftrightarrow \text{flex}^1_B) \quad \neg(\text{flex}^1_B \rightarrow \text{flex}^2_B)}{\text{flex}^2_B}\ (C)$$

Bob tests the negotiation relation by:

$$\frac{A : \mathbf{essDis}(B : \text{flex}^1_B) \cap A : \text{flex}^1_A \quad (\text{stub}_B \wedge \tau_{B,A}(\text{flex}^1_A)) \wedge \neg(\text{flex}^2_B \wedge \tau_{B,A}(\text{flex}^1_A))}{B : \mathbf{essDis}(A : \text{flex}^1_A) \cap B : \text{flex}^2_A}\ (ED\text{-}ED)$$

Bob says to Alice that they are in essence disagreement and makes a proposal flex^2_B.

The system continues the MN by:

$$\frac{*(A,B) \quad A : \text{flex}^1_A \quad B : \mathbf{essDis}(A : \text{flex}^1_A) \quad B : \text{flex}^2_B}{\mathit{Negotiate}(A,B)}\ (N)$$

Alice receives flex^2_B and she makes a weakening or a changing action because Bob said they are not in agreement nor in relative disagreement. Suppose Alice generalises her CAF by:

$$\frac{\text{flex}^1_A \rightarrow \text{flex}^2_A \quad \neg(\text{stub}_A \leftrightarrow \text{flex}^1_A)}{\text{flex}^2_A}\ (W)$$

Alice tests the negotiation relation by:

$$\frac{B : \mathbf{essDis}(A : \text{flex}^1_A) \cap B : \text{flex}^2_B \quad (\text{flex}^2_A \wedge \tau_{A,B}(\text{flex}^2_B)) \wedge \neg(\text{flex}^2_A \rightarrow \tau_{A,B}(\text{flex}^2_B)) \wedge \neg(\text{flex}^2_A \leftarrow \tau_{A,B}(\text{flex}^2_B))}{A : \mathbf{comp}(B : \text{flex}^2_B) \cap A : \text{flex}^2_A}\ (ED\text{-}Co)$$

Alice says to Bob that they are in compatibility and makes a proposal flex^2_A.

$$\frac{*(B,A) \quad B : \text{flex}^2_B \quad A : \mathbf{comp}(B : \text{flex}^2_B) \quad A : \text{flex}^2_A}{\mathit{Negotiate}(B,A)}\ (N)$$

Bob receives flex^2_A and he makes a weakening or a changing action because Alice said they are not in agreement nor in relative disagreement. Suppose Bob changes her CAF by:

$$\frac{\text{flex}^2_B \quad \neg(\text{stub}_B \leftrightarrow \text{flex}^2_B) \quad \neg(\text{flex}^2_B \rightarrow \text{flex}^3_B)}{\text{flex}^3_B}\ (C)$$

Bob tests the negotiation relation by:

$$\frac{A : \mathbf{comp}(B : \text{flex}^2_B) \cap A : \text{flex}^2_A \quad (\text{flex}^3_B \rightarrow \tau_{B,A}(\text{flex}^2_A)) \wedge \neg(\text{flex}^3_B \leftarrow \tau_{B,A}(\text{flex}^2_A))}{B : \mathbf{relDis}(A : \text{flex}^2_A) \cap B : \text{flex}^3_B}\ (Co\text{-}RD)$$

Bob says to Alice that they are in relative disagreement and makes a proposal flex^3_B.

The system continues the MN by:

$$\frac{*(A,B) \quad A : \text{flex}^2_A \quad B : \mathbf{relDis}(A : \text{flex}^2_A) \quad B : \text{flex}^3_B}{\mathit{Negotiate}(A,B)}\ (N)$$

Alice receives flex_B^2 and she has not to make a weakening or a changing action because Bob said they are in relative disagreement. Alice accepts the proposal of Bob by:

$$\frac{B : \textbf{relDis}(A : \text{flex}_A^2) \cap B : \text{flex}_B^3}{A : \textbf{agree}(B : \text{flex}_B^3) \cap A : \tau_{A,B}(\text{flex}_A^2)} \ (\textit{RD-Ag})$$

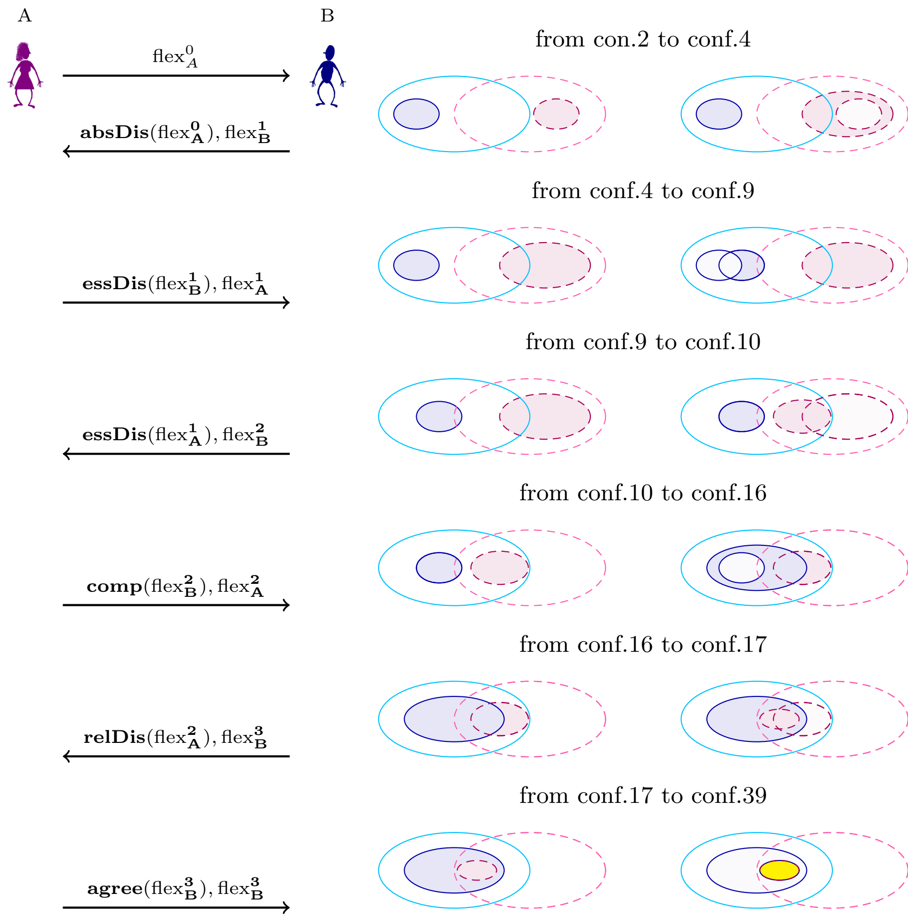
Alice says to Bob that they are in agreement and that they have a common angle that is flex_B^3.

The system closes the MN by:

$$\frac{*(B,A) \quad B : \text{flex}_B^3 \quad A : \textbf{agree}(B : \text{flex}_B^3)}{\textit{Agreement}(B,A)} \ (A)$$

with a positive outcome, flex_B^3.

In Figure 4.10 I show the message passing flow between Alice and Bob (Figure 4.10(a)), and the changes of the E/Y configurations (Figure 4.10(b)). The MN results in a path, showed in Figure 4.11, from node 2 to node 39 of the graph in Figure 4.9.



(a) Message passing (b) E/Y configuration changing

Figure 4.10. A MN scenario between Alice and Bob with consistent stubbornness knowledge: the message passing flow (a) and the changes of their CAFs (b).

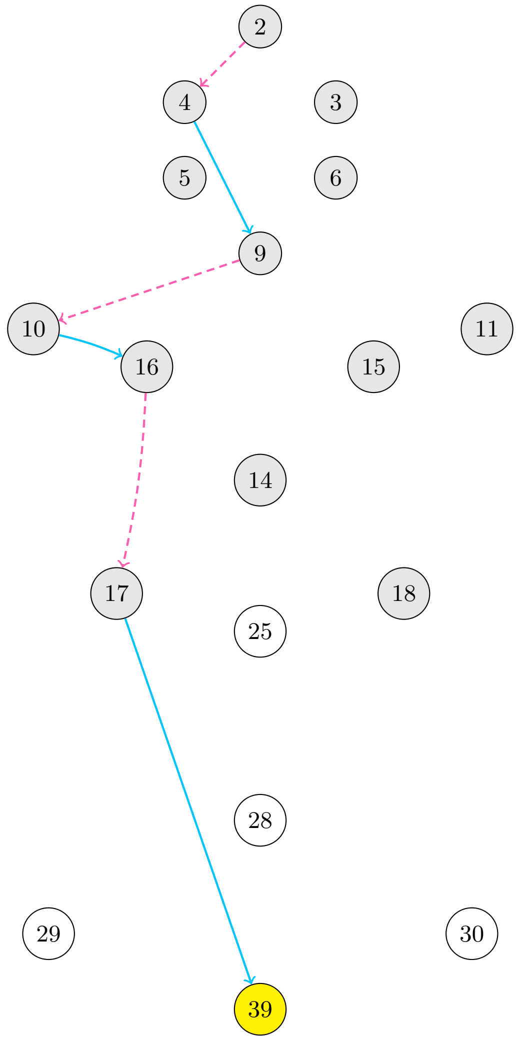


Figure 4.11. The MN path of the Alice and Bob message passing in Figure 4.10.

5

Attitudes and Strategies

5.1 Introduction: contexts and approaches

Agency of people is the result of thinking and planning. Humans make actions in order to obtain their goals or to go along with someone's wishes, goals, benefits, etc. A recluse performs actions which are useful only for himself, instead a social agent that is performing actions affects the environment of the society and therefore the agency of the other agents. Societies are norm regulated and may have global task to complete, or resources to share, etc. The social aspect of an action takes the changes of the environment into account. The consequences of an action are relevant in choosing the actions to perform for those agent that cares about the others. There are many ways in taking care about people. In particular the attitudes with respect to the others are two: collaborative and competitive. A collaborative agent takes care about the opponents in a positive way that is by regarding to their wishes and to the benefits that her actions produces to the opponents. Conversely, a competitive agent perform actions that contrast with the opponents goals and do not improve the social welfare. The competitive attitude is typical of agent in playing games where the goal is to win. Instead, a collaborative attitude is of the agent playing in the society as active part of it and completing group tasks as her own.

In both cases, the agency of an agent in a society depends on the agency of the other components. The difference of the behaviour lays on the justification of the actions that is the strategy of the agent. Formally, a strategy is a sequence of functions. The domain of the k-th element of a strategy is a sequence of actions of length k and its range is a set of feasible actions.

In Game Theory, the strategy of a player depends upon:

1. the last own move;
2. the last moves of the others;
3. the utility function.

The moves of the players are feasible actions of the game and each player does not know the reason of the opponents behaviour: it may be the willingness to win the game, or to contrast the winning of opponents, or to improve the probability of the winning of someone in the game, or a combination of them. The utility function of an agent's strategy assigns a value, as the computational cost or the distance from the goal, to each feasible action and it implements the wishes of the player during the interaction with the other ones. The utility of an action depends upon the environment state and it evaluates the degree of happiness of an agent about to reach a state of the environment from the current one. In negotiation scenarios, the first bids the agents make are their preferred ones and thus if they are competitive, their happiness decreases as the negotiation continues. A competitive agent tries to prevent to push away from her initial viewpoint because it is her preferred one and if she has to make new proposal different from the initial viewpoint, she does it by minimally changing the previous one. In the same way, a collaborative agent firstly bids the proposal she prefers but, her happiness does not decrease as the negotiation continues; a collaborative agent is as much happy as the meaning negotiation seems to end positively. The goal of both collaborative and competitive agents is to agree about a shared viewpoint but their behaviour is different in the choice of the next proposal.

The results obtained in this chapter have been carried out within the streams of Strategic Argumentation [152]: I am indebted with those scholars for their inspirational work.

In the following sections I formalise the MN strategy of agents by means of their attitudes. In Section 5.2 I define the negotiating agent attitudes by the ethical components of a multiple agent system (EMAS). Then I formalise the strategies of agent by a Defeasible Theory in Section 5.3.

5.2 Attitudes in MN

The attitude of an agent is a set of behavioral rules expressing duties and prohibitions of the agent. An attitude is therefore a representation of the ethical reasoning of an agent. A widely accepted tool for ethical reasoning is Deontic Logic.

Deontic logic is the branch of symbolic logic that has been the most concerned with the contribution that the following notions make to what follows from what:

- permissible (permitted): which action can be performed;
- impermissible: which actions are forbidden;
- obligatory (duty, required): which actions have to be performed.

Modal operators tag actions with $\bigcirc$ for obligatory action, with $\Box$ for necessary action and with $\Diamond$ for permitted action.

Duties and prohibitions are actions that must, for duties, or not, for prohibitions, be performed with respect to a criterion of evaluating the behaviour of the agent. There are actions that are always prohibitions or duties such as steals, but in general the actions are evaluated in different ways depending on the situations in which they take place. For instance, to hit somebody is permitted only in boxing match and in everyday life it is forbidden.

The ethical rules express the behavioral laws for agents in a MAS and there are a set of ethical rules for each type of MAS: an everyday life MAS has different rules from a MAS of boxing match. Laws are specific for the type of the agents societies and there is a set of laws for each relevant aspect of the society itself. In fact, legality, society, altruism, selfishness are ways to describe the behaviour of an entity with respect to a system configuration. Legality, society, altruism and selfishness are henceforth called as *contexts* for evaluating actions.

The priority of a context over the others produce an order between the feasible actions and different priorities lead to different orderings of actions. An altruistic person thinks that the welfare of the society is the principal motivation in behaving. Conversely, a selfish agent thinks that the principal motivation in performing actions is to improve her advantage. The priority among contexts is intrinsic into the agent definitions.

Agents belonging to the same society behave in different ways because they have different goals and different feasible actions and, possibly, different behaving rules that is a different agency attitude. Therefore, the attitude of an agent belonging to a MAS is intrinsic in her design and may be different from the attitudes of the other agent belonging to the same MAS. In my previous work [49], I define this type of MAS as *ethical* and I formalise it by:

Definition 5.1. *An* ethical multiple agent environment *(EMAS) is a tuple* $\mathcal{M}=\{\mathrm{Ag}, \mathrm{Act}, \aleph(\cdot), e(\cdot,\cdot)\}$*, where elements of* Ag *are agents, elements of* Act *are actions, and* $e(,)$ *is a function that evaluates actions for every agent.*
For every agent ag*,* $\aleph(\mathrm{ag})$ *actions that the agent can perform, called the* feasible actions *and a function* $e(x, \mathrm{ag})$ *that evaluates the action* x *for that agent.*

An EMAS is a multiple agent system in which the agents perform actions that are not imposed by a supervisor but that are chosen by themselves. In the definition of EMAS, the evaluation function $e(\cdot,\cdot)$ takes as input the name of the agent because each agent has her own perception of the world and an attitude that may be different from the other ones. Moreover, the evaluation function is contextualised and it provides a values for each of the contexts being relevant for the EMAS. For instance, if the relevant contexts are legality, social utility and personal advantage then the evaluation function of an action for an agent gives a ternary that contains the value of the action with respect to each of the three relevant contexts.

In Meaning Negotiation, the relevant contexts are:

- the welfare of the MAS;
- the personal advantage.

The actions of the agent are making proposal and accepting or rejecting the others' ones. When an agent has to make a proposal she evaluates it with respect to the relevant contexts, MAS welfare and personal advantage. The proposal is positive with respect to the MAS welfare if it improves the possibility of ending the MN in a positive way. Such a proposal is said to be *collaborative*. Conversely, the proposal is positive with respect to the personal advantage if it minimally changes the state of the agent whatever the MAS condition be. Such a proposal is said to be *competitive* because it is useful only to the agent who performs it.

The attitude of a negotiating agent is an ordering of the two contexts, MAS welfare and personal advantage henceforth indicated by `Wel` and `Per` respectively. In Meaning Negotiation, the agents may change behaviour over time and thus they may change their attitude. It happens when some conditions raise or when the process takes too much time and for instance, a competitive agent becomes collaborative in order to conclude the process as soon as possible. A temporal factor is introduce in the ordering between the contexts and the attitude of an agent is called *static* if it never changes over time, or *dynamic* in the opposite case. The temporal factor is the number of steps occurred in the MN. Making a proposal causes a new step of the MN thus an increment of the temporal factor.

Let $\mathcal{C} = \{\texttt{Wel}, \texttt{Per}\}$ be the set of MN contexts and $\Lambda(\text{ag})^k = \langle \mathcal{C}, \rhd^k \rangle$ the attitude of the agent ag at the k-th step of the MN process where $\rhd^k$ is the k-th order between contexts.

The possible attitudes of the agents in MN are:

absolutely collaborative : in all the MN steps the agent with an absolutely collaborative attitude chooses the best action to perform with respect to the MAS welfare; that is $\texttt{Wel} \rhd^k \texttt{Per}$ for all k;

absolutely competitive : in all the MN steps the agent with an absolutely competitive attitude chooses the best action to perform with respect her own advantage; that is $\texttt{Per} \rhd^k \texttt{Wel}$ for all k;

alternating : an agent with an alternating attitude chooses the next action to perform as a collaborative agent if in the previous step she chose a competitive action, or as a competitive agent if in the previous step she chose a collaborative action; that is $\texttt{Wel} \rhd^k \texttt{Per}$ if $\texttt{Per} \rhd^{k-1} \texttt{Wel}$ or $\texttt{Per} \rhd^k \texttt{Wel}$ if $\texttt{Wel} \rhd^{k-1} \texttt{Per}$;

competitive-meets-collaborative : a competitive-meets-collaborative agent behaves like an absolutely competitive agent for the first k MN steps and behaves like an absolutely collaborative agent for all the next MN steps; for all $k_1 \leq k$ $\texttt{Per} \rhd^{k_1} \texttt{Wel}$ and for all $k_2 \geq k$ $\texttt{Wel} \rhd^{k_2} \texttt{Per}$;

collaborative meets competitive : a collaborative-meets-competitive agent behaves like an absolutely collaborative agent for the first k MN steps and behaves like an absolutely competitive agent for all the next MN steps; for all $k_1 \leq k$ $\texttt{Wel} \rhd^{k_1} \texttt{Per}$ and for all $k_2 \geq k$ $\texttt{Per} \rhd^{k_2} \texttt{Wel}$;

randomly : a randomly agent behaves in an unpredictable ways. This is the most general attitude of an agent in a MN process and it extends all the other attitudes and there is not a mathematical way to describe this attitude type as the previous ones. A randomly agent may decide to change her attitudes many times during the process.

The competitive-meets-collaborative and the collaborative-meets-competitive attitudes allow agents to change their behaviour once during the MN. I name the time of changing attitude as the *changing period* and I indicate with χ_i the changing period of the agent i.

The absolutely competitive, absolutely collaborative and alternating attitudes are static because the agent with these attitudes chooses the next action to perform and the next proposal in a deterministic ways. Conversely, a competitive-meets-collaborative, a collaborative-meets-competitive and a randomly attitudes are dynamic because the agent with those attitudes has many feasible actions and she chooses the next one by deciding if she maintains the previous attitude or not. In this sense the choice of the action is non deterministic, the next action is the result of the choice from many ones. Table 5.1 shows the graphical representations of the attitudes of an agent with respect to the collaborative and competitive perspective. The attitudes are distinguished between static and dynamic.

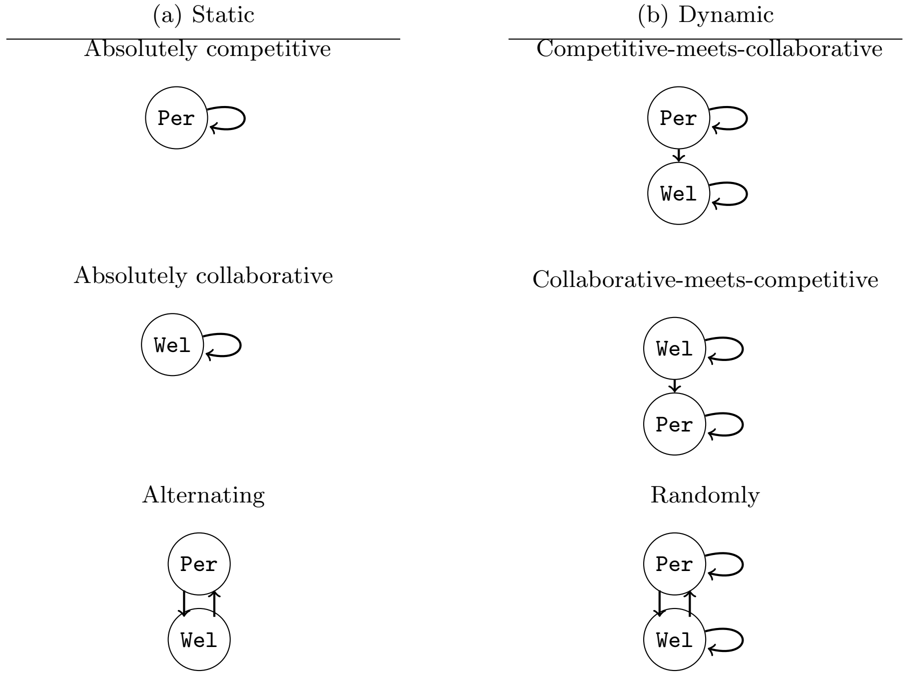


Table 5.1. Attitudes in a competitive and collaborative perspectives.

In the next section I formalise the MN strategy of an agent as an implementation of the attitude of the same agent.

5.3 Strategy by Attitudes

In this section I formalise the Meaning Negotiation strategy of an agent as a defeasible theory.

The current literature have dealt with the problem of formalising the strategical behaviour of agents in MAS, i.e. of choosing the next step to do, in many ways. The general approach is to model it as a non-monotonic reasoning. An agent is an automata in which the symbols in input are the actions the agent can perform and the states are the environment situations reached by performing actions. For each state, there may be many feasible actions and the agent has to choose which action to perform. The choice of the next state is usually modelled in two ways:

1. holding condition: actions are combined to conditions of occurrence to establish when an action may be performed;
2. preference: a measure of happiness or preference is coupled with each of the possible reachable state and the choice goes to the best one.

The first approach of testing the precondition verification to make actions is the basic idea of formalisms such timed automata, situation calculus and event calculus.

Timed Automata is a theory for modeling and verifying real time systems. Example of other formalisms with the same purposes are, timed Petri Nets, timed process algebras, and real time logics [12,33,97,149,187]. In the original theory of timed automata, a timed automaton is a finite-state Büchi automaton extended with a set of real-valued variable modeling clocks. Constraints on the clocks variables are used to restrict the behaviour of an automaton, and Büchi accepting conditions are used to enforce progress properties.

The situation calculus is a logic formalism designed for representing and reasoning about dynamical domains. It was first introduced by John McCarthy in [117]. The main version of the situational calculus that is presented in this article is based on that introduced by Ray Reiter [132]. It is followed by sections about McCarthy's 1986 version and a logic programming formulation.

The event calculus is a logical language for representing and reasoning about actions and their effects first presented by Robert Kowalski and Marek Sergot in [103]. It was extended by Murray Shanahan and Rob Miller in the 1990s [122, 123, 159]. The basic components of the event calculus, as with other similar languages for reasoning about actions and change are fluents and actions. In the event calculus, one can specify the value of fluents at some given time points, the actions that took place at given time points, and the effects of actions.

All the above formalisms model the cause-and-effect principle. The causes of event occurrence are time passing or environment changes. The disadvantage of the first approach is their non-determinism: when the same condition produces more than two events the agent, or the automaton in general, is not able to choose which to perform.

The second approach of having preferences between states of the environment is the mainly used in Game Theory in which preference is valued by a probability distribution. Markov Chains is the formalism used in Game theory. Markov Chains give a probability value to each reached state by condition holding. Therefore, the choice of which action to perform between two or more actions having the same precondition, is made by regarding their probability. The problem of the Markov Chains is about which is the probability distribution. As Markov Chains, the Defeasible Logic allows different actions with the same preconditions. The actions are represented by the rules and the choice of the action to perform is implemented by the superiority relation between rules. The advantage of the Defeasible Logic is that it not necessary to know all the automaton states in order to choose the next action to perform.

In the following subsection I present the main properties of the Defeasible Logic formalism (Section 5.3.1) and then I formalise the MN agent strategy as a Defeasible Theory making distinction from negotiating agent and the referee (Section 5.3.2).

5.3.1 Defeasible Logic

Defeasible logic, originally created by Donald Nute with a particular concern about efficiency and implementation, is a simple and efficient rule based non-monotonic formalism. Over the year the logic has been developed and extended, and several variants have been proposed.

The main intuition of the logic is to be able to derive "plausible" conclusions from partial and sometimes conflicting information. Conclusions are tentative conclusions, in the sense that a conclusion can be withdrawn when we have new pieces of information.

Defeasible Logic is a sceptical formalism, meaning that it does not support contradictory conclusions. In cases where there is some support for concluding ϕ but also support for concluding $\neg\phi$, the reasoning mechanism does not conclude either of them. The contradiction is resolved by a priority relation between the supports. A *defeasible theory*, i.e. a knowledge base in Defeasible Logic, consists of two kinds of knowledge: facts and rules. *Facts* denote simple pieces of information that are deemed to be true regardless of the other knowledge items. They are indisputable statements represented by ground literals. For example, "Tweety is a penguin" is represented by $Penguin(Tweety)$ A *rule* describes the relationship between a set of literals, *premises*, and a literal, *conclusion*. Rules specify the strength of the relation between premises and conclusion by having different kinds of rules. Rules distinguish between *strict rules*, *defeasible rules* and *defeaters* representing respectively, by expressions of the form $A_1, \ldots A_n \rightarrow B$, $A_1, \ldots A_n \Rightarrow B$, $A_1, \ldots A_n \leadsto B$, where $A_1, \ldots A_n$ is a possibly empty set of prerequisites and B is the conclusion of the rule.

Strict rules are rules in the classical sense: whenever the premises are true then so is the conclusion. They are used for definitional clauses and the conclusion of a strict rule is a fact. An example of a strict rule is "Penguins are birds", formally: $Penguin(X) \rightarrow Bird(X)$;

Defeasible rules are rules that can be defeated by contrary evidence. The meaning of a defeasible rule is "whenever the premises are true then presumably so is the conclusion". An example of defeasible rule is " Birds usually fly": $Bird(X) \Rightarrow Fly(X)$. The idea is that if we know that X is a bird, then we may conclude that X can fly *unless there is other evidence suggesting that she may not fly*;

Defeaters are special kind of rules. They are used to prevent conclusion, not to support them. For example: $Heavy(X) \leadsto \neg Fly(X)$ states that if something is heavy then it might not fly. This rule prevents the derivation of $Fly(X)$ and it cannot be used to support a $\neg Fly(X)$ conclusion.

The prevention from concluding contradictions is made by the *superiority relation* among rules. The superiority relation is used to define priorities among rules, that is, where one rule may override the conclusion of another rule. For example: $Bird(X) \Rightarrow Fly(X)$ and $r' : Penguin(X) \Rightarrow \neg Fly(X)$ which contradict one another, no conclusive decision can be made about whether a Tweety can fly or not. But if a superiority relation is introduce as $r' \succ r$ then it can be concluded that Tweety cannot fly since it is a penguin.

Conclusions can be classified as definite or defeasible. A definite conclusion is a conclusion that cannot be withdrawn when new information is available. A defeasible conclusion is a tentative conclusion that might be withdrawn by new pieces of information. In addition the logic is able to tell whether a conclusion is or is not provable. Thus it is possible to have the following 4 types of conclusions:

- Positive definite conclusions: meaning that the conclusion is provable using only facts and strict rules;
- Negative definite conclusions: meaning that it is not possible to prove the conclusion using only facts and strict rules;
- Positive defeasible conclusions: meaning that the conclusions can be defeasible proved;
- Negative defeasible conclusions: meaning that one can show that the conclusion is not even defeasibly provable.

Strict derivations are obtained by forward chaining of strict rules, while a defeasible conclusion A can be derived if there is a rule whose conclusion is A, whose prerequisites (antecedent) have either already been proved or given in the case at hand (i.e., facts), and any stronger rule whose conclusion is $\neg A$ (the negation of A) has prerequisites that fail to be derived. In other words, a conclusion A is (defeasibly) derivable when:

- A is a fact; or
- there is an applicable strict or defeasible rule for A, and either
  - all the rules for $\neg A$ are discarded (i.e., not applicable) or
  - every applicable rule for $\neg A$ is weaker than an applicable strict or defeasible rule for A.

Alternatively the reasoning process can be explained in terms of arguments with a three phase process:

1. Give an argument for the conclusion to be proved;
2. Consider all possible counter-arguments for the conclusion;
3. Rebut the counter-arguments:
   - Show that a counter-argument is not valid (e.g., some of the premises do not hold);
   - Defeat a counter-argument by a stronger argument supporting the conclusion.

By changing the definitions of "applicable", "discarded rules", "arguments" and "counter-arguments" it is possible to capture several different intuitions of non-monotonic reasoning (e.g., ambiguity propagation vs ambiguity blocking).

A defeasible theory $\mathcal{D}$ is a triple $\langle \mathcal{F}, \mathcal{R}, \succ \rangle$ where $\mathcal{F}$ is the set of facts, $\mathcal{R} = \mathcal{R}_s \cup \mathcal{R}_d \cup \mathcal{R}_{dft}$ is the set of strict, defeasible rules and defeaters, and $>$ is the superiority relation on $\mathcal{R}$.

A rule $r \in \mathcal{R}$ is formed by an antecedent or body $A(r)$ and a consequent o head $C(r)$. $A(r)$ consists of a finite sequence of literal while $C(r)$ contains a single literal.

We denote by $\mathcal{C}(q)$ the set of rules having q as consequence.

A conclusion derived form the theory $\mathcal{D}$ is a tagged literal and is categorised according to how the conclusion can be proved:

- $+\Delta q$ if q is *definitely provable* (only facts and strict rules are used in the derivation);
- $-\Delta q$ if q is not *definitely provable* (it is different from proving that $+\Delta\neg q$ so that it is definitely provable that $\neg q$);

- $+\partial q$ if q is *defeasibly provable*, then only defeasible rules and/or defeaters are used in the derivation;
- $-\partial q$ if q is not *defeasibly provable*.

A derivation in defeasible logic is a finite sequence $P = (P(1), P(2), \dots, P(n))$ of tagged literals. Each tagged literal satisfies some proof conditions. A proof condition corresponds to the inference rules corresponding to one of the four kinds of conclusions I mentioned above. $P(1 \dots i)$ denotes the initial part of the sequence P of length i. In Table 5.2 I state the conditions for strictly and defeasible derivable conclusions.

$+\mathbf{\Delta}$:	$-\mathbf{\Delta}$:
If $P(i+1) = +\Delta q$ then	If $P(i+1) = -\Delta q$ then
$\exists r \in \mathcal{R}_s[q]$	$\forall r \in \mathcal{R}_s[q]$
$\forall a \in A(r) : +\Delta a \in P(1 \dots i)$	$\exists a \in A(r) : -\Delta a \in P(1 \dots i)$
$+\partial$:	$-\partial$:
If $P(i+1) = +\partial q$ then	If $P(i+1) = -\partial q$ then
1. $+\Delta q \in P(1 \dots i)$	1. $-\Delta q \in P(1 \dots i)$
2.	2.
a) $\exists r \in \mathcal{R}_{sd}[q] \forall a \in A(r) : +\partial a \in P(1 \dots i)$ and	a) $\forall r \in \mathcal{R}_{sd}[q] \exists a \in A(r) : -\partial a \in P(1 \dots i)$ or
b) $\forall p \in \mathcal{C}(q) . -\Delta p \in P(1 \dots i)$ and	b) $\exists p \in \mathcal{C}(q) + \Delta p \in P(1 \dots i)$ or
c) $\forall s \in \mathcal{R}[\mathcal{C}(q)]$:	c) $\exists s \in \mathcal{R}[\mathcal{C}(q)]$:
i. $\exists a \in A(s) : -\partial a \in P(1 \dots i)$ or	i. $\forall a \in A(s) : +\partial a \in P(1 \dots i)$ and
ii. $\exists b \in \mathcal{R}_{sd}[q]$ such that $\forall a \in A(b) : +\partial a \in P(1 \dots i)$ and $b \prec s$	ii. $\forall b \in \mathcal{R}_{sd}[q]$ such that $\exists a \in A(b) : -\partial a \in P(1 \dots i)$ or $b \not\prec s$

Table 5.2. Proof conditions for definite and defeasible derivations.

5.3.2 Defeasible MN Strategies

In this thesis I follow a game theoretic approach to model the Meaning Negotiation problem. The agents behave like players of Bargaining or English Auction Games and their agency capabilities depends upon the number of the involved agents and upon the role they have in the Game, whether a referee or not. In Game Theory, the strategy of an agent is a function taking the history of the game, i.e. the proposals made by agents, and the utility function of the agent herself as input and mapping them into a subset of the feasible actions. The strategy is personal and none of the agents knows which is the strategy of the opponents because knowing the strategy of an agent is knowing which are the next actions she may perform and this causes fraudulent behaviours of the agents. Suppose Alice knows that Bob always choose the propose x when she propose y, if Alice does not want x she never makes the proposal y or viceversa if she wants to obtain x.

The history of the game is a key element in choosing the next action, i.e. the next proposal to perform. Knowing the proposals of the agents drives an agent to understand and forecasts which is the course of the negotiation, whether ending or not. In the previous chapter, I formalise the Meaning Negotiation Deductive system in which the agents involved asserts proposals and they also inform the opponents about the negotiation relation of agreement or disagreement they tested. This is an important additional information that helps agent in choosing the next action to perform and in understanding the provisional negotiation situation both for collaborative and competitive agents. Let the scenario depicted in Figure 5.1 be a Meaning Negotiation beginning in which Alice proposes φ and receives the counterproposal of Bob ψ coupled with the negotiation relation evaluation $\mathbf{essDis}(Alice : \varphi)$. Suppose Alice and Bob have their knowledge as in

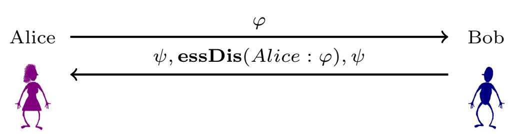


Figure 5.1. A MN scenario

configuration number 25 of Table 4.4. Alice and Bob do not know the relation between their knowledge, each agent infers only the relation between her knowledge and the received proposal. From the assertion $\mathbf{essDis}(Alice : \varphi)$, Alice knows that Bob thinks that her viewpoint is not equivalent to his own and that his stubbornness knowledge is consistent with her viewpoint, thus they are in one of the configurations in Table 4.6. Alice evaluates the counterproposal of Bob, ψ. After the evaluation, Alice knows they may be in one of the configurations number 11, 13, 25, 26, 27 or 42a. Suppose Alice is collaborative; she accepts it because she knows that ψ is an acceptable common angle. The negotiation relation becomes agreement and the negotiation ends positively. Suppose Alice is competitive; she does not accept the counterproposal of Bob even if she knows it is an acceptable one. Alice competitively hopes that Bob will meet her own proposal and makes a new offer that is not better than her previous one. This choice is a strategical move and the goal is to make Bob acting collaboratively. The persisting essence disagreement relation drives Bob to think that he has to make proposals towards Alice's viewpoint.

The utility function for a given player assigns a number for every possible outcome of the game with the property that a higher number implies that the outcome is more preferred. In this sense, the utility function of an agent is a long term expression of the agent's attitude.

The attitude of a negotiating agent is an ordering of the evaluation contests which are relevant for the MN process and it chooses the next MN situation to raise with respect to what the agent prefers. Obviously, being in a MN process, each involved agent prefers to end the MN in positive than in negative way, but the goal of a competitive agent is to have as outcome of the negotiation an angle of her initial viewpoint which is minimally different from it. Conversely, the goal of a collaborative agent is to end the negotiation as soon as possible even if it leads herself to release many points of her initial viewpoint.

A negotiating agent evaluates and chooses the next proposal to assert by her attitude, her received offers from the opponents.

The evaluation of the proposal to perform is obtained by considering which is the negotiation state the system reaches if the agent makes it. The evaluations are the disagreement and agreement relations among agents: absolute-disagreement, essence-disagreement, compatibility, relative-disagreement and agreement. The order among the evaluations is

$$absDis < essDis < comp < relDis < agree$$

where agree is the best and absDis is the worst.

Strategy of a negotiating agent in 1-1 MN

I define the strategy of a negotiating agent as a defeasible theory in which the facts are negotiations assertions made by agents, the rules are expressions of the actions of an agent and the superiority relation is an implementation of the agent attitude.

Negotiation strategy results in orderings of defeasible negotiation rules that depend upon the attitude. Therefore a defeasible theory of meaning negotiation strategy per agent can be defined in Definition 5.2.

Definition 5.2 (Defeasible Negotiation Strategy). *A negotiation strategy of an agent is a defeasible theory* $\mathfrak{S}^k = \langle \mathcal{F}^k, \mathcal{R}^k, \succ^k \rangle$ *where:*

- $\mathcal{F}^k = \mathcal{N}^k \cup \mathcal{F}l^x$ *and:*
  - $\mathcal{N}^k$ *is the set of negotiation assertions like* $i : \phi$ *or* $i : \mathbf{absDis}(j : \psi)$*;*
  - $\mathcal{F}l^k$ *is the set of the agent's viewpoint at the* k^{th} *stage of the negotiation like* flex_i^k*;*
- $\mathcal{R}^k$ *is the set of defeasible negotiation rules;*
- $\succ^k$ *is the superiority relation among rules in* $\mathcal{R}^k$*.*

The parameter k *represents the negotiation stage.*

I assume that the agents are synchronised, thus the parameter k denotes the k^{th} proposal of each agents.

Facts, rules and the superiority relations have the parameter k. It is a temporal factor needed to represent the dynamism of the negotiation process, i.e. the assertions made by agents, and of the attitude of the agent. The choice of the next proposal depends upon what the opponents said (facts), which are the feasible action at the k-th stage of the negotiation (rules) and the behaviour the agent have (superiority relation).

In the previous section I said that the evaluation of an action is contextualised; here, the proposal is not evaluated as how much it is collaborative or how much it is competitive. The collaborative and competitive properties of an action are with respect to the feasible actions of the agent. The rules of the strategy defeasible theory are the feasible actions and the superiority relation is the attitude of the agent and it also evaluates the degree of collaborations and of competition of the actions with respect the feasible ones.

The set of defeasible rules for a MN strategy are of two kinds:

1. $\mathcal{R}^k_{\text{I}}$ is the set of the internal rules for the actions a MN agent can perform to changing her current angle to a new one by weakening it or by making a changing theory action;
2. $\mathcal{R}^k_{\text{A}}$ is the set of assertive rules representing the assertion the agent can make in the negotiation.

The first type of rules represents action that the agent internally does in order to find a new angle; as said in the previous chapters, the internal actions are of weakening or changing the knowledge of the agent. The second type of rules is the implementation of the deductive rules in Table 4.8 and Table 4.9 that produce the negotiation assertion of the agent.

The internal rules of $\mathcal{R}^k_{\text{I}}$ are in Table 5.3 and they are defeasible rules because for each flex^x the agent may make either of a weakening and a changing action.

rule name	rule description
w:	$\text{flex}^k, (\text{flex}^k \vee \text{flex}^{k+1}), (\text{flex}^k \rightarrow \text{flex}^{k+1}), \neg(\text{flex}^k \leftrightarrow \text{flex}^{k+1}) \Rightarrow \text{flex}^{k+1}$
c:	$\text{flex}^k_i, \neg(\text{stub}_i \leftrightarrow \text{flex}^k_i), \neg(\text{flex}^k_i \rightarrow \text{flex}^{k+1}_i) \Rightarrow \text{flex}^{k+1}$
s:	$\text{flex}^k \leftrightarrow \text{stub} \Rightarrow \text{stub}$

Table 5.3. The internal rules $\mathcal{R}^k_{\text{I}}$ of a negotiating agent.

The assertive rules of $\mathcal{R}^k_{\text{A}}$ are in Table 5.4. These rules have the parameter x which counts how many assertions the agent has already made during the negotiation. All the rules in $\mathcal{R}^k_{\text{A}}$ consist of three parts:

- the proposal made by the opponent $(j : \varphi)$;
- the evaluation the opponent made of her previous offer (for instance j : $\mathbf{absDis}(i : \text{flex}^k)$);
- the new possible proposal of the agent η such that $+\partial\eta$ by the rules in $\mathcal{R}^k_{\text{I}}$;
- the evaluation of η with respect to the proposal made by the opponent (for instance $(\text{stub} \vee \varphi) \wedge \neg(\eta \vee \varphi)$);
- the consequent of each rule is the assertion of the new current angle of the agent $(i : \eta)$.

The superiority relation is an ordering among the defeasible rules and thus of the feasible actions; it depends on the attitude of the agent. The meaning negotiation attitudes I discussed in the previous section are absolutely collaborative, absolutely competitive, alternating, competitive-meets-collaborative, collaborative-meets-competitive and randomly. The first two attitudes are the basic ones and all the others are extensions of them and I define the superiority relation for each of the negotiation attitudes by defining the superiority relations for the first two types. Absolutely collaborative and absolutely competitive strategies are *pure* or

rule name	rule description
ad-ad:	$j:\varphi, j:\mathbf{absDis}(i:\text{flex}^k), \eta, \neg(\text{stub}_i \wedge \varphi) \Rightarrow i:\eta$
ad-ed:	$j:\varphi, j:\mathbf{absDis}(i:\text{flex}^k), \eta, (\text{stub}_i \vee \varphi) \wedge \neg(\eta \wedge \varphi) \Rightarrow i:\eta$
ad-co:	$j:\varphi, j:\mathbf{absDis}(i:\text{flex}^k), \eta, (\eta \vee \varphi) \wedge \neg(\eta \rightarrow \varphi) \wedge \neg(\eta \leftarrow \varphi) \Rightarrow i:\eta$
ad-rd:	$j:\varphi, j:\mathbf{absDis}(i:\text{flex}^k), \eta, ((\eta \rightarrow \varphi) \wedge \neg(\eta \leftarrow \varphi)) \Rightarrow i:\eta$
ad-ag:	$j:\varphi, j:\mathbf{absDis}(i:\text{flex}^k), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i:\eta$
ed-ad:	$j:\varphi, j:\mathbf{essDis}(i:\text{flex}^k), \eta, \neg(\text{stub}_i \wedge \varphi) \Rightarrow i:\eta$
ed-ed:	$j:\varphi, j:\mathbf{essDis}(i:\text{flex}^k), \eta, (\text{stub}_i \vee \varphi) \wedge \neg(\eta \wedge \varphi) \Rightarrow i:\eta$
ed-co:	$j:\varphi, j:\mathbf{essDis}(i:\text{flex}^k), \eta, (\eta \vee \varphi) \wedge \neg(\eta \rightarrow \varphi) \wedge \neg(\eta \leftarrow \varphi) \Rightarrow i:\eta$
ed-rd:	$j:\varphi, j:\mathbf{essDis}(i:\text{flex}^k), \eta, ((\eta \rightarrow \varphi) \wedge \neg(\eta \leftarrow \varphi)) \Rightarrow i:\eta$
ed-ag:	$j:\varphi, j:\mathbf{essDis}(i:\text{flex}^k), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i:\eta$
co-ad:	$j:\varphi, j:\mathbf{comp}(i:\text{flex}^k), \eta, \neg(\text{stub}_i \wedge \varphi) \Rightarrow i:\eta$
co-ed:	$j:\varphi, j:\mathbf{comp}(i:\text{flex}^k), \eta, (\text{stub}_i \vee \varphi) \wedge \neg(\eta \wedge \varphi) \Rightarrow i:\eta$
co-co:	$j:\varphi, j:\mathbf{comp}(i:\text{flex}^k), \eta, (\eta \vee \varphi) \wedge \neg(\eta \rightarrow \varphi) \wedge \neg(\eta \leftarrow \varphi) \Rightarrow i:\eta$
co-rd:	$j:\varphi, j:\mathbf{comp}(i:\text{flex}^k), \eta, ((\eta \rightarrow \varphi) \wedge \neg(\eta \leftarrow \varphi)) \Rightarrow i:\eta$
co-ag:	$j:\varphi, j:\mathbf{comp}(i:\text{flex}^k), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i:\eta$
rd-ag:	$j:\varphi, j:\mathbf{relDis}(i:\text{flex}^k), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i:\eta$

Table 5.4. The assertive rule in $\mathcal{R}^k_{\mathrm{A}}$ of the negotiating agent i receiving offers from the agent j.

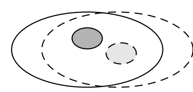
static strategies [128]. Let $\succ_{Cl}$ the superiority relation for the attitude of absolutely collaborative. The superiority relation $\succ_{Cl}$ orders the defeasible rules in $\mathcal{R}^k_{\mathrm{A}}$ by preferring those that improves the negotiation status between the agents. Therefore, whatever be the superiority relation among the rules in $\mathcal{R}^k_{\mathrm{I}}$:

$$\begin{array}{l}\text{ad-ag} \succ_{Cl} \text{ad-rd} \succ_{Cl} \text{ad-co} \succ_{Cl} \text{ad-ed} \succ_{Cl} \text{ad-ad}\\ \text{ed-ag} \succ_{Cl} \text{ed-rd} \succ_{Cl} \text{ed-co} \succ_{Cl} \text{ed-ed} \succ_{Cl} \text{ed-ad}\\ \text{co-ag} \succ_{Cl} \text{co-rd} \succ_{Cl} \text{co-co} \succ_{Cl} \text{co-ed} \succ_{Cl} \text{co-ad}\end{array}$$

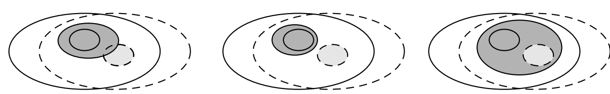
Let $\succ_{Cp}$ the superiority relation for the attitude of absolutely competitive. The superiority relation $\succ_{Cp}$ orders the defeasible rules in $\mathcal{R}^k_{\mathrm{A}}$ by preferring those that minimally change the provisional negotiation status between the agents. Therefore, whatever be the superiority relation among the rules in $\mathcal{R}^k_{\mathrm{I}}$:

$$\begin{array}{l}\text{ad-ad} \succ_{Cp} \text{ad-ed} \succ_{Cp} \text{ad-co} \succ_{Cp} \text{ad-rd} \succ_{Cp} \text{ad-ag}\\ \text{ed-ed} \succ_{Cp} \text{ed-co} \succ_{Cp} \text{ed-rd} \succ_{Cp} \text{ed-ag} \succ_{Cp} \text{ed-ad}\\ \text{co-co} \succ_{Cp} \text{co-rd} \succ_{Cp} \text{co-ag} \succ_{Cp} \text{co-ed} \succ_{Cp} \text{co-ad}\end{array}$$

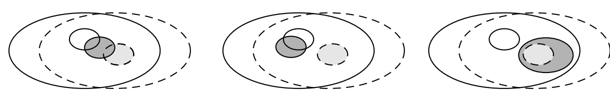
The independence of the superiority relation between the weakening and changing actions in $\mathcal{R}^k_{\mathrm{I}}$ seems to be contradictory with the definition of collaborative and competitive attitude I gave above. In fact, the absolutely competitive attitude is defined as the behaviour of minimally changing the agent's initial viewpoint; "changing" means both weakening and changing theory even if it seems more competitive to change theory than to weaken it. Let Alice and Bob be two negotiating agents and that Alice is a competitive agent and Bob a collaborative one. Suppose their knowledge are as in Figure 5.2(a) and that Alice has to choose the next proposal. Alice is represented by plain lines and Bob by dashed lines. Both agent recognise an essence disagreement situation. Alice may perform a weakening internal action by applying the (w) rule in Table 5.3 and the result is one of the situation in Figure 5.2(b). Otherwise, Alice may perform a changing theory internal action by applying the rule (c) in Table 5.3 and the result is one of the situation in Figure 5.2(c). Both the internal actions may lead to the same situations: they may preserve the essence disagreement or produce compatibility or relative disagreement. The preference ordering between the internal actions is irrelevant to the attitude of the agent.



(a) initial situation



(b) Weakening actions



(c) Changing theory actions

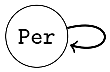
Figure 5.2. Alice internal actions. Alice is represented by plain lines. The flexible part of E/Y of Alice with a shaded background represents her current proposal and the one with no shaded background is her previous proposal. Bob is represented by dashed lines.

All the other types of superiority relations are:

- **competitive-meets-collaborative** if the superiority relation is such that there exists $\chi \in \mathbb{N}$ which is the changing period, such that for all $k_1 < k$ and $k_2 \geq k$, $\succ_1^k = \succ_{Cp}$ and $\succ_2^k = \succ_{Cl}$. Conversely for a **collaborative-meets-competitive** superiority relation.
- **alternating** if the superiority relation is such that for all $k \in \mathbb{N}$ if $\succ^k = \succ_{Cp}$ then $\succ^{k+1} = \succ_{Cl}$ and if $\succ^k = \succ_{Cl}$ then $\succ^{k+1} = \succ_{Cp}$.
- **randomly** if the superiority relation is such that there exist $k \in \mathbb{N}$ such that if $\succ^k$ is competitive meets collaborative then there exists $k_1 > k$ such that $\succ^{k_1}$ is collaborative meets competitive or viceversa.

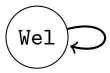
Table 5.5 the implementation of each negotiation attitude by the superiority relation.

Absolutely Competitive



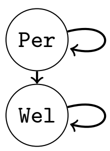
$\succ_{Cp}$:
ad-ad $\succ_{Cp}$ ad-ed $\succ_{Cp}$ ad-co $\succ_{Cp}$ ad-rd $\succ_{Cp}$ ad-ag
ed-ed $\succ_{Cp}$ ed-co $\succ_{Cp}$ ed-rd $\succ_{Cp}$ ed-ag $\succ_{Cp}$ ed-ad
co-co $\succ_{Cp}$ co-rd $\succ_{Cp}$ co-ag $\succ_{Cp}$ co-ed $\succ_{Cp}$ co-ad

Absolutely Collaborative



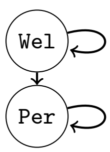
$\succ_{Cl}$:
ad-ag $\succ_{Cl}$ ad-rd $\succ_{Cl}$ ad-co $\succ_{Cl}$ ad-ed $\succ_{Cl}$ ad-ad
ed-ag $\succ_{Cl}$ ed-rd $\succ_{Cl}$ ed-co $\succ_{Cl}$ ed-ed $\succ_{Cl}$ ed-ad
co-ag $\succ_{Cl}$ co-rd $\succ_{Cl}$ co-co $\succ_{Cl}$ co-ed $\succ_{Cl}$ co-ad

Competitive-meets-collaborative



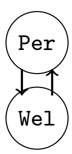
There exists $k \in \mathbb{N}$ such that for all $k_1, k_2.k_1 < k \leq k_2$. $\succ_1^k = \succ_{Cl}$ and $\succ_2^k = \succ_{Cp}$

Collaborative-meets-competitive



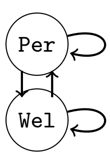
There exists $k \in \mathbb{N}$ such that for all $k_1, k_2.k_1 < k \leq k_2$. $\succ_1^k = \succ_{Cl}$ and $\succ_2^k = \succ_{Cp}$

Alternating



for all $k \in \mathbb{N}$ if $\succ^k = \succ_{Cp}$ then $\succ^{k+1} = \succ_{Cl}$ and if $\succ^k = \succ_{Cl}$ then $\succ^{k+1} = \succ_{Cp}$

Randomly



there exist k such that if $\succ^k$ is competitive meets collaborative then there exists $k_1 > k$ such that $\succ^{k_1}$ is collaborative meets competitive or viceversa.

Table 5.5. The superiority relations for each negotiation attitude of Table 5.1.

There are situations in which the assertive action of an agent makes the negotiation status worse. These actions are called *violations*. An agent makes a violations when she performs an action that produces a worsening of the negotiation situation among the involved agents with respect to the previous negotiation status. The rules (ed-ad), (co-ed) and (co-ad) are violations and both collaborative and competitive agents treat violations in the same way. The goal of each agent in the negotiation is to reach an agreement thus violations are the least preferred actions. In Table 5.6 I give a preference number to actions with respect to the attitude of the agent: the preference numeration is such that a lower value means more preferred. Gray cells identify the violations actions. The absolutely competitive and

		$\mathbf{R}(\eta, \varphi)$					
		absolute dis.	essence dis.	compatibility	relative dis.	agreement	**attitude**
$j : \mathbf{R}(\text{flex}^x, \varphi)$	absolute dis.	1	2	3	4	5	C_l
		1	5	4	3	2	C_p
	essence dis.	1	2	3	4	5	C_l
		1	5	4	3	2	C_p
	compatibility	1	2	3	4	5	C_l
		1	2	5	4	3	C_p
	relative dis.					5	C_l
						5	C_p

Table 5.6. Preference order of assertive actions for the collaborative and the competitive agents. Gray cells identify the violations. $\mathbf{R}(\eta, \varphi)$ indicates the relation between the new proposal η and the offer of the opponent φ, and $j : \mathbf{R}(\text{flex}^x, \varphi)$ indicates the relation the opponent states with the previous proposal of the agent. Cells with no number represents not reachable situations.

absolutely collaborative attitude are equivalent with respect to violations and they are dual for legitimate actions.

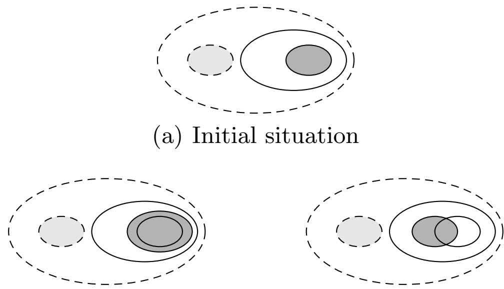
There are situations in which a violation is the only feasible action. For instance when agents are as in Figure 5.3, the agent represented by plain line can only make a violation whatever be the internal state she choose to perform.

The situations in which that only violations are feasible actions are those that are instances of configuration number 8 in Table 4.3.

The above strategical rules are for bilateral negotiating agents. In fact the antecedent of each rules contains the proposal of one opponent and her evaluation of the previous proposal of the agent; the choice of the next action is based upon the evaluation of the proposal of a single opponent.

Strategy of the auctioneer in 1-n MN

When the involved agents are more than two, the MN is formalised as an English Auction Game (Section 3.4) in which an agent is reserved to be the referee, ty-



(a) Initial situation

(b) Weakening

(c) Changing theory

Figure 5.3. Only violations are feasible actions. The agent identified by the plain line, say Alice, received by the opponent the evaluation of her previous proposal: essence disagreement. Whatever be the next proposal of Alice, it is a violation because she finds that they are in absolute disagreement.

pically the first bidding agent. In MN by English Auction the negotiating agents behave as in the Bargaining Game (Section 3.3) with the exception of the auctioneer. Even if the internal actions of the auctioneer, i.e. the way by which a new proposal is found by the previous one, are the same of a negotiating agent (Table 5.3), the assertive rules of the auctioneer have to consider the proposals and the evaluations of all the negotiating agents. The first idea to model the auctioneer strategic behaviour is of writing a set of rules reserved to the auctioneer, in which the proposals and the evaluations of all the negotiating agent are in the antecedent of the rules. This causes a polynomial increase of the number of the rules: if the negotiating agents are n, the number of the rules are $5 \times n$ where 5 is the number of the possible evaluations of a proposal (absolute disagreement, essence disagreement, compatibility, relative disagreement, agreement). Moreover, the set of the rules has to be changed and new rules are added to it, when a new member enters the MAS and in the MN process.

The solution I propose to formalise the auctioneer's behaviour by a defeasible theory is by extending the superiority relation with a total ordering between the rules. Let me explain the reason of it. Suppose that there are 5 negotiating agents making 5 different proposals, $\varphi_1 \nleftrightarrow \varphi_2 \nleftrightarrow \varphi_3 \nleftrightarrow \varphi_4 \nleftrightarrow \varphi_5$, and evaluating in 5 different ways the previous proposal of the auctioneer, $R_1 \neq R_2 \neq R_3 \neq R_4 \neq R_5$. For instance, $R_1 =$ **absDis**, $R_2 =$ **essDis**, $R_3 =$ **comp**, $R_4 =$ **relDis** and $R_5 =$ **agree**. The auctioneer knows that she probably reaches an agreement with agents 4 and 5, but she cannot know if an agreement with the other agents is possible or not. We imagine that the auctioneer has a set of the feasible proposals and each of them is labeled with a subset of the rules that the auctioneer uses to infer the proposal. The cardinality of this subset of rules is equal to the number of the negotiating agents because it contains a rule for each of the negotiating agents. The label of each proposal identifies the changes of the negotiation relations between the auctioneer and each of the negotiating proposal whenever the auctioneer decides to perform that proposal. See Example 5.3.

Example 5.3. Let Alice (A) be the auctioneer and Bob (B), Charles (C) and Edgar (E) three negotiating agents. Suppose that after the first proposal φ_A of Alice, each negotiating agent counter-proposes a different assertion $\varphi_B \not\leftrightarrow \varphi_C \not\leftrightarrow \varphi_E$ and that B : **absDis**($A : \varphi_A$), C : **essDis**($A : \varphi_A$), E : **comp**($A : \varphi_A$). Alice has three feasible proposals φ_A^1, φ_A^2 and φ_A^3 such that:

- Alice proposes φ_A^1:
  - Alice and Bob are in absolute disagreement; the rules Alice applies is `ad-ad`;
  - Alice and Charles are in compatibility; the rules Alice applies is `ed-co`;
  - Alice and Edgar are in agreement; the rules Alice applies is `co-ag`;
- Alice proposes φ_A^2:
  - Alice and Bob are in agreement; the rules Alice applies is `ad-ag`;
  - Alice and Charles are in essence disagreement; the rules Alice applies is `ed-ed`;
  - Alice and Edgar are in agreement; the rules Alice applies is `co-ag`;
- Alice proposes φ_A^3:
  - Alice and Bob are in compatibility; the rules Alice applies is `ad-co`;
  - Alice and Charles are in agreement; the rules Alice applies is `ed-ag`;
  - Alice and Edgar are in compatibility; the rules Alice applies is `co-co`.

Suppose Alice is collaborative, then:

- she prefers the proposal φ_A^2 with respect the counter-proposal of Bob because `ad-ag`$\succ_{Cl}$`ad-co`$\succ_{Cl}$`ad-ad`;
- she prefers the proposal φ_A^3 with respect the counter-proposal of Charles because `ed-ag`$\succ_{Cl}$`ed-co`$\succ_{Cl}$`ed-ed`;
- she equally prefers the proposals φ_A^1 and φ_A^2 with respect the counter-proposal of Bob because `co-ag`$\succ_{Cl}$`co-co`.

Each of the feasible proposal leads to an agreement with a subset of the negotiating agents, but which is the best one?

The choice of the next proposal has to reflects the preference of the auctioneer about all the pairs of negotiation situations before the proposal and after it. Therefore, the preference relation which is implemented by the superiority relation produce a total order between the rules.

Moreover, the set of the rules has to be extended to represents all the combinations of pre and post MN situations of actions. The choice of the next actions may leads to a violation when the auctioneer makes a proposal that is no more in agreement with the opponent's one, i.e. whenever the auctioneer makes a proposal that gets the MN situation worse with respect to a subset of the negotiating agents. The rules corresponding to violation actions are named *violation rules*; conversely, the rules that do not correspond to violations actions are named *legitimate rules*. The new set of legitimate rules is in Table 5.7.

Violation rules are `ed-ad`, `co-ad`, `co-ed`, `rd-ad`, `rd-ed`, `rd-co`, `rd-rd`, `ag-ad`, `ag-ed`, `ag-co` and `ag-rd` in Table 5.8.

The superiority relation for collaborative and competitive agent between legitimate rules is depicted in Figure 5.4 as a direct acyclic graph in which nodes are the rules in Table 5.7 and the edges represent the order: if there is an edge from the node x to the node y then $y \succ_{att} x$ where *att* is *Cl* or *Cp*.

rule name	rule description
ad-ad:	$j : \varphi, j : \mathbf{absDis}(i : \text{flex}^x), \eta, \neg(\text{stub}_i \wedge \varphi) \Rightarrow i : \eta$
ad-ed:	$j : \varphi, j : \mathbf{absDis}(i : \text{flex}^x), \eta, (\text{stub}_i \vee \varphi) \wedge \neg(\eta \wedge \varphi) \Rightarrow i : \eta$
ad-co:	$j : \varphi, j : \mathbf{absDis}(i : \text{flex}^x), \eta, (\eta \vee \tau_{i,j}(\varphi)) \wedge \neg(\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$
ad-rd:	$j : \varphi, j : \mathbf{absDis}(i : \text{flex}^x), \eta, (\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$
ad-ag:	$j : \varphi, j : \mathbf{absDis}(i : \text{flex}^x), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i : \eta$
ed-ed:	$j : \varphi, j : \mathbf{essDis}(i : \text{flex}^x), \eta, (\text{stub}_i \vee \varphi) \wedge \neg(\eta \wedge \varphi) \Rightarrow i : \eta$
ed-co:	$j : \varphi, j : \mathbf{essDis}(i : \text{flex}^x), \eta, (\eta \vee \tau_{i,j}(\varphi)) \wedge \neg(\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$
ed-rd:	$j : \varphi, j : \mathbf{essDis}(i : \text{flex}^x), \eta, (\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$
ed-ag:	$j : \varphi, j : \mathbf{essDis}(i : \text{flex}^x), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i : \eta$
co-co:	$j : \varphi, j : \mathbf{comp}(i : \text{flex}^x), \eta, (\eta \vee \tau_{i,j}(\varphi)) \wedge \neg(\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$
co-rd:	$j : \varphi, j : \mathbf{comp}(i : \text{flex}^x), \eta, (\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta)s \Rightarrow i : \eta$
co-ag:	$j : \varphi, j : \mathbf{comp}(i : \text{flex}^x), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i : \eta$
rd-ag:	$j : \varphi, j : \mathbf{relDis}(i : \text{flex}^x), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i : \eta$
ag-ag:	$j : \varphi, j : \mathbf{agree}(i : \text{flex}^x), \eta, (\eta \leftrightarrow \varphi) \Rightarrow i : \eta$

Table 5.7. The legitimate rules in $\mathcal{R}_A^k$ of the auctioneer i receiving offers from the negotiating agent j.

The superiority relation for collaborative and competitive agent between violation rules is depicted in Figure 5.5 as a direct acyclic graph in which nodes are the rules in Table 5.8 and the edges represent the order.

A legitimate action is always preferred to a violation. In this way, the superiority relation is a total order between the rules.

Strategies vs Subjective Hierarchy

A negotiating agent is defined by a tuple in which the first element is the expression language and the second is a set of axioms representing the knowledge base of the agent. The last element is the stubbornness set which is the set of axioms the agent never concedes. The agent is always competitive with respect to her stubbornness set. No actions, weakening or changing, are performable on formulas belonging to $\mathcal{L}_\mathcal{S}$: this is a competitive behaviour because no actions on it means that the negotiation relation between the agents does not change. Even if the definitions of the attitude and the stubbornness set of an agent seem to be untied, the cardinality of the stubbornness set leads to an intrinsic competition of the agent's behaviour. The last attitude of every type of agent, absolutely flexible, imperfectly committed or absolutely stubborn, is competitive unless the stubbornness set is empty.

The following theorems, whose proofs are left to the reader, follow from the above discussion .

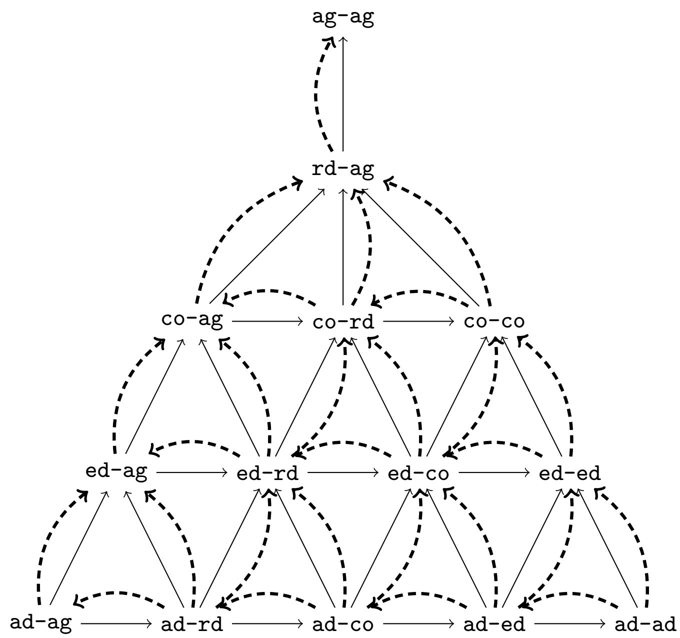


Figure 5.4. Superiority relation between legitimate rules. The plain edges identify competitive superiority relation and the dashed edges identify the collaborative ones.

Theorem 5.4. *Let* $\text{TheoryTree}_i = \langle \text{V}, \text{E} \rangle$ *be the subjective hierarchy of the agent* i*. The attitude of the agent* i *is absolutely competitive for all* k *when* $\text{flex}_i^k \leftrightarrow \text{stub}_i$.

rule name	rule description
ed-ad:	$j : \varphi, j : \textbf{essDis}(i : \text{flex}^k), \eta, \neg(\text{stub}_i \wedge \varphi) \Rightarrow i : \eta$
co-ad:	$j : \varphi, j : \textbf{comp}(i : \text{flex}^k), \eta, \neg(\text{stub}_i \wedge \varphi) \Rightarrow i : \eta$
co-ed:	$j : \varphi, j : \textbf{comp}(i : \text{flex}^k), \eta, (\text{stub}_i \vee \varphi) \wedge \neg(\eta \wedge \varphi) \Rightarrow i : \eta$
rd-ad:	$j : \varphi, j : \textbf{relDis}(i : \text{flex}^k), \eta, \neg(\text{stub}_i \wedge \varphi) \Rightarrow i : \eta$
rd-ed:	$j : \varphi, j : \textbf{relDis}(i : \text{flex}^k), \eta, (\text{stub}_i \vee \varphi) \wedge \neg(\eta \wedge \varphi) \Rightarrow i : \eta$
rd-co:	$j : \varphi, j : \textbf{relDis}(i : \text{flex}^k), \eta, (\eta \vee \tau_{i,j}(\varphi)) \wedge \neg(\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$
rd-rd:	$j : \varphi, j : \textbf{relDis}(i : \text{flex}^k), \eta, (\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$
ag-ad:	$j : \varphi, j : \textbf{agree}(i : \text{flex}^k), \eta, \neg(\text{stub}_i \wedge \varphi) \Rightarrow i : \eta$
ag-ed:	$j : \varphi, j : \textbf{agree}(i : \text{flex}^k), \eta, (\text{stub}_i \vee \varphi) \wedge \neg(\eta \wedge \varphi) \Rightarrow i : \eta$
ag-co:	$j : \varphi, j : \textbf{agree}(i : \text{flex}^k), \eta, (\eta \vee \tau_{i,j}(\varphi)) \wedge \neg(\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$
ag-rd:	$j : \varphi, j : \textbf{agree}(i : \text{flex}^k), \eta, (\eta \rightarrow \tau_{i,j}(\varphi)) \wedge \neg(\tau_{i,j}(\varphi) \rightarrow \eta) \Rightarrow i : \eta$

Table 5.8. The violation rules in $\mathcal{R}_{\text{A}}^k$ of the auctioneer i receiving offers from the negotiating agent j.

Proof Suppose that the current disagreement relation between agents is x and that the agent i is in stubbornness position at time k, i.e. $\text{flex}_i^k \leftrightarrow \text{stub}_i$. By definition, the $k+1$ proposal of i is still stub_i so that the disagreement relation raised is again x and the defeasible rule corresponding to the choice of the next proposal is $\mathrm{x}-\mathrm{x}$. Because $\mathrm{x}-\mathrm{x}$ is preferred over all the other rules, the attitude of the agent is absolutely competitive. □

Theorem 5.5. *Let* $\text{TheoryTree}_i = \langle \mathrm{V}, \mathrm{E} \rangle$ *be the subjective hierarchy of the agent i and suppose that i is absolutely flexible. The attitude of the agent i is collaborative-meets-competitive where the change-parameter* $\chi_i = 1$.

Proof Agent i is absolutely flexible then her subjective hierarchy has only two connected node, the initial proposal t^0 and the stubbornness node s. By definition, an absolutely flexible agent proposes only one time her initial angle and if it is not accepted by the opponent, she proposes her last angle. Let x the disagreement relation between the agent when agent i proposes t^0. After having proposed t^0, agent i proposes s and it possibly produces a new disagreement relation between agents, say y, that improves the negotiation situation between agents. The defeasible rules used by i are $\mathrm{x}-\mathrm{y}$ in which y possibly is better than y. The attitude of i prefers the $\mathrm{x}-\mathrm{y}$ rules to the $\mathrm{x}-\mathrm{x}$ ones thus it is collaborative. At the following negotiation steps, the agent is in her stubbornness position and she becomes absolutely competitive as proved in Theorem 5.4. The resulting attitude of the agent is therefore collaborative-meets-competitive and the change of attitude raises after the initial proposal so that $\chi_i = 1$. □

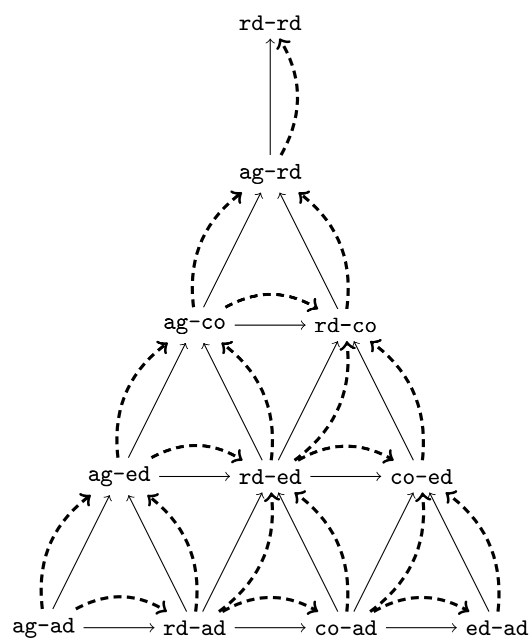


Figure 5.5. Superiority relation between violation rules. The plain edges identify competitive superiority relation and the dashed edges identify the collaborative ones.

Theorem 5.6. *Let* $\text{TheoryTree}_i = \langle \mathrm{V}, \mathrm{E} \rangle$ *be the subjective hierarchy of the agent* i *and suppose that* i *is absolutely stubborn. The attitude of the agent* i *is absolutely competitive.*

Proof When an agent is absolutely stubborn, her subjective hierarchy has only one node corresponding to her stubbornness knowledge. The agent always proposes the same proposal and thus preserves the disagreement relation between the agents. As proved in Theorem 5.4 the agent has an absolutely competitive attitude. □

6

Related Work

6.1 Introduction

In this chapter I present the main contributions of the Artificial Intelligence scholars to the solution of the problem of the Meaning Negotiation and to all the formalisms to which it is based. In particular, when dealing with the Meaning Negotiation, the researchers have identify three main aspects to formalise:

- the knowledge of the agents;
- the ways the agents coordinate and communicate in a negotiation;
- how the agents strategically negotiate.

The representation of the agents' knowledge focuses upon all the information the knowledge has to contain and how it has to be formalised in order to make agents able to negotiate. Moreover, the agents negotiate by making concession and in terms of knowledge it is translated in a *weakening* or *generalising* operation to the set of beliefs.

During a negotiation the communication of the agents follows a negotiation protocol that guides the negotiation process. The protocol adopted in the majority of the studies, is the alternating offer one of Rubinstein, extended by many recent works [71, 105, 143] and those based upon the Contract Net protocol of FIPA community [8, 34, 115]. The definition of the negotiation protocol is outside the scope of this thesis. I assume that the feasible actions of agents are to accept or reject a received offer and to make a proposal.

Another important point in Meaning Negotiation is how agents reason during the negotiation, i.e. how they interpret and understand the negotiation development, how they build the next proposal to perform and finally how they strategically move.

In the following sections I present how the knowledge of the agents has been modeled (Section 6.2), then I show the two main approaches of the current literature about the Meaning Negotiation process (Section 6.3) and finally a presentation of the strategic agent formalisations is in Section 6.4.

6.2 Knowledge Representation

The problem of representing the knowledge of agents and entities is widely studied in Artificial Intelligence community and it has a large number of ways in which the knowledge is treated.

Knowledge of agents contains many information: it contains agents' beliefs, their desires and how they want to communicate to each other [53], and what they know about the knowledge of another agent, etc. The expression language of the agent represents itself the knowledge of the agent.

Typically, the knowledge of an agent is represented by the epistemic operator K_i which enables agent to do not know everything in the world and have an incomplete knowledge. The epistemic operator produces an accessibility relation between the interpretation worlds by which a world is accessible from another if the agent adds new information to her knowledge. The *common knowledge* and *"everybody knows"* modal operators are built from K_i [64]. Having a group of agents G, $E_G(e) = \bigcap_{i \in G} K_i e$ formalises the fact that *everybody in G knows e*. The common knowledge operator is fixed-point defined by $C_G(e) = \bigcap_{k=1}^{\infty} E_G^k(e)$.

In [74], the authors discuss about the contextual aspect of the knowledge. They propose the *local model semantics* (LMC) as a foundation to reasoning with contexts. The claim is that reasoning is mainly *local* and uses only part of what is potential available; this part is called *context*. However, there is *compatibility* among the reasoning performed in differen contexts. In their model, the agents have a *viewpoint* that is the perspective by which they represent their beliefs about the world. The authors identify the problem of agents perceiving two different situations in the same way and thus of having incomplete knowledge.

In Meaning Negotiation scenarios, the incompleteness of the knowledge of the agent is not the unique problem. In [68, 69], the author discusses about how the agents represents the meaning of a concept. The agents have two ways of defining the notion of a concept: *classical*, inferred by $\vdash$, and *typical*, inferred by $|\!\sim$. The same idea is basic in the non monotonic reasoning mechanisms of defeasible logic [129] and default reasoning [16].

In the following subsection I describe the problems of ambiguity and uncertainty in knowledge representation.

6.2.1 Ambiguity and Vagueness

Vague and ambiguous definitions for concepts are dealt with massively in Knowledge Representation communities. These problems can interfere with negotiation of meaning.

The *ambiguity* causes many different meaning of terms and even if it is vital in the communication of learning agents [166], it may lead to *misunderstanding* situations [118–120]. The ambiguity raises when agents use nouns, adjectives, verbs requiring a comparison terms. In [165], the authors specify how to interpret the relative adjective (for instance "tall") by means of a model formalising the representation questions:

- How are comparison classes represented?
- What kind of knowledge determines comparison class?

- what are conceptual linkages between degree expressions and comparison classes at the knowledge level?

The model requires a domain ontology definition and a way to determine the interrelations between the degrees of concept definition. These interrelations are studied in [25] as a form of dynamic vagueness.

The authors in [145] specify the semantics of the adjectives in terms of a comparison and they propose a way to make a taxonomy of ambiguous adjectives.

A different and more recent approach is [116] in which the problem of word sense disambiguation (WDS) is solved by a system based upon the strength, the relevance and the occurrences of terms. The system is supported by WordNet [7].

The *vagueness* is a different problem. A concept is vague whenever it is not always possible to denote all the elements representing it. Vagueness is typical of terms in spatial and temporal knowledge [32]. A typical example is in [31] in which the author examines the ways in which the meaning of "forest" can be represented.

Vagueness is a consequence of *uncertainty* and incomplete knowledge of the agent. In [150] the author makes a distinction between *epistemic uncertainty* and *conceptual uncertainty*. The former is caused by the incomplete knowledge about the facts of the world. The latter is caused by the incomplete knowledge about the meaning of the terms used by agents.

The vagueness and uncertainty are generally approached in two ways: by *fuzzy sets* in which there are more than two degree of true [85], and by *super valuations*. Borderline cases (for a predicate like bald) are those for which some competent speakers would judge that the predicate applies (is true) and some others not (they judge it to be false).

In [135], the uncertainty and vagueness are formalised by means of *rough sets* by assuming that the meaning of concepts is identified uniquely by the elements representing it. The vagueness is described by two delimiting lines: one line delimits the elements that certainly represent the concept and a second line groups together the elements that certainly do not represent the concept. The elements in the middle of the two lines are *vague elements*.

The community of Artificial Intelligence has dealt with the problem of vagueness also by modal logic. The idea is to define a modal operator to represent what is *unquestionable* and what is *necessary* [30, 86].

6.3 Negotiation Problem

The Meaning Negotiation problem has reached large attention in the Artificial Intelligence community. Two are the most general approaches to the problem of finding a shared knowledge from many different and possibly inconsistent ones. The first way to model the Meaning Negotiation process is by viewing it as a conflict resolution. The participants of a negotiation litigate about how to share something and they may disagree in many ways [91].

The second way to model Meaning Negotiation is as a set of operations made to the beliefs' sets of the agents involved. The scope is to construct a commonly accepted knowledge.

In the following sections I present the main contributions of the Artificial Intelligence community in dealing with the Meaning Negotiation Problem from the conflict resolution perspective (Section 6.3.1) and the shared knowledge construction (Section 6.3.2).

6.3.1 Meaning Negotiation as conflict resolution: Argumentation Theory

Argumentation theory, or argumentation, is the interdisciplinary study of how humans should, can, and do reach conclusions through logical reasoning, that is, claims based, soundly or not, on premises. It includes the arts and sciences of civil debate, dialogue, conversation, and persuasion. It studies rules of inference, logic, and procedural rules in both artificial and real world settings.

Argumentation includes debate and negotiation which are concerned with reaching mutually acceptable conclusions [22,106,133,157]. It also encompasses eristic dialog, the branch of social debate in which victory over an opponent is the primary goal. This art and science is often the means by which people protect their beliefs or self-interests in rational dialogue, in common parlance, and during the process of arguing.

Argumentation is used in law, for example in trials, in preparing an argument to be presented to a court, and in testing the validity of certain kinds of evidence. Also, argumentation scholars study the post hoc rationalizations by which organizational actors try to justify decisions they have made irrationally.

The main approaches to the Argumentation theory are: the pragma-dialectical theory and the argumentative schemes.

The *pragma-dialectical theory*, developed by Frans H. van Eemeren and Rob Grootendorst (see [172, 174]), is an argumentation theory that is used to analyze and evaluate argumentation in actual practice. Unlike strictly logical approaches (which focus on the study of argument as product), or purely communication approaches (which emphasize argument as a process), pragma-dialectics was developed to study the entirety of an argumentation as a discourse activity. Thus, the pragma-dialectical theory views argumentation as a complex speech act that occurs as part of natural language activities and has specific communicative goals.

The pragma-dialectical theory combines a pragmatic perspective of the argumentative interaction by means of speech acts and moves, with rules' identification to state the validity of an argument.

The argumentation is viewed as a critical discussion about the resolution of a conflicts. In this ideal model of a critical discussion, four discussion stages are distinguished that the discussion parties have to go through to resolve their difference of opinion (see [173] pp.85-88; [174], pp.34-35; [175], pp.59-62):

1. the confrontation stage: the interlocutors establish that they have a difference of opinion;
2. opening stage: they decide to resolve this difference of opinion. The interlocutors determine their points of departure: they agree upon the rules of the discussion and establish which propositions they can use in their argumentation;

3. argumentation stage: the protagonist defends his/her standpoint by putting forward arguments to counter the antagonists objections or doubt;
4. concluding stage: the discussion parties evaluate to what extent their initial difference of opinion has been resolved and in whose favor.

The ideal model stipulates ten rules that apply to an argumentative discussion. Violations of the discussion rules are said to frustrate the reasonable resolution of the difference of opinion and they are therefore considered as fallacies.

The ten rules (see [172], pp.182-183):

1. *Freedom rule*: Parties must not prevent each other from advancing standpoints or from casting doubt on standpoints;
2. *Burden of proof rule* A party that advances a standpoint is obliged to defend it if asked by the other party to do so;
3. *Standpoint rule* A party's attack on a standpoint must relate to the standpoint that has indeed been advanced by the other party;
4. *Relevance rule* A party may defend a standpoint only by advancing argumentation relating to that standpoint.;
5. *Unexpressed premise rule* A party may not deny premise that he or she has left implicit or falsely present something as a premise that has been left unexpressed by the other party;
6. *Starting point rule* A party may not falsely present a premise as an accepted starting point nor deny a premise representing an accepted starting point;
7. *Argument scheme rule* A party may not regard a standpoint as conclusively defended if the defense does not take place by means of an appropriate argumentation scheme that is correctly applied;
8. *Validity rule* A party may only use arguments in its argumentation that are logically valid or capable of being made logically valid by making explicit one or more unexpressed premises;
9. *Closure rule* A failed defense of a standpoint must result in the party that put forward the standpoint retracting it and a conclusive defense of the standpoint must result in the other party retracting its doubt about the standpoint;
10. *Usage rule* A party must not use formulations that are insufficiently clear or confusingly ambiguous and a party must interpret the other partys formulations as carefully and accurately as possible.

The representation of *Argumentative schemes* constitutes one of the central topics in current argumentation theory and they represent common patterns of reasoning used in everyday conversational discourse. Important contributions to the study of argument schemes have been made by Douglas Walton [55–57, 141, 141]. As considered by him, argument schemes technically have the form of an inference rule: an argument scheme has a set of premises and a conclusion. Argument schemes are not classified according to their logical form but according to their content. Many argument schemes in fact express epistemological principles or principles of practical reasoning.

The argumentation schemes approach is based upon the Toulmin model of the argumentation [170]. Toulmin defines the argument as the structure in Figure 6.1. Toulmin proposed a layout containing six interrelated components for analyzing arguments:

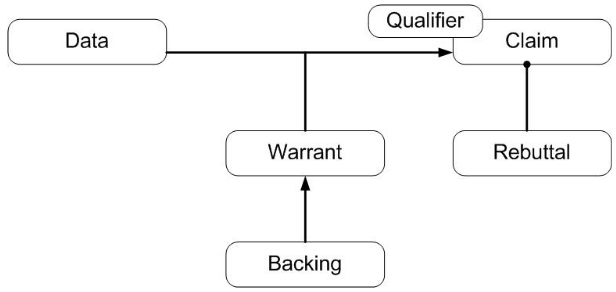


Figure 6.1. The Toulmin model

Claim : A conclusion whose merit must be established. For example, if a person tries to convince a listener that he is a British citizen, the claim would be "I am a British citizen."(1);

Evidence (Data) : A fact one appeals to as a foundation for the claim. For example, the person introduced in 1 can support his claim with the supporting data "I was born in Bermuda."(2);

Warrant : A statement authorizing movement from the data to the claim. In order to move from the data established in 2, "I was born in Bermuda," to the claim in 1, "I am a British citizen," the person must supply a warrant to bridge the gap between 1 and 2 with the statement "A man born in Bermuda will legally be a British citizen."(3);

Backing : Credentials designed to certify the statement expressed in the warrant; backing must be introduced when the warrant itself is not convincing enough to the readers or the listeners. For example, if the listener does not deem the warrant in 3 as credible, the speaker will supply the legal provisions as backing statement to show that it is true that "A man born in Bermuda will legally be a British citizen.";

Rebuttal : Statements recognizing the restrictions which may legitimately be applied to the claim. The rebuttal is exemplified as follows: "A man born in Bermuda will legally be a British citizen, unless he has betrayed Britain and has become a spy of another country.";

Qualifier Words or phrases expressing the speakers degree of force or certainty concerning the claim. Such words or phrases include "probably," "possible," "impossible," "certainly," "presumably," "as far as the evidence goes," and "necessarily." The claim "I am definitely a British citizen" has a greater degree of force than the claim "I am a British citizen, presumably.";

The first three elements, *claim*, *evidence* and *warrant* are considered as the essential components of practical arguments, while the second triad, *qualifier*, *backing* and *rebuttal* may not be needed in some arguments.

The process of resolving conflicts between agents by argumentation involves not only a negotiation dialogue, but also a *persuasion* one [181]. The participants in a negotiation by argumentation propose arguments to the opponents and make counterproposals in two way: by rebutting and or by undercutting the proposals of the opponents. Rebuttal of a rule claiming c, is made by a rule in which the claim is the negation of c. A rule r undercuts a rule r' if the claim of r is the negation of some of the premises of r'.

When no undercut and rebuttal rules are available, an agent can accept the argument posted by someone else in the system in two ways [61]:

- *skeptical*: the argument is acceptable until somebody else claims the contrary ;
- *credulous*: the argument is wholeheartedly accepted.

In [60] the author explores the mechanisms humans use in argumentation to state the correctness, the appropriateness and the acceptability of arguments.

To persuade the opponents about the validity of the argument she proposes, the proponent has to *justify* it [100,137,140,153,169,180] or to have its proof. Recent investigations have dealt with the problem about who has the burden of proving a claim and which argument produces a burden of proof [66,77,131,142,179]. In [92] a complete survey of the logical models of arguments is presented.

Argumentation Theory is largely used in legal reasoning to model the interactions according to the legal debate rules [27,52,79,104]. In particular, in [26], the authors formalise an argumentation framework in order to model the definitions of *objectively* and *subjectively acceptable*, and *indefensible* argument. The definition of the above degrees of acceptance of an argument is based upon a value given to the arguments and a form of preference between them that the agents have.

Legal reasoning typically requires a variety of argumentation schemes to be used together. A legal case may raise issues requiring argument from precedent cases, rules, policy goals, moral principles, jurisprudential doctrine, social values and evidence. Systems supporting the application of argumentation schemes as Carneades [77,78], and Araucaria [147,148] intend to be tools for argument construction, evaluation and visualisation.

In [114], the authors present a brief survey of argumentation in multi-agent systems. It is not only brief, but rather idiosyncratic, and focuses on the areas of research of belief revision, agent communication and reasoning.

6.3.2 Meaning Negotiation as a Beliefs' operation

Meaning Negotiation was studied in the Artificial Intelligence community as the process of merging information becoming from different sources. The problem of how the merging has to be done was approached in two steps:

- how the different sources have inconsistent beliefs and how they are mutually reliable;
- how and when beliefs causing conflicts have to be merged into the knowledge base.

The first point was studied by the *information fusion* researchers and the second by the *belief revision* ones.

In [83] the author makes a survey of the contributions from the artificial intelligence research literature about logic-based information fusion. The assumption made by the early approaches were:

- Information sources are mutually independent;
- All sources exhibit the same level of importance;

- The level of information importance is also constant.

The main assumption regards the completely reliance of all the information sources as in [39]. More realistic approaches suppose that the information sources are not equally reliable and that some source is preferred with respect to the available ones. In [82] the reliability of the information sources is defined as a preference order. Another precedent approach assume a weight applied to the beliefs for each source by which they come [111].

In the situations in which the information sources are equally reliable, the merging is said *non-prioritized* otherwise a degree of certainty or plausibility is given to the belief [67].

When the beliefs coming from the different sources, they have to be merged in order to *minimally change* the initial knowledge base. The operation needed to add new information into a knowledge base is known as *revision* and it involves only conflicting beliefs during a negotiation process. The general approach of *maximal adjustment* is to remove the present belief causing the conflict and adding the new one. In [29] the author present a *disjunctive maximal adjustment* in which the belief are weighted and thus not always removed or simply added into the knowledge base.

The merging[1] of beliefs was defined by two operators [110]: *majority* and *arbitration*. Both make assumptions upon the information sources. The former revises the knowledge base by belief belonging to the majority number of information sources. The latter revises the knowledge bases by the beliefs belonging to the most reliable information sources.

In [102] the author defines the postulates regulating the merging operators by assuming that there are *integrity constant* to assure.

Thus, in a belief merging and information fusion literature, the negotiation is modeled as a two stage processes: contraction of the beliefs causing the conflict and expansions by the new knowledge [39]. In [188] the author define a way to formalise the negotiation process as a function and he proposes a set of postulates, similar to the AGM ones for revision for the negotiation function.

6.4 Negotiation Strategies

Decision making, often viewed as a form of reasoning towards actions to be taken, has raised the interest of many scholars including philosophers, economists, psychologists, and computer scientists for a long time. Any decision problem amounts to selecting the “best” or sufficiently “good” action(s) that are feasible among different alternatives, given some available information about the current state of the world and the consequences of potential actions. Note that available information may be incomplete or pervaded with uncertainty. Besides, the goodness

[1] One can be tempted to assume that arbitration and majority operators can be fruitfully employed to solve any admissible problem of negotiation. However, as clarified in Chapter 5 and specifically declined for bargaining and English Auction models in Chapter 3 negotiation is the process of reaching agreements not the underlying semantic theory about the models. Therefore, although I can model the resulting theory by the theory of belief revision, negotiation processes are out of scope in these theories.

of an action is judged by estimating, maybe by means of several criteria, how much its possible consequences fit the preferences or the intentions of the decision maker. This agent is assumed to behave in a rational way [55, 138, 139] at least in the sense that his decisions should be as much as possible consistent with his preferences. However, it may be the case that more requiring view of rationality is demanded, such as demanding for the conformity of decision makers behavior with postulates describing how a rational agent should behave. Decision problems have been considered from different points of view. Classical decision theory, as developed mainly by economists, has focused on making clear what is a rational decision maker. Thus, they have looked for principles for comparing different alternatives. A particular decision principle, such as the classical expected utility, has been justified on the basis of a set of rationality postulates to which the preference relation between actions should obey. This means that in this approach, rationality is captured through a set of postulates that describe what is a rational decision behavior.

From a Meaning negotiation perspective, rationality in decision making of agents are generally approached in three main research areas: Intention Theory, Game Theory and Argumentation Theory.

In the following sections I present a compact survey about the main features of strategy of agents in negotiation by means of BDI agent (Section 6.4.1), of Game Theory (Section 6.4.2) and of Argumentation Theory (Section 6.4.3)

6.4.1 Beliefs-Desires-Intentions: BDI agents

One of the firstly explored approaches of formalising the self-interest behaviour of an agent is by means of *BDI agents*. In [45], the authors attempt to show how the various components of an agent's cognitive make-up could be combined to form a logic of rational agency. The theory of intention defines a many-sorted, first-order, multi-modal logic with equality in which a modal operator is defined for both belief and goal. The semantics of the modal operator is given via possible-worlds: the belief and goal accessibility relations are assigned to each agent in the MAS. Some works about BDI agents for agency are [73, 127, 158].

The meaning of the basic operators are:

- (Bel i φ) agent i belives φ;
- (Goal i φ) agent i has goal of φ;
- (Happens α) action α will happen next;
- (Done α) action α has just happened;

Intentionality is defined by a construct:

$$(\text{Int } i\alpha) = (\text{PGoal } i \ (\text{Done } i \ (\text{Bel } i \ (\text{Happens } \alpha))?; \alpha))$$

The meaning of the above definition is: the agent i has the intention of α iff she thinks that α is feasible and the performance of α is a persistent goal.

Implementations of the BDI agents are given in many research areas. In particular in non-monotonic reasoning.

In [35, 36] the knowledge of the agents as premises of actions are layered in order to give a weight to actions, thus a preference. The preconditions of actions may be absolutely true, usually verified, weak, absolutely false or possible.

Agency is formalised by means of defeasible logic rules, distinguished in belief, intention, agency and obligation rules [81]. In [80], the defeasible rules for belief, intention, agency and obligation may attack each other. The superiority relation among them generates the type of the agent behaviour: social, strongly social, independent, pragmatic, selfish, etc. (see Table 2 and 3 in [80]).

6.4.2 Game Theory

Game theory is a closely related to decision theory, which studies interactions between self-interested agents. In particular, it studies the problems of how interaction strategies can be designed that will maximise the welfare of an agent in a multi-agent encounter, and how protocols or mechanisms can be designed that have certain desirable properties. Notice that decision theory can be considered to be the study of games against nature, where nature is an opponent that does not seek to gain the best payout, but rather acts randomly. Many of the applications of game theory in agent systems have been used to analyse multi-agent interactions, particularly those involving negotiation and co-ordination. In [134] the authors motivate the use of the Game Theory features in agents' behaving strategically with respect to the decision theory. They compare the Bayesian network and the Markov decision processes with the Game Theory studies.

In the early Game Theory approaches, it was assumed that agents in MAS are benevolent in the sense that they share a common goal and that they are happy to help out whenever asked. Over time, however, it has come to be recognised that in fact, benevolence is the exception; self-interest is the norm.

Benevolent and self-interested agents have different behavioral rules and they interact with one another in *cooperative* or *adversarial* ways respectively [169].

The classic game theoretic question asked of any particular multi-agent encounter is: what is the bestmost rationalthing an agent can do? In most multi-agent encounters, the overall outcome will depend critically on the choices made by all agents in the scenario. This implies that in order for an agent to make the choice that optimises its outcome, it must reason strategically.

Computer science brings two important considerations to the game theoretic study of negotiation and bargaining [94]:

1. Game theoretic studies of rational choice in multi-agent encounters typically assume that agents are allowed to select the best strategy from the space of all possible strategies, by considering all possible interactions. It turns out that the search space of strategies and interactions that needs to be considered has exponential growth, which means that the problem of finding an optimal strategy is in general computationally intractable;
2. The emergence of the Internet and World-Wide Web has provided an enormous commercial imperative to the further development of computational negotiation and bargaining techniques [125];

Strategies of agents involved in a game, are defined in terms of *expected utility*: an agent evaluates the reachable states by means of actions by evaluating the payoffs the execution of the actions produce. The expected utility is a numerical function. The feasibility and the payoffs of the actions are measured in terms of probability. Moreover, the strategical behaviour also depends upon the agency of the opponents thus the agents have to consider the *acceptability* of their own actions [152].

The formalisation of an agent's strategy in negotiation is bounded to the properties of the interaction protocols: guaranteed success, maximising social welfare, Pareto efficiency, individual rationality, stability, simplicity and distribution. The Zeuthen strategy [151] says:

- the agent that should concede is the one with the most to lose from the negotiation breaking down;
- the concession that should be made is the minimum required to change the balance of risk so that the other agent is required to concede on subsequent rounds.

The recent approach to formalise the strategy of an agent is to find a set of criteria with respect to which evaluate the feasible actions [115]. In particular, the agents assume evaluating criteria in dependence of the role they have in the negotiation: seller or buyer, proponent or opponent [99].

6.4.3 Argumentation in Negotiation

The argumentation approach on choosing action to perform is based upon the so-called *practical syllogism* [55]:

- G is a goal for agent X;
- Doing action A is sufficient for agent X to carry out goal G;
- Then, agent X ought to do action A.

The above syllogism is in essence an argument in favor of the execution of the action A. In fact it is translated in the following argument [23]:

AS1 : In the circumstances R
We should perform action A;
Whose effect will results in state of affairs S;
Which will realise a goal G;
Which will promote some value V.

However, this does not mean that the action is warranted. In fact, counter-arguments may be built or provided against the action. Those counter-arguments are built from critical questions identified in [55] for the above syllogism. In particular, relevant questions are:

- "Are there alternative ways of realizing G?"
- "Is doing A feasible?"
- "Has agent X other goals than G?"
- "Are there other consequences of doing A which should be taken into account?"

In [18, 100], the above syllogism has been extended to explicitly take into account the reference to ethical values in arguments. However, the idea of using arguments for justifying or discarding candidate decisions is certainty very old, and its account in the literature at least dates back to Aristotle.

Solving a decision problem amounts to defining a pre-ordering, usually a complete one, on a set of possible options (or candidate decisions), on the basis of the different consequences of each decision.

Argumentation is used in [13, 14, 19, 24, 28, 58] for ordering the set of options. An argumentation-based decision process can be decomposed into the following steps:

1. Constructing arguments in favor/against statements (pertaining to beliefs or decisions);
2. Evaluating the strength of each argument;
3. Determining the different conflicts among arguments;
4. Evaluating the acceptability of arguments;
5. Comparing decisions on the basis of relevant "accepted" arguments;

The arguments are dived into two types:

- *epistemic argument* justifying beliefs and based themselves upon beliefs;
- *practical argument* justifying options and are built from both beliefs and preferences/goals.

The choice of the argument representing the action to perform is made by testing which are the argument *pro* and which are the *cons*. Moreover, the general approach is to use a preference relation among arguments [13, 21, 58, 89] or some sort of measure of the happiness of the reached states as a quantitative reasoning [15, 18, 70, 131].

A different approach is to define tactics and strategies [65,189] depending upon:

- *Time*: If an agent has a time deadline by which an agreement must be in place, these tactics model the fact that the agent is likely to concede more rapidly as the deadline approaches. The shape of the curve of concession is a function depending on time that is what differentiates tactics in this set;
- *Resources*: These tactics model the pressure in reaching an agreement that the limited resources - e.g. remaining bandwidth to be allocated, money, or any other- and the environment - e.g. number of clients, number of servers or economic parameters - impose upon the agent's behaviour. The functions in this set are similar to the time dependent functions except that the domain of the function is the quantity of resources available instead of the remaining time;
- *Imitative*: In situations in which the agent is not under a great deal of pressure to reach an agreement, it may choose to use imitative tactics that protect it from being exploited by other agents. In this case, the counter offer depends on the behaviour of the negotiation opponent. The tactics in this family differ in which aspect of their opponent's behaviour they imitate, and to what degree the opponent's behaviour is imitated.

6.5 Summary

Negotiation Frameworks	Negotiation Protocols	Negotiation Strategies
S. Kraus et al. [106]	S. Kraus [105]	J.L. Pollock [138]
S. Parsons et al. [133]	A. Ragone et al. [143]	J.L. Pollock [139]
K. Atkinson et al. [22]	N. Gatti [71]	W. Douglas [55]
M. Schroeder et al. [157]	S. Aknine et al. [8]	P. Cohen et al. [45]
F. H. van Eemeren et al. [174]	M.P. Georgeff et al. [73]	N. Naoyuki et al. [127]
F. H. Van Eemeren [172]	P. McBurney et al. [115]	Kiam Tian Seow et al. [158]
F. H. van Eemeren et al. [173]	M. Bichler [34]	J. Blee et al. [36]
F. H. van Eemeren et al. [175]		J. Blee et al. [35]
W. Douglas [55]		G. Governatori et al. [81]
H. Prakken et al. [141]		G. Governatori et al. [80]
W. Douglas [56]		S. Parsons et al. [134]
W. Douglas et al. [57]		S. Thakur et al. [169]
H. Prakken et al. [141]		N. R. Jennings et al. [94]
S. Toulmin [170]		A. Moukas et al. [125]
D.N. Walton et al. [181]		R. Roth et al. [152]
P.M. Dung et al. [61]		J. S. Rosenschein et al. [151]
P.M. Dung [60]		P. McBurney et al. [115]
J. L. Pollock [137]		N.C. Karunatillake et al. [99]
W. Douglas [180]		K. Atkinson et al. [23]
S. Rubinelli [153]		K. Atkinson [18]
K. Atkinson et al. [100]		K. Atkinson et al. [100]
S. Thakur et al. [169]		L. Amgoud et al. [13]
A. Farley et al. [66]		L. Amgoud et al. [14]
W. Douglas [179]		T. J. M. Bench-Capon et al. [28]
H. Prakken et al. [142]		K. Atkinson [24]
N. Oren et al. [131]		K. Atkinson et al. [19]
T.F. Gordon et al. [77]		S. Doutre et al. [58]
C. Ches nevar et al. [92]		K. Atkinson et al. [21]
A. Daskalopulu et al. [52]		Masahide Horita [89]
T.F. Gordon et al. [79]		B. Anrig et al. [15]
T.J.M. Bench-Capon [27]		N. Oren et al. [131]
R.A. Kowalski et al. [104]		D. Gaertner et al. [70]
T.Bench-Capon et al. [26]		P. Faratin et al. [65]
T.F. Gordon et al. [78]		I. Zukerman et al. [189]
T.F. Gordon et al. [77]		
C. Reed et al. [147]		
C. Reed et al. [148]		
N. Maudet et al.		
E. Grégoire et al. [83]		
R. Booth [39]		
E. Grégoire [82]		
L. Jinxin [111]		
E. Fermé et al. [67]		
S. Benferhat et al. [29]		
P. Liberatore et al. [110]		
S. Konieczny [102]		
D. Zhang et al. [188]		

Table 6.1. Summary of the current Artificial Intelligence approaches to MN problem

7

Conclusion and Future Works

In this thesis I formalised the process of reaching an agreement about the meaning of a set of terms among two or more than two agents. The agents start the negotiation process with an initial proposal and concede to each other about the other's viewpoint until a common definition of the terms is obtained. The agents have a limit in negotiation, since some of their knowledge is unquestionable, from each agent's viewpoint, and therefore, she will never concede about that knowledge. Consequently, after being flexible for a first phase of the negotiation process, when the agreement cannot be obtained, the agent becomes stubborn about her unquestionable knowledge. If this situation is symmetric, the disagreement condition becomes perpetual and the two agents keep on proposing the same incompatible definitions for the terms under negotiation. The system controls the procedure in what condition is reached. When the agreement condition is reached the agents agree about a common definition of the terms and the systems ends the negotiation with positive outcome, when the agents reach a perpetual disagreement condition the system ends the negotiation by stating that the agreement cannot be reached.

The work I presented is independent of the number of the involved agents and of the language they use to communicate indeed, the goal was to find a general model for the MN process in which the participants have their own beliefs and their own preferences with respect to the outcomes of the negotiation. Therefore, I derived a general framework in which Negotiation of Meaning, as a process, is exhibited in a unified manner.

The research plan that produces the formalisms was incremental, by adding one agent at a time. Moreover, the order of the presentation of this thesis reflects the research stages I passed through and the approaches to MN I investigated. I first analyse and formalise the MN as a game depending on the number of involved agents: Bargaining for bilateral negotiation, and English Auction for a more-than-two negotiation.

I provided the algorithms automating the MN games and I proved they are correct and complete.

Consequently, I presented a comprehensive view of the structure of the Meaning Negotiation process from a reasoning perspective. The theory I provided is complete in the sense that the possible ways in which an automation of the reasoning underlying the process of looking for an agreement in a multiple agent system are all included in the framework. The formalism I provide is a deduction system in which agents communicate to each other not only the proposals, but also the disagreement conditions they reached. The process is governed by a set of rules that manage the transitory disagreement condition the agents have reached so far.

As I remarked above, the literature has dealt with many different issues of the negotiation of meaning, but what has been only partially treated is the description of the process of reaching agreement conditions. This was the focus of this research, whose main results can be summarized in three points:

- I defined the agreement conditions and, more specifically, I classified the ways in which agents can be in disagreement. This refines the state-of-the-art, where the sole distinguishable conditions are agreement and disagreement ones.
- I defined rules for deriving streams of dialog among meaning negotiating agents.
- I defined a deduction system, *MND*, based upon these rules, which derives a stream of dialog that ends with an agreement (or disagreement) condition.

Although these results are only a first step, they show the usefulness, strength and potential of this approach.

Finally, I studied the problem of representing and formalising the strategical behaviour of agents. I proposed a Defeasible theory of strategy for each agent in which the defeasible rules are the feasible actions, divided into internal (choosing the next proposal) and assertive (making proposal). Facts are the assertions made during the MN, thus the defeasible theory is parameterised with a temporal factor which is the number of negotiation rounds. The superiority relation implements the attitude of agents: collaborative, i.e. it looks for the improvement of the welfare of the multiple agent system, or competitive, i.e. it looks for the improvement of personal advantage, or any combination of these.

The thesis is, for the best of my knowledge, the first attempt to model the MN in a general and comprehensive way: I specified properties and requirements of negotiating agent definition, I formalise a reasoning system MND and the protocol of the negotiation interaction by means of the corresponding game.

7.1 Future Work

Much is still to be done, in particular in the investigation of the formal properties of *MND*, such as soundness and completeness built constructively. The proofs of consistency and adequacy do not fix the relation to a given semantics, which is to be exhibited for a proof of soundness and a proof of completeness. Usually, a deduction system can be proved sound and complete against a standard interpretation of the language, which is difficult to circumscribe in our case, because of the presence of the relations between agents to be represented. A standard definition of the semantics for the *MND* systems is therefore needed in front of any further investigation of the soundness and completeness properties.

It would also be interesting to develop a decision making algorithm for those cases in which the system is decidable, in particular for finite signatures in addition to the case of competitive agents I considered here. This would foster both the automation of the subjective decision process (i.e., the automation of the deduction system alone) and the automation of the whole process per se (i.e., the definition of a procedure to establish the agreement terminal conditions). I shall also clarify how the different choices that every agent makes with respect to the sequence of proposals affect the general strategies and results of the MN process.

There is also room for a complete study of the ways in which strategies become tactics, and the differences arising in different situations depending upon the nature of the terms involved in the negotiation. Is it the case that negotiating terms in medical context is equivalent to negotiating terms in a legal context? Another open question is whether the negotiation purpose affects the process in any way, and also whether there is any influence of the order in which the negotiation proceeds term by term.

The investigation I carried out can also be extended by studying the ways in which trust functions between agents can be connected to specific strategies in choosing the next action.

Jointly with the definition of an algorithm for negotiating a common angle, this study can also enlarge the boundary of decidable cases. In particular, agents using some specific strategies can apply the rules in a finite number of steps even if the signature is infinite.

It would be interesting to define formally a family of semantics that result compatible with the deduction system. In relation to these semantics, in particular, I need a proof of soundness and completeness. Such an investigation would also bring to a study of automation, in particular it would be interesting to understand computability properties of the system and develop a procedure, and, in those cases in which the system results decidable, if any, an algorithm for decision making. Note that the automation process has two façades, namely the automation of the subjective decision process (the automation of the deduction system alone), and the automation of the whole process per se, namely the definition of a procedure, if possible, to establish the agreement terminal conditions.

Finally, I envisage two further extensions of our approach: (i) to applications in information security, e.g., investigating the relationships between the MN process and the management of authorization policies in security protocols and web services, and (ii) to extensions of e-learning and legal reasoning systems by modules to align the system and the user knowledge in order to prevent misunderstandings or to remove the incorrect interpretation models as in [17].

A

List of Articles

- Matteo Cristani, Elisa Burato: Modelling Social Attitudes of Agents. KES-AMSTA 2007: 63-72; [48]

- Elisa Burato, Matteo Cristani: Contract clause negotiation by game theory. ICAIL 2007: 71-80; [41]

- Matteo Cristani, Elisa Burato, Nicoletta Gabrielli: Ontology-Driven Compression of Temporal Series: A Case Study in SCADA Technologies. DEXA Workshops 2008: 734-738; [51]

- Matteo Cristani, Elisa Burato: Approximate solutions of moral dilemmas in multiple agent system. Knowl. Inf. Syst. 18(2): 157-181 (2009); [49]

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